Ideal Gases and Thermodynamics
A-Level Worksheet

9702/MJ/23/42/Q2

1 **(a)** **(i)** State what is meant by an ideal gas.

....

....

.... [2]

(ii) State the temperature, in degrees Celsius, of absolute zero.

temperature = ... °C [1]

(b) A sealed vessel contains a mass of 0.0424 kg of an ideal gas at 227 °C.
The pressure of the gas is 1.37×10^5 Pa and the volume of the gas is 0.640 m^3.

Calculate:

(i) the number of molecules of the gas in the vessel

number of molecules = ... [3]

(ii) the mass of one molecule of the gas

mass = ... kg [1]

(iii) the root-mean-square (r.m.s.) speed *v* of the molecules of the gas.

v = ... $m s^{-1}$ [3]

(c) The gas in **(b)** is now cooled gradually to absolute zero.

On Fig. 2.1, sketch the variation with thermodynamic temperature T of the r.m.s. speed of the molecules of the gas.

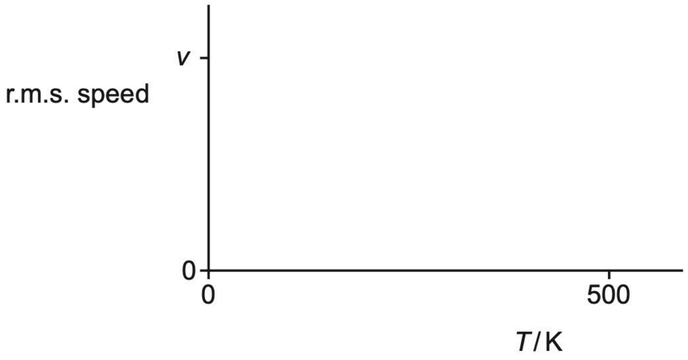

Fig. 2.1

[2]

[Total: 12]

9702/FM/23/42/Q2

2 **(a)** State what is meant by an ideal gas.

....

....

.... [2]

(b) A fixed amount of helium gas is sealed in a container. The helium gas has a pressure of 1.10×10^5 Pa, and a volume of $540\,\text{cm}^3$ at a temperature of 27 °C.

The volume of the container is rapidly decreased to $30.0\,\text{cm}^3$. The pressure of the helium gas increases to 6.70×10^6 Pa and its temperature increases to 742 °C, as illustrated in Fig. 2.1.

initial state	final state
1.10×10^5 Pa	6.70×10^6 Pa
$540\,\text{cm}^3$	$30.0\,\text{cm}^3$
27 °C	742 °C

Fig. 2.1

No thermal energy enters or leaves the helium gas during this process.

(i) Show that the helium gas behaves as an ideal gas.

[2]

(ii) The first law of thermodynamics may be expressed as

$$\Delta U = q + W.$$

Use the first law of thermodynamics to explain why the temperature of the helium gas increases.

....

....

....

....

.... [2]

(iii) The average translational kinetic energy E_K of a molecule of an ideal gas is given by

$$E_K = \frac{3}{2}kT$$

where k is the Boltzmann constant and T is the thermodynamic temperature.

Calculate the change in the total kinetic energy of the molecules of the helium gas.

change in kinetic energy = ... J [3]

(c) The mass of nitrogen gas in another container is 24.0 g at a temperature of 27 °C. The gas is cooled to its boiling point of –196 °C. Assume all the gas condenses to a liquid.

For this change the specific heat capacity of nitrogen gas is 1.04 $\text{kJ kg}^{-1}\text{K}^{-1}$.

The specific latent heat of vaporisation of nitrogen is 199 kJ kg^{-1}.

Determine the thermal energy, in kJ, removed from the nitrogen gas.

energy = ... kJ [3]

[Total: 12]

9702/ON/22/42/Q3

3 **(a)** The equation of state for an ideal gas can be written as

$$pV = NkT.$$

State the meaning of each of the symbols in this equation.

p: ....

V: ....

N: ....

k: ....

T: ....
[3]

(b) Use the equation in **(a)** to show that the average translational kinetic energy E_K of a molecule of an ideal gas is given by

$$E_K = \frac{3}{2}kT.$$

[2]

(c) The mass of an oxygen molecule is 5.31×10^{-26} kg. Assume that oxygen behaves as an ideal gas.

(i) Use the equation in **(b)** to determine the root-mean-square (r.m.s.) speed u of an oxygen molecule at 23 °C.

u = ... $\mathrm{m\,s^{-1}}$ [3]

(ii) A fixed mass of oxygen gas at initial pressure *P* is sealed in a cylindrical container by a movable piston at one end, as shown in Fig. 3.1.

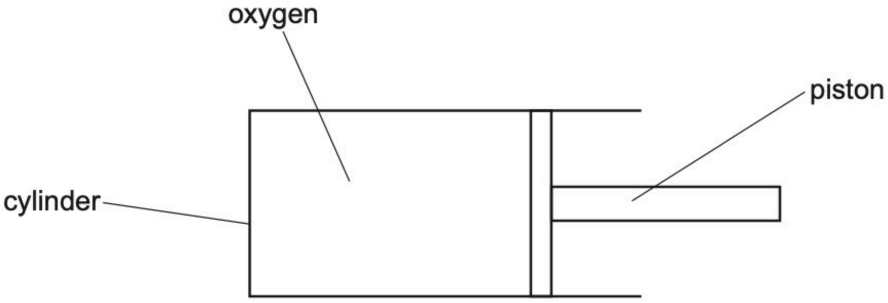

Fig. 3.1

The temperature of the gas is 23 °C.

The piston is slowly moved into the cylinder so that the oxygen gas is compressed. At all times, the gas and the container remain in thermal equilibrium with the surroundings.

On Fig. 3.2, sketch the variation with pressure of the r.m.s. speed of the oxygen molecules as the pressure increases.

Fig. 3.2

[2]

[Total: 10]

4 A fixed mass of an ideal gas is initially at a temperature of 17 °C.
The gas has a volume of 0.24 m^3 and a pressure of 1.2×10^5 Pa.

(a) **(i)** State what is meant by an ideal gas.

....

....

.... [2]

(ii) Calculate the amount *n* of gas.

n = ... mol [2]

(b) The gas undergoes three successive changes, as shown in Fig. 3.1.

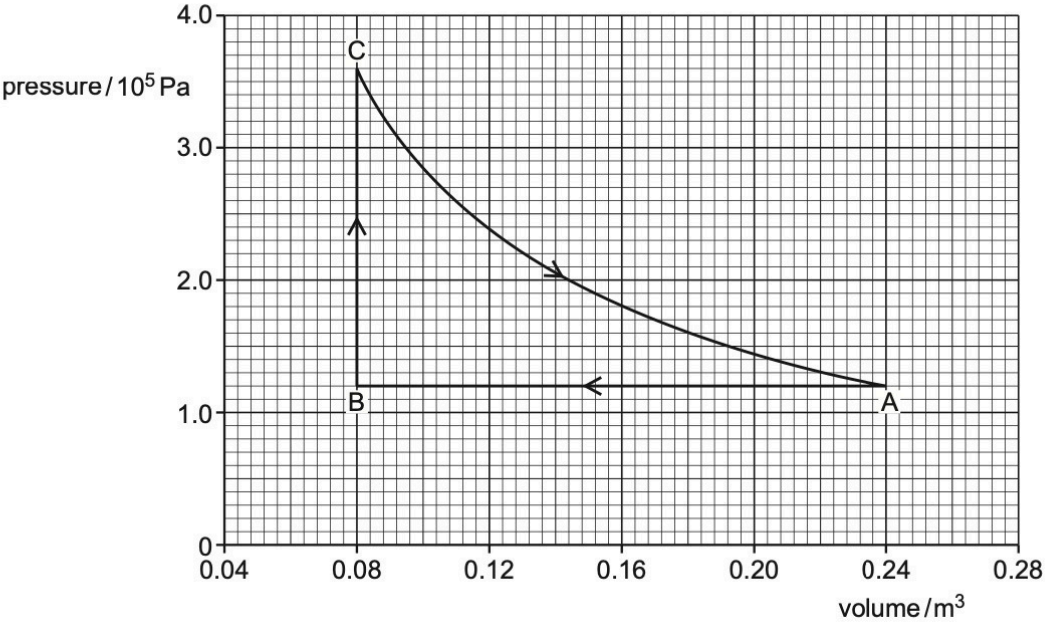

Fig. 3.1

The initial state is represented by point A. The gas is cooled at constant pressure to point B by the removal of 48.0 kJ of thermal energy.

The gas is then heated at constant volume to point C.

Finally, the gas expands at constant temperature back to its original pressure and volume at point A. During this expansion, the gas does 31.6 kJ of work.

(i) Show that the magnitude of the work done during the change AB is 19.2 kJ.

[2]

(ii) Complete Table 3.1 to show the work done on the gas, the thermal energy supplied to the gas and the increase in internal energy of the gas, for each of the changes AB, BC and CA.

Table 3.1

change	work done on gas / kJ	thermal energy supplied to gas / kJ	increase in internal energy of gas / kJ
AB		–48.0	
BC			
CA	–31.6		

[5]

[Total: 11]

S21/43/Q2

5 An ideal gas is contained in a cylinder by means of a movable frictionless piston, as illustrated in Fig. 2.1.

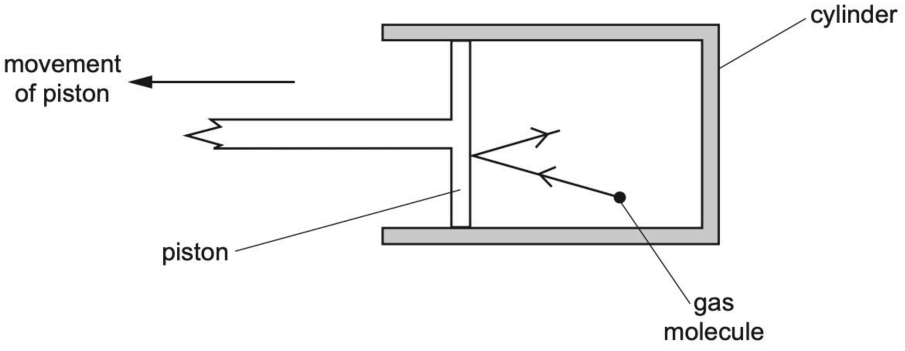

Fig. 2.1

Initially, the gas has a volume of $1.8 \times 10^{-3}\,\text{m}^3$ at a pressure of $3.3 \times 10^5\,\text{Pa}$ and a temperature of 310 K.

(a) Show that the number of gas molecules in the cylinder is 1.4×10^{23}.

[2]

(b) Use kinetic theory to explain why, when the piston is moved so that the gas expands, this causes a decrease in the temperature of the gas.

....

....

....

.... [3]

(c) The gas expands so that its volume increases to $2.4 \times 10^{-3}\,\text{m}^3$ at a pressure of $2.3 \times 10^5\,\text{Pa}$ and a temperature of 288 K, as shown in Fig. 2.2.

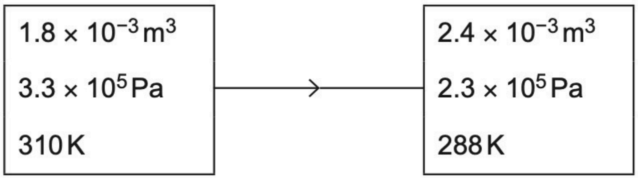

Fig. 2.2

(i) The average translational kinetic energy E_K of a molecule of an ideal gas is given by

$$E_K = \frac{3}{2}kT$$

where k is the Boltzmann constant and T is the thermodynamic temperature.

Calculate the increase in internal energy ΔU of the gas during the expansion.

ΔU = ... J [3]

(ii) The work done by the gas during the expansion is 76 J.

Use your answer in **(i)** to explain whether thermal energy is transferred to or from the gas during the expansion.

....

....

.... [2]

[Total: 10]

S21/42/Q2

6 An ideal gas has a volume of $3.1 \times 10^{-3}\,\text{m}^3$ at a pressure of $8.5 \times 10^5\,\text{Pa}$ and a temperature of 290 K, as shown in Fig. 2.1.

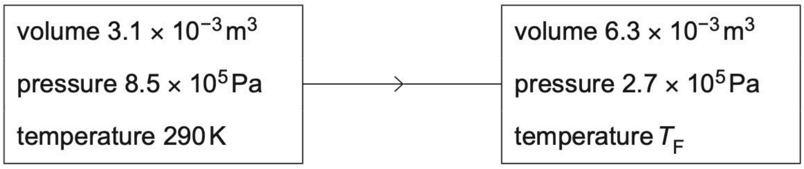

Fig. 2.1

The gas suddenly expands to a volume of $6.3 \times 10^{-3}\,\text{m}^3$. During the expansion, no thermal energy is transferred. The final pressure of the gas is $2.7 \times 10^5\,\text{Pa}$ at temperature T_F, as shown in Fig. 2.1.

(a) Show that the number of gas molecules is 6.6×10^{23}.

[3]

(b) **(i)** Show that the final temperature T_F of the gas is 190 K.

[1]

(ii) The average translational kinetic energy E_K of a molecule of an ideal gas is given by

$$E_K = \frac{3}{2}kT$$

where T is the thermodynamic temperature and k is the Boltzmann constant.

Calculate the increase in internal energy ΔU of the gas.

ΔU = ... J [3]

(c) Use the first law of thermodynamics to explain why the external work w done on the gas during the expansion is equal to the increase in internal energy in **(b)(ii)**.

....

....

.... [2]

[Total: 9]

7 **(a)** The first law of thermodynamics may be expressed as *W20/43/Q2*

$$\Delta U = (+q) + (+w)$$

where ΔU is the increase in internal energy of the system.

State the meaning of:

$+q$ ....

....

$+w$. ....

.... [2]

(b) The variation with pressure p of the volume V of a fixed mass of an ideal gas is shown in Fig. 2.1.

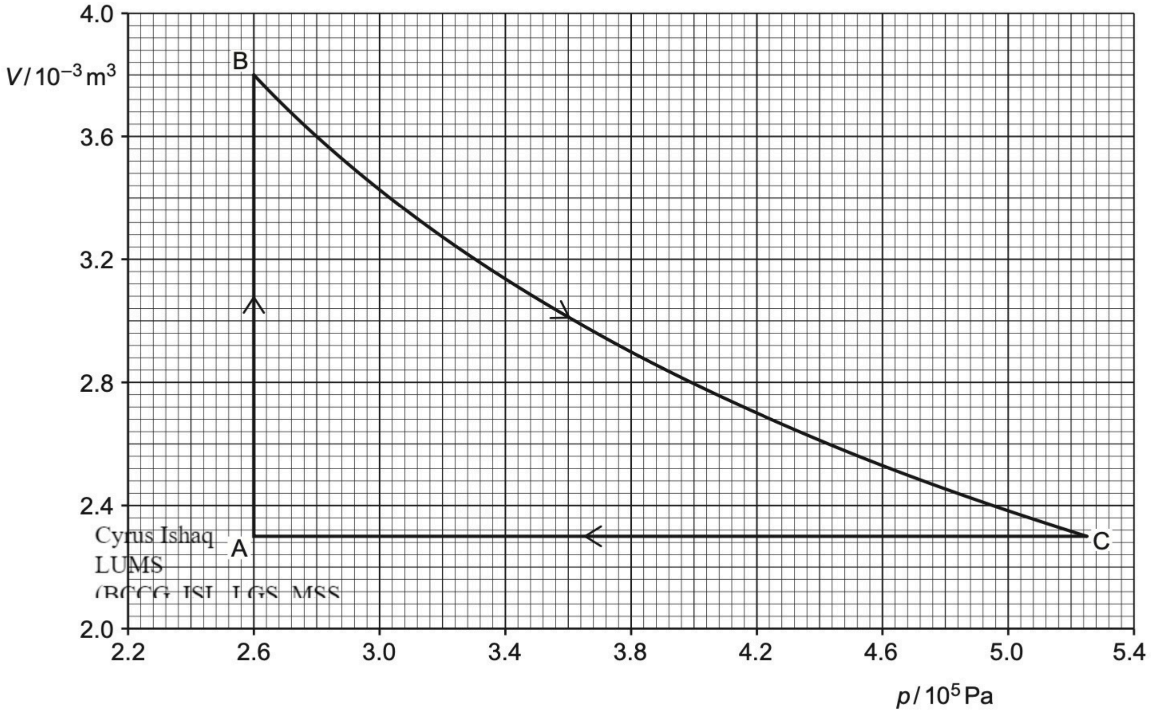

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Fig. 2.1

The gas undergoes a cycle of changes A to B to C to A.

During the change A to B, the volume of the gas increases from $2.3 \times 10^{-3}\,\text{m}^3$ to $3.8 \times 10^{-3}\,\text{m}^3$.

(i) Show that the magnitude of the work done during the change A to B is 390 J.

[1]

(ii) State and explain the total change, if any, in the internal energy of the gas during one complete cycle.

....

....

.... [2]

(c) During the change A to B, 1370 J of thermal energy is transferred to the gas.

During the change B to C, no thermal energy enters or leaves the gas. The work done on the gas during this change is 550 J.

Use these data and the information in **(b)** to complete Table 2.1.

Table 2.1

change	q / J	w / J	ΔU / J
A to B	....	....	....
B to C	....	....	....
C to A	....	....	....

[4]

[Total: 9]

8 **(a)** State what is meant by the *internal energy* of a system. ***W20/42/Q2***

....

....

.... [2]

(b) The atoms of an ideal gas occupy a container of volume $2.30 \times 10^{-3}\,\text{m}^3$ at pressure $2.60 \times 10^5\,\text{Pa}$ and temperature 180 K, as illustrated in Fig. 2.1.

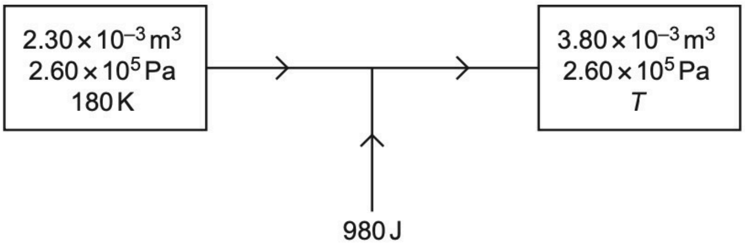

Fig. 2.1

The gas is heated at constant pressure so that its volume becomes $3.80 \times 10^{-3}\,\text{m}^3$ at a temperature T.

For the fixed mass of gas, calculate:

(i) the amount of substance, in mol

amount = ... mol [2]

(ii) the temperature T, in K.

T = ... K [2]

(c) During the change in **(b)**, the thermal energy supplied to the gas is 980 J.

(i) Determine the work done on the gas during this change. Explain your working.

work done = ... J [3]

(ii) Determine the change ΔU in internal energy of the gas.

ΔU = ... J [1]

[Total: 10]

9 A fixed mass of an ideal gas is at a temperature of 21 °C. The pressure of the gas is 2.3×10^{5} Pa and its volume is $3.5 \times 10^{-3}\,m^{3}$.

(a) **(i)** Calculate the number *N* of molecules in the gas.

N = ... [2]

(ii) The mass of one molecule of the gas is 40 u.
Determine the root-mean-square (r.m.s.) speed of the gas molecules.

r.m.s. speed = ... $m\,s^{-1}$ [2]

(b) The temperature of the gas is increased by 84 °C.

Calculate the value of the ratio $\dfrac{\text{new r.m.s. speed of molecules}}{\text{original r.m.s. speed of molecules}}$.

ratio = ... [2]

[Total: 6]

M20/42/Q2

10 A large container of volume 85 m^3 is filled with 110 kg of an ideal gas. The pressure of the gas is 1.0×10^5 Pa at temperature T.

The mass of 1.0 mol of the gas is 32 g.

(a) Show that the temperature T of the gas is approximately 300 K.

[3]

(b) The temperature of the gas is increased to 350 K at constant volume. The specific heat capacity of the gas for this change is 0.66 J kg^{-1} K^{-1}.

Calculate the energy supplied to the gas by heating.

energy = ... J [2]

(c) Explain how movement of the gas molecules causes pressure in the container.

....

....

....

....

....

....

(d) The temperature of a gas depends on the root-mean-square (r.m.s.) speed of its molecules.

Calculate the ratio:

$$\frac{\text{r.m.s. speed of gas molecules at 350 K}}{\text{r.m.s. speed of gas molecules at 300 K}}.$$

ratio = ... [2]

[Total: 10]

ON23/41/Q2

11 **(a)** Define specific heat capacity.

....

....

.... [2]

(b) An ideal gas of mass 0.35 kg is heated at a constant pressure of 2.0×10^5 Pa so that its internal energy increases by 7600 J. During this process, the volume of the gas increases from 0.038 m^3 to 0.063 m^3 and the temperature increases by 56 °C.

(i) Show that the magnitude of the work done on the gas is 5000 J.

[1]

(ii) Explain whether the work done on the gas is positive or negative.

....

....

.... [2]

(iii) Determine the magnitude of the thermal energy q transferred to the gas.

q = ... J [2]

(iv) Calculate the specific heat capacity of the gas for this process. Give a unit with your answer.

specific heat capacity = ... unit .... [2]

(c) The gas in **(b)** is now heated at constant volume rather than at constant pressure. The increase in internal energy of the gas is the same as in **(b)**.

Use the first law of thermodynamics to explain whether the specific heat capacity of the gas for this process is less than, the same as, or greater than the answer in **(b)(iv)**.

....

....

....

....

.... [3]

[Total: 12]

12 **(a)** The product pV for an ideal gas is given by ON23/41/Q3

$$pV = \frac{1}{3}Nm\langle c^2\rangle$$

where p is the pressure of the gas and V is the volume of the gas.

(i) State the meaning of the symbols N, m and $\langle c^2\rangle$ in this equation.

N: ....

m: ....

$\langle c^2\rangle$: ....
[3]

(ii) Use the equation of state for an ideal gas to show that the average translational kinetic energy E_K of a molecule of the gas at thermodynamic temperature T is given by

$$E_K = \frac{3}{2}kT.$$

[2]

(b) The surface of a star consists mainly of a gas that may be assumed to be ideal. The molecules of the gas have a root-mean-square (r.m.s.) speed of 9300 m s^{-1}.

The mass of a molecule of the gas is 3.34×10^{-27} kg.

Determine, to three significant figures, the temperature of the surface of the star.

temperature = ... K [2]

(d) The gas at the surface of a star has a very high pressure.

Use the basic assumptions of the kinetic theory to suggest why, in practice, a gas at the surface of a star is unlikely to behave as an ideal gas.

....

....

....

.... [2]

ON 23/42/Q3

13. **(a)** State what is meant by the internal energy of a system.

....

....

.... [2]

(b) Use the first law of thermodynamics to explain what happens to the internal energy:

(i) of a spring when it is stretched at constant temperature within its elastic limit

....

....

....

....

.... [3]

(ii) of a sample of water when it evaporates from a rain puddle on a hot day.

....

....

....

....

.... [3]

[Total: 8]

14. **(a)** By referring to both kinetic energy and potential energy, explain what is meant by the internal energy of an ideal gas.

....

....

....

.... [2]

(b) A fixed mass of an ideal gas at a temperature of 20 °C is sealed in a cylinder by a piston, as shown in Fig. 2.1.

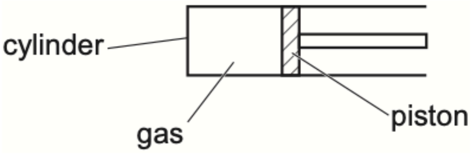

Fig. 2.1

The initial volume of the gas is $1.24 \times 10^{-4}\,\text{m}^3$.
Thermal energy is supplied to the gas and its volume increases by $5.20 \times 10^{-5}\,\text{m}^3$.

(i) The piston is freely moving so that the gas is always at atmospheric pressure.

Atmospheric pressure is $1.01 \times 10^5\,\text{Pa}$.

Calculate the work done by the gas.

work done by gas = ... J [2]

(ii) Calculate the final thermodynamic temperature T of the gas.

T = ... K [2]

(iii) The mass of the gas is 16 g. For this expansion, there is a net transfer of 960 J of thermal energy to the gas.

Calculate the specific heat capacity c of the gas at this pressure.

c = ... $\mathrm{J\,kg^{-1}\,K^{-1}}$ [2]

(c) The gas in **(b)** is allowed to return to its starting temperature. The piston is now fixed in position.

Thermal energy is supplied to increase the temperature to the same final temperature as in **(b)**.

Use the first law of thermodynamics to suggest and explain how the specific heat capacity of the gas for this situation compares with the value in **(b)(iii)**.

....

....

....

.... [3]

[Total: 11]

15. **(a)** **(i)** State what is meant by an ideal gas. MJ24/41/Q3

....

....

.... [2]

(ii) Use one of the basic assumptions of the kinetic theory to explain what can be deduced about the potential energy associated with the random motion of molecules in an ideal gas.

....

....

.... [2]

(b) A sample of 0.26 m^3 of an ideal gas is at pressure 2.0×10^5 Pa and temperature 290 K.

Determine:

(i) the number *N* of molecules of the gas

N = ... [2]

(ii) the average translational kinetic energy E_K of one molecule of the gas

E_K = ... J [2]

(iii) the internal energy of the gas. Explain your reasoning.

internal energy = ... J [2]

(c) The volume *V* of the gas in **(b)** is now varied, keeping its pressure constant.

On Fig. 3.1, sketch the variation with *V* of the internal energy *U* of the gas.

[2]

[Total: 12]

MJ24/42/Q2

16 **(a)** With reference to thermal energy, state what is meant by two objects being in thermal equilibrium.

....

....

.... [1]

(b) Two cylinders X and Y each contain a sample of an ideal gas. The samples are in thermal equilibrium with each other.

X has a volume of $0.0260\,\text{m}^3$ and contains 0.740 mol of gas at a pressure of $1.20 \times 10^5\,\text{Pa}$. Y has a volume of $0.0430\,\text{m}^3$ and contains gas at a pressure of $2.90 \times 10^5\,\text{Pa}$. Data for the two cylinders are shown in Fig. 2.1.

Fig. 2.1

(i) Show that the temperature of the gas in X is 234 °C.

[3]

(ii) Determine the number *N* of molecules of the gas in Y. Explain your reasoning.

N = ... [3]

(iii) The gas in X consists of molecules that each have a mass that is four times the mass of a molecule of the gas in Y.

Explain how the root-mean-square (r.m.s.) speed of the molecules in X compares with the r.m.s. speed of the molecules in Y.

....

....

....

....

.... [3]

[Total: 10]

MJ24/42/Q3

17. **(a)** State what is meant by the internal energy of a system.

....

....

.... [2]

(b) With reference to molecular kinetic and potential energies, describe and explain how the internal energy of the system changes when:

(i) a gas is heated at constant volume so that its temperature increases

....

....

....

....

.... [3]

(ii) a wire is stretched within its elastic limit at constant temperature.

....

....

....

....

.... [3]

[Total: 8]

ON24/41/Q3

18 **(a)** **(i)** State what is meant by the Avogadro constant.

....

....

.... [1]

(ii) State the relationship between the Avogadro constant N_A, the molar gas constant R and the Boltzmann constant k.

[1]

(b) Two samples X and Y of ideal gases are both at thermodynamic temperature T.

Sample X has volume V and consists of N molecules, each of mass m.
Sample Y has volume $2V$ and consists of $2N$ molecules, each of mass $2m$.

(i) Complete Table 3.1 by giving expressions, in terms of some or all of N, m, T, V and the constants in **(a)(ii)**, for the quantities indicated.

Table 3.1

	sample X	sample Y
pressure		
amount of substance		
mean-square speed of molecules		
internal energy		

[4]

(ii) The temperature of sample X is now varied.

On Fig. 3.1, sketch the variation with thermodynamic temperature of the root-mean-square (r.m.s.) speed of the molecules of the gas.

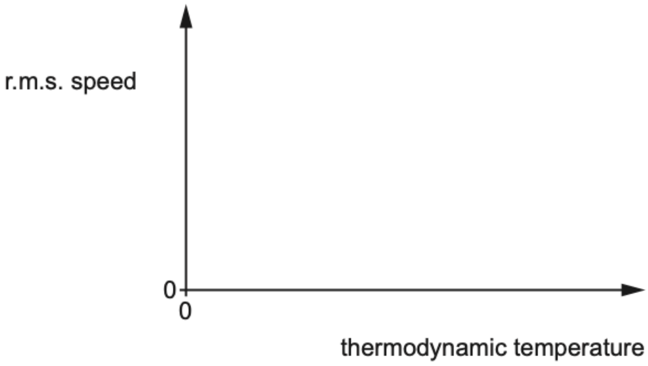

Fig. 3.1

[2]

[Total: 8]

19 **(a)** State **three** of the basic assumptions of the kinetic theory of gases.

1 ....

....

2 ....

....

3 ....

....
[3]

(b) Explain how molecular movement causes the pressure exerted by a gas.

....

....

....

....

.... [3]

(c) Fig. 4.1 shows the variation with thermodynamic temperature T of the mean-square speeds $\langle c^2 \rangle$ for two gases X and Y.

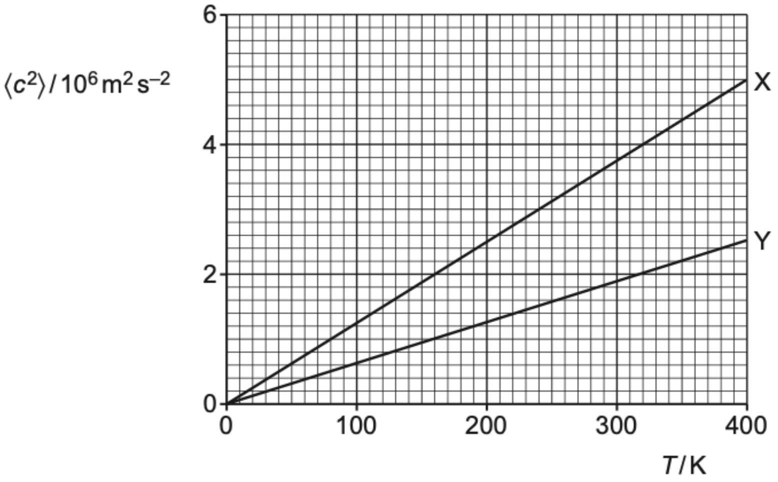

Fig. 4.2 shows the variation with T of the product pV for samples of the two gases, where p is the pressure of the gas and V is the volume of the gas.

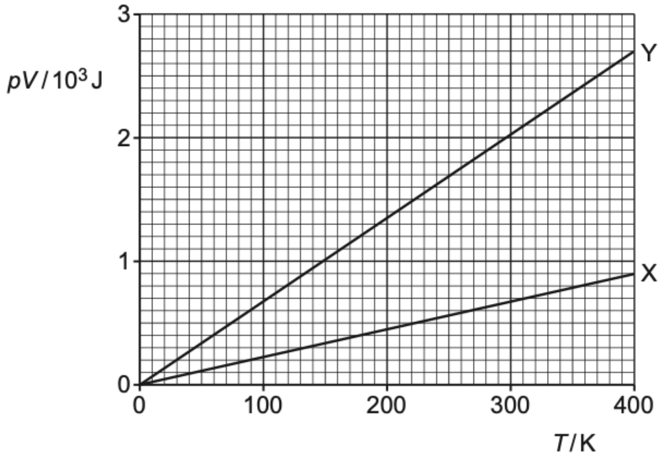

Fig. 4.2

State **three** conclusions about the gases and their samples that may be drawn from Fig. 4.1 and Fig. 4.2. The conclusions may be qualitative or quantitative. Use the space below for any working that you need.

1 ....

....

2 ....

....

3 ....

....

[3]

[Total: 9]

20 Nitrogen may be assumed to be an ideal gas. A fixed amount of nitrogen gas is contained at a constant pressure of 1.6×10^5 Pa.

The variation of the volume V of the gas with the temperature θ of the gas is shown in Fig. 3.1.

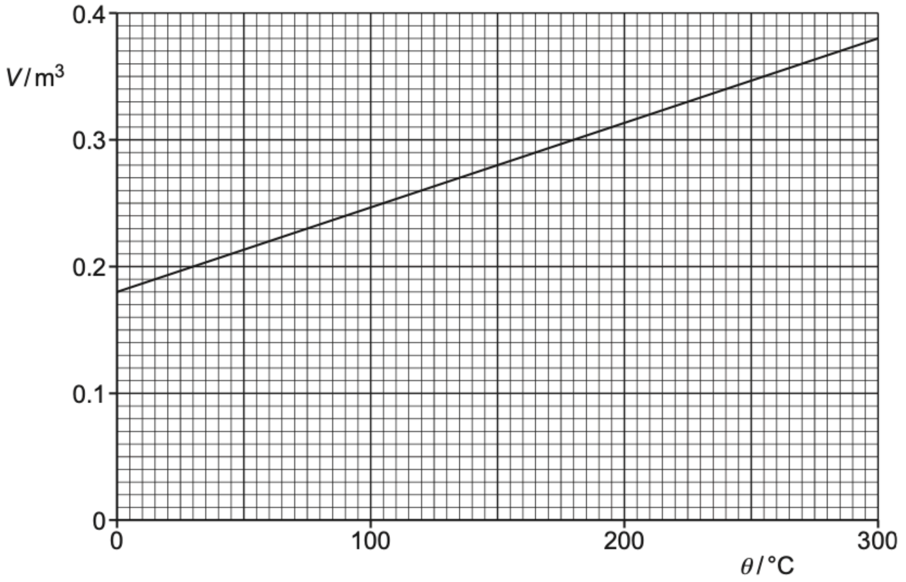

Fig. 3.1

(i) The temperature of the nitrogen gas is increased from 0 °C to 210 °C. Determine the work done on the gas.

work done = ... J [3]

(ii) Determine the number N of molecules of nitrogen gas.

N = ... [2]

(iii) The mass of a nitrogen molecule is 4.7×10^{-26} kg.

Calculate the root-mean-square (r.m.s.) speed of a nitrogen molecule at 210 °C.

r.m.s. speed = ... m s^{-1} [2]

[Total: 12]

MJ25/41/Q4

21 **(a)** **(i)** State what is meant by the internal energy of a system.

....

....

.... [2]

(ii) Explain why the internal energy of an ideal gas is directly proportional to the thermodynamic temperature of the gas.

....

....

....

.... [2]

(b) A sample of an ideal gas at thermodynamic temperature *T* has internal energy *U*.

The gas is compressed so that its temperature increases to 3*T*.
During this compression, work *W* is done on the gas.

The gas is then cooled at constant volume so that its temperature decreases to 2*T*.

Complete Table 4.1 to show, in terms of some or all of *W*, *T* and *U*, the work done on the gas, the thermal energy supplied to the gas and the increase in internal energy of the gas for each of the two processes.

Table 4.1

	work done on gas	thermal energy supplied to gas	increase in internal energy of gas
compression	$+W$		
cooling			

[4]

[Total: 8]

22 **(a)** Define specific heat capacity.

....

....

.... [2]

(b) A block of aluminium has a volume of $3.612 \times 10^{-3}\,\text{m}^3$ at a temperature of 0 °C.

Aluminium has a density of $2.700 \times 10^{3}\,\text{kg}\,\text{m}^{-3}$ at 0 °C.
It has a density of $2.620 \times 10^{3}\,\text{kg}\,\text{m}^{-3}$ at 500 °C.

The block is heated so that its temperature increases from 0 °C to 500 °C at an atmospheric pressure of $1.01 \times 10^{5}\,\text{Pa}$.
The increase in internal energy of the block is 4.38 MJ.

(i) Calculate the mass of the block.

mass = ... kg [2]

(ii) Show that the volume of the block at a temperature of 500 °C is $3.722 \times 10^{-3}\,\text{m}^3$.

[1]

(iii) Use the information in **(b)(ii)** to determine the magnitude of the work done on the block when its temperature is raised from 0 °C to 500 °C.

work done = ... J [2]

(iv) Explain whether the work done on the block is positive or negative.

....

....

.... [2]

(v) Use the first law of thermodynamics to determine, to three significant figures, a value for the specific heat capacity of aluminium. Explain your reasoning. Give a unit with your answer.

specific heat capacity = ... unit .... [3]

(c) Without further calculation, suggest with a reason how doubling the pressure in **(b)** is likely to affect the answer in **(b)(v)**.

....

....

.... [1]

[Total: 13]

23 **(a)** The equation of state for an ideal gas may be written as MJ25/42/Q4

$$pVA = NBT$$

where p is the pressure of the gas, V is the volume of the gas, A is the Avogadro constant, B is another constant and N is the number of molecules of the gas.

(i) State the meaning, in the equation, of the symbol T.

.... [1]

(ii) Identify the constant B.

.... [1]

(b) The product pV for an ideal gas is also given by

$$pV = \tfrac{1}{3}Nm\langle c^2\rangle.$$

(i) State the meanings, in this equation, of the symbols m and $\langle c^2\rangle$.

m: ....

$\langle c^2\rangle$: ....
[2]

(ii) Use the equations in **(a)** and **(b)** to derive an expression, in terms of A, B and T, for the mean kinetic energy E_K of a molecule of the gas.

E_K = ... [2]

(c) On Fig. 4.1, sketch the variation with T of the root-mean-square (r.m.s.) speed of the molecules of an ideal gas.

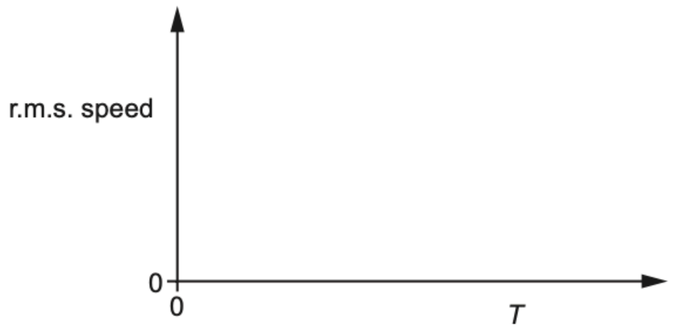

Fig. 4.1

[2]

[Total: 8]

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24 **(a)** State what is meant by an ideal gas.

....

....

.... [2]

(b) An ideal gas at a pressure of 1.6×10^5 Pa has a density of $1.9\,\text{kg}\,\text{m}^{-3}$.

(i) Show that the root-mean-square (r.m.s.) speed of molecules of this gas is approximately $500\,\text{m}\,\text{s}^{-1}$.

[3]

(ii) One molecule of the gas has a mass of 4.7×10^{-26} kg.

Determine the thermodynamic temperature of the gas.

temperature = ... K [2]

(c) Calculate the internal energy *U* of 6.0 mol of the gas in **(b)**. Explain your reasoning.

U = ... J [3]

[Total: 10]

Question	Answer	Marks
1 (a)(i)	(gas that obeys) $pV \propto T$ (for all values of p, V and T)	M1
	where T is thermodynamic temperature	A1
(a)(ii)	temperature = –273.15 °C	A1
(b)(i)	$pV = NkT$	C1
	$N = (1.37 \times 10^5 \times 0.640) / (1.38 \times 10^{-23} \times (227 + 273))$	C1
	$= 1.27 \times 10^{25}$	A1
(b)(ii)	mass $= 0.0424 / (1.27 \times 10^{25})$ $= 3.34 \times 10^{-27}$ kg	A1
(b)(iii)	$\frac{1}{2}m\langle c^2\rangle = (3/2)kT$	C1
	$3.34 \times 10^{-27} \times v^2 = 3 \times 1.38 \times 10^{-23} \times 500$	C1
	$v = 2490\ \text{m s}^{-1}$	A1
	or	
	$pV = \frac{1}{3}(Nm)\langle c^2\rangle$ <u>and</u> Nm = mass of gas	(C1)
	$0.0424 \times v^2 = 3 \times 1.37 \times 10^5 \times 0.640$	(C1)
	$v = 2490\ \text{m s}^{-1}$	(A1)
2(c)	sketch: line from (0, 0) to (500, v)	B1
	line with decreasing positive gradient throughout	B1

Question	Answer	Marks
2(a)	gas for which $pV \propto T$	M1
	where T is thermodynamic temperature	A1
2(b)(i)	evidence of two temperature conversions between °C and K	B1
	two calculations shown, one for each state e.g. $\dfrac{1.10\times10^5\times540\times10^{-6}}{(273+27)} = 0.198$ **and** $\dfrac{6.70\times10^6\times30\times10^{-6}}{(273+742)} = 0.198$	A1
2(b)(ii)	work is done on the gas	M1
	internal energy increases (so temperature increases)	A1
2(b)(iii)	$pV = NkT$ e.g. $N = \dfrac{1.10\times10^5\times540\times10^{-6}}{1.38\times10^{-23}\times300}$ $= 1.435 \times 10^{22}$ $\Delta E_k = (3/2)\,k\Delta TN$	C1
	$= (3/2) \times 1.38 \times 10^{23} \times (742 - 27) \times \dfrac{1.10\times10^5\times540\times10^{-6}}{1.38\times10^{-23}\times300}$	C1
	$= 212$ J	A1
2(c)	$E = mc\Delta\theta$ **and** $E = mL$	C1
	$\Delta\theta = (27 + 196)$ or 223	C1
	$E = 0.0240 \times 1.04 \times (27 + 196) + 0.0240 \times 199$ $= 10.3$ kJ	A1

Question	Answer	Marks
3(a)	p = pressure (of gas), V = volume (of gas) **and** k = Boltzmann constant	**B1**
	N = number of molecules	**B1**
	T = thermodynamic temperature	**B1**
3(b)	($pV = NkT$ and $pV = \frac{1}{3}Nm\langle c^2\rangle$ leading to) $NkT = \frac{1}{3}Nm\langle c^2\rangle$	**M1**
	algebra leading to $(3/2)kT = \frac{1}{2}m\langle c^2\rangle$ **and** use of $\frac{1}{2}m\langle c^2\rangle = E_K$ leading to $(3/2)kT = E_K$	**A1**
3(c)(i)	$T = 296$ K	**C1**
	$\frac{1}{2}m\langle c^2\rangle = (3/2)kT$ $\frac{1}{2} \times 5.31 \times 10^{-26} \times u^2 = (3/2) \times 1.38 \times 10^{-23} \times 296$	**C1**
	$u = 480$ m s^{-1}	**A1**
3(c)(ii)	line passing through (P, u)	**B1**
	horizontal straight line	**B1**

<table>
<tr><th>Question</th><th>Answer</th><th>Marks</th></tr>
<tr><td>4 (a)(i)</td><td>a gas that obeys $pV \propto T$</td><td>M1</td></tr>
<tr><td></td><td>where p = pressure, V = volume, T = thermodynamic temperature</td><td>A1</td></tr>
<tr><td>(a)(ii)</td><td>$T = (273 + 17)$ K</td><td>C1</td></tr>
<tr><td></td><td>$n = pV / RT$
$= (1.2 \times 10^5 \times 0.24) / [8.31 \times (273 + 17)]$
$= 12$ mol</td><td>A1</td></tr>
<tr><td>(b)(i)</td><td>work done $= p\Delta V$</td><td>C1</td></tr>
<tr><td></td><td>$= 1.2 \times 10^5 \times (0.24 - 0.08) = 19200$ J (= 19.2 kJ)</td><td>A1</td></tr>
<tr><td>(b)(ii)</td><td>AB work done correct (19.2)</td><td>A1</td></tr>
<tr><td></td><td>BC work done correct (0)</td><td>A1</td></tr>
<tr><td></td><td>CA increase in internal energy correct (0) and CA thermal energy correct (31.6)</td><td>A1</td></tr>
<tr><td></td><td>AB increase in internal energy calculated correctly from work done – 48.0</td><td>A1</td></tr>
<tr><td></td><td>BC increase in internal energy correctly calculated so the final column adds up to zero and BC thermal energy same as increase in internal energy

(Fully correct table:
<table>
<tr><td>AB</td><td>19.2</td><td>–48.0</td><td>–28.8</td></tr>
<tr><td>BC</td><td>0</td><td>28.8</td><td>28.8</td></tr>
<tr><td>CA</td><td>–31.6</td><td>31.6</td><td>0</td></tr>
</table>
)</td><td>A1</td></tr>
</table>

5(a)	$pV = NkT$	**C1**
	$N = (1.8 \times 10^{-3} \times 3.3 \times 10^{5}) / (1.38 \times 10^{-23} \times 310) = 1.4 \times 10^{23}$	**A1**
	or	
	$pV = nRT$ **and** $nN_A = N$	**(C1)**
	$N = (1.8 \times 10^{-3} \times 3.3 \times 10^{5} \times 6.02 \times 10^{23}) / (8.31 \times 310) = 1.4 \times 10^{23}$	**(A1)**
(b)	speed of molecule decreases on impact with moving piston	**B1**
	mean square speed (directly) proportional to (thermodynamic) temperature **or** mean square speed (directly) proportional to kinetic energy (of molecules) **or** kinetic energy (of molecules) (directly) proportional to (thermodynamic) temperature	**B1**
	kinetic energy (of molecules) decreases (so temperature decreases)	**B1**
(c)(i)	$\Delta U = 3/2 \times k \times \Delta T \times N$	**C1**
	$= 3/2 \times 1.38 \times 10^{-23} \times (288 - 310) \times 1.4 \times 10^{23}$	**C1**
	$= -64$ J	**A1**
(c)(ii)	decrease in internal energy is less than work done by gas	**M1**
	(thermal energy is) transferred to the gas (during the expansion)	**A1**

6 (a)	$pV = nRT$	**C1**
	$pV = nRT$ **and** $N = nN_A$ **or** $pV = NkT$	**C1**
	$3.1 \times 10^{-3} \times 8.5 \times 10^{5} = (N \times 290 \times 8.31) / (6.02 \times 10^{23})$ so $N = 6.6 \times 10^{23}$ **or** $3.1 \times 10^{-3} \times 8.5 \times 10^{5} = N \times 1.38 \times 10^{-23} \times 290$ so $N = 6.6 \times 10^{23}$	**A1**
(b)(i)	$(3.1 \times 10^{-3} \times 8.5 \times 10^{5}) / 290 = (6.3 \times 10^{-3} \times 2.7 \times 10^{5}) / T$ so $T = 190$ K **or** $6.3 \times 10^{-3} \times 2.7 \times 10^{5} = 6.6 \times 10^{23} \times 1.38 \times 10^{-23} \times T$ so $T = 190$ K	**A1**
b)(ii)	$\Delta U = 3/2 \times k \times \Delta T \times N$	**C1**
	$= 3/2 \times 1.38 \times 10^{-23} \times (190 - 290) \times 6.6 \times 10^{23}$	**C1**
	$= -1400$ J	**A1**
(c)	$\Delta U = q + w$	**M1**
	$q = 0$ so $\Delta U = w$	**A1**

6

<table>
<tr><td>7(a)</td><td>$+q$: thermal energy transfer to system</td><td>B1</td></tr>
<tr><td></td><td>$+w$: work done on system</td><td>B1</td></tr>
<tr><td>(b)(i)</td><td>(W =) $2.6 \times 10^5 \times (3.8 - 2.3) \times 10^{-3} = 390$ J</td><td>A1</td></tr>
<tr><td>(b)(ii)</td><td>no (total) change (in internal energy)</td><td>B1</td></tr>
<tr><td></td><td>gas returns to its original temperature</td><td>B1</td></tr>
<tr><td>(c)</td><td>A to B row all correct (1370, – 390, 980)</td><td>B1</td></tr>
<tr><td></td><td>B to C row all correct (0, 550, 550)</td><td>B1</td></tr>
<tr><td></td><td>C to A row: ΔU adds to the other two ΔU values to give zero</td><td>B1</td></tr>
<tr><td></td><td>C to A row: $w = 0$ and q adds to w to give ΔU value
complete correct answer:
<table>
<tr><td>change</td><td>q / J</td><td>w / J</td><td>ΔU / J</td></tr>
<tr><td>A to B</td><td>(+)1370</td><td>–390</td><td>(+)980</td></tr>
<tr><td>B to C</td><td>0</td><td>(+)550</td><td>(+)550</td></tr>
<tr><td>C to A</td><td>–1530</td><td>0</td><td>–1530</td></tr>
</table></td><td>B1</td></tr>
</table>

8(a)	sum of potential energy and kinetic energy (of particles)	**B1**
	(total) energy of random motion of particles	**B1**
(b)(i)	$pV = nRT$	**C1**
	$2.60 \times 10^5 \times 2.30 \times 10^{-3} = n \times 8.31 \times 180$ $n = 0.400$ mol	**A1**
(b)(ii)	$(2.30 \times 10^{-3}) / 180 = (3.80 \times 10^{-3}) / T$ **or** $2.60 \times 10^5 \times 3.80 \times 10^{-3} = 0.400 \times 8.31 \times T$	**C1**
	$T = 297$ K	**A1**
(c)(i)	$\Delta W = p\Delta V$ $= 2.60 \times 10^5 \times (2.30 - 3.80) \times 10^{-3}$	**C1**
	= (–)390 J	**A1**
	negative because work is done by gas **or** negative because work is done against atmospheric pressure **or** negative because volume of gas increases	**B1**
(c)(ii)	$\Delta U = (980 - 390)$ = 590 J	**A1**

9(a)(i)	$pV = NkT$ or $pV = nRT$ and $N = nN_A$ $N = \dfrac{2.3\times10^{5}\times3.5\times10^{-3}}{1.38\times10^{-23}\times294}$	C1
	= $\mathbf{2.0\times10^{23}}$	A1
(a)(ii)	$pV = \dfrac{1}{3}Nmc^2$ $c^2 = \dfrac{3\times2.3\times10^{5}\times3.5\times10^{-3}}{2.0\times10^{23}\times40\times1.66\times10^{-27}}$ = 182 000 r.m.s. speed = **430** m s^{-1}	C1
	or $\frac{1}{2}mc^2 = \frac{3}{2}kT$	A1
	$c^2 = \dfrac{3\times1.38\times10^{-23}\times294}{40\times1.66\times10^{-27}}$ = 183 000	(C1)
	r.m.s.speed = 430 m s^{-1}	(A1)
(b)	$c^2 = \dfrac{3\times2.0\times10^{23}\times1.38\times10^{-23}\times(294+84)}{2.0\times10^{23}\times40\times1.66\times10^{-27}}$ $c^2 = 236000$ $c = 485$	C1
	$ratio\left(=\dfrac{485}{430}\right)=1.1$	A1
	OR $v \propto \sqrt{T}$ or $v^2 \propto T$	(C1)
	$ratio = \sqrt{\dfrac{273+21+84}{273+21}}$ or $\sqrt{\dfrac{378}{294}}$ ratio = **1.1**	(A1)

10 (a)	n = 110 / 0.032 or 110000 / 32 or 3440	C1
	$pV = nRT$	C1
	$T = (1.0\times10^{5}\times85)/(8.31\times(110/0.032)) = 300$ K	A1
(b)	$E = mc\Delta\theta$ = 110 × 0.66 × 50	C1
	= **3600** J	A1
(c)	Any 3 from: • molecule collides with wall • momentum of molecule changes during collision (with wall) • force on molecule so force on wall • many forces act over surface area of container exerting a pressure	B3
(d)	$KE \propto T$ $v \propto \sqrt{T}$	C1
	ratio = $\sqrt{(350/300)}$ = **1.1**	A1

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Q11 a)	(thermal) energy per unit mass (to change temperature)	**B1**
	(thermal) energy per unit change in temperature	**B1**
2(b)(i)	work done $= p\Delta V$ $= (2.0 \times 10^5) \times (0.063 - 0.038) = 5000$ J	**A1**
2(b)(ii)	gas is expanding (against external pressure)	**B1**
	gas does work / work is done by gas, so (work done on gas is) negative	**B1**
2(b)(iii)	$\Delta U = q + W$	**C1**
	$7600 = q + (-5000)$ $q = 12\,600$ J	**A1**
2(b)(iv)	specific heat capacity $= q / m\Delta T$ $= 12600 / (0.35 \times 56)$	**C1**
	$= 640$ J kg^{-1} K^{-1}	**A1**
2(c)	same gain in internal energy so same temperature rise	**B1**
	no change in volume so no work done **or** no work done so less thermal energy needed (for same change in internal energy)	**B1**
	less thermal energy needed (for same temperature change) so lower specific heat capacity	**B1**

Q12 a)(i)	N: number of molecules (of the gas)	**B1**
	m: mass of one molecule (of the gas)	**B1**
	$<c^2>$: mean square speed (of molecules)	**B1**
3(a)(ii)	$pV = NkT$	**M1**
	$NkT = ⅓Nm<c^2>$ **and** $E_K = ½m<c^2>$ leading to $E_K = (3/2)\,kT$	**A1**
3(b)	$½ \times 3.34 \times 10^{-27} \times 9300^2 = (3/2) \times 1.38 \times 10^{-23} \times T$	**C1**
	$T = 6980$ K	**A1**
3(d)	(very high pressure so) molecules are (very) close together (*not just 'nearer'*)	**B1**
	forces between molecules are not negligible **or** volume of molecules not negligible compared with gas volume	**B1**

Q13 a)	sum of potential energy and kinetic energy (of particles)	**B1**
	(total) energy of random motion of particles	**B1**
3(b)(i)	no thermal energy <u>transferred</u>	**B1**
	work is done on the spring (increasing the potential energy of particles)	**M1**
	so internal energy increases	**A1**
3(b)(ii)	thermal energy transferred to water	**B1**
	work is done by water (expanding against atmosphere as it vaporises)	**B1**
	more thermal energy transferred than work done so internal energy increases	**B1**

Q14 a)	total kinetic energy associated with random motion of molecules	**M1**
	plus total potential energy (of molecules) but potential energy is zero	**A1**
2(b)(i)	$W = p\Delta V$	**C1**
	$= 1.01 \times 10^{5} \times 5.20 \times 10^{-5}$ $= (+)5.25$ J	**A1**
2(b)(ii)	$V \propto T$ or $V / T =$ constant	**C1**
	$1.24 / (273 + 20) = (1.24 + 0.520) / T$ $T = 416$ K	**A1**
2(b)(iii)	$c = Q / m\Delta T$	**C1**
	$= 960 / (0.016 \times (416 - 293))$ $= 490$ J kg^{-1} K^{-1}	**A1**
2(c)	no change in volume so no work is done (by the gas)	**B1**
	(same temperature change so) same change in internal energy	**B1**
	less thermal energy needs to be supplied so *c* is less	**B1**

Q15 (a)(i)	gas for which $pV \propto T$	**M1**
	where *T* is thermodynamic temperature	**A1**
3(a)(ii)	no intermolecular forces	**B1**
	(so) potential energy is zero	**B1**
3(b)(i)	$pV = NkT$	**C1**
	$N = (2.0 \times 10^{5} \times 0.26) / (1.38 \times 10^{-23} \times 290)$ $= 1.3 \times 10^{25}$	**A1**
3(b)(ii)	$E_K = (3/2)\,kT$	**C1**
	$E_K = (3/2) \times 1.38 \times 10^{-23} \times 290$ $= 6.0 \times 10^{-21}$ J	**A1**
3(b)(iii)	internal energy = total KE + PE of molecules **or** PE = 0 so internal energy = total KE of molecules	**B1**
	internal energy $= 1.3 \times 10^{25} \times 6.0 \times 10^{-21}$ $= 7.8 \times 10^{4}$ J	**A1**
3(c)	straight line with positive gradient	**B1**
	line passing through the origin	**B1**

Q16 a)	(if in thermal contact) no <u>net transfer</u> of (thermal) energy (between them)	**B1**
2(b)(i)	$pV = nRT$	**C1**
	$T = (1.20 \times 10^5 \times 0.0260) / (0.740 \times 8.31)$ $(= 507\ \text{K})$	**M1**
	temperature = 507 – 273 = 234 °C	**A1**
2(b)(ii)	thermal equilibrium <u>so</u> temperatures (of X and Y) are equal	**B1**
	$pV = NkT$	**C1**
	$N = (2.90 \times 10^5 \times 0.0430) / (1.38 \times 10^{-23} \times 507)$ $= 1.78 \times 10^{24}$	**A1**
2(b)(iii)	• (molecular) kinetic energy is proportional to temperature **or** kinetic energy (of molecules) is same in both cylinders • kinetic energy proportional to mass × mean-square speed **or** temperature proportional to mass × mean-square speed **or** r.m.s. speed proportional to √(temperature / mass) • mean-square speed inversely proportional to mass **or** r.m.s. speed inversely proportional to √(mass) *Any two bulleted points, 1 mark each*	**B2**
	r.m.s. speed (of molecules) in X is half r.m.s. speed (of molecules) in Y	**B1**

Q17 a)	sum of potential energy and kinetic energy	**B1**
	(total) energy of random motion of particles	**B1**
3(b)(i)	no change in separation so no change in (molecular) potential energy	**B1**
	temperature increases so kinetic energy (of molecules) increases	**B1**
	kinetic energy increases and potential energy unchanged, so internal energy increases	**B1**
3(b)(ii)	temperature constant so no change in (molecular) kinetic energy	**B1**
	separation increases so potential energy (of molecules) increases	**B1**
	potential energy increases and kinetic energy unchanged, so internal energy increases	**B1**

Q18 3(a)(i)	number of particles per unit amount of substance	**B1**
3(a)(ii)	$N_A = R / k$	**B1**
3(b)(i)	X pressure and Y pressure <u>both</u> = NkT / V	**B1**
	X amount = N / N_A **and** Y amount = $2N / N_A$	**B1**
	X mean-square speed = $3kT / m$ **and** Y mean-square speed = $3kT / 2m$	**B1**
	X internal energy = $3NkT / 2$ **and** Y internal energy = $3NkT$	**B1**
3(b)(ii)	line passing through the origin and not returning to either axis	**B1**
	curve with positive decreasing gradient	**B1**

Q19

(a)	- molecules are in (constant) random motion - (all) collisions between molecules are (perfectly) elastic - no forces between molecules (except during collisions) - volume of molecules is negligible (compared with volume of gas) - collisions involving molecules are instantaneous *Any three points, 1 mark each*	**B3**
4(b)	- molecules collide with (walls of) container - momentum of molecule changes during collision (with walls) - change in momentum is caused by force on molecule by wall - molecule experiences force from wall so molecule exerts force on wall - many molecules exerting force across the area of the wall leads to pressure (on the wall) *Any three points, 1 mark each*	**B3**
4(c)	*Any three bulleted points from:* - both gases are ideal *Up to 2 points from:* - mass of one molecule of gas X is 3.3×10^{-27} kg - mass of one molecule of gas Y is 6.6×10^{-27} kg - mass of one molecule of gas Y is double mass of one molecule of gas X *Up to 2 points from:* - sample of X contains 0.27 mol / 1.6×10^{23} molecules - sample of Y contains 0.81 mol / 4.9×10^{23} molecules - sample of Y contains treble the amount of gas / number of molecules as sample of X *Up to 2 points from:* - mass of gas X is 5.4×10^{-4} kg - mass of gas Y is 3.2×10^{-3} kg - mass of gas Y is six times mass of gas X	**B3**

Q20

3(b)(i)	work done = $p\Delta V$	**C1**
	$= (1.6 \times 10^5) \times (0.18 - 0.32)$	**C1**
	$= -2.2 \times 10^4$ J	**A1**
3(b)(ii)	$pV = NkT$	**C1**
	$N = (1.6 \times 10^5 \times 0.18) / (1.38 \times 10^{-23} \times 273)$ $= 7.6 \times 10^{24}$	**A1**
3(b)(iii)	$\frac{1}{2}m\langle c^2\rangle = (3/2)kT$	**C1**
	r.m.s. speed = $\sqrt{[(3 \times 1.38 \times 10^{-23} \times (210 + 273) / (4.7 \times 10^{-26})]}$ $= 650$ ms^{-1}	**A1**

Q21

(a)(i)	sum of potential energy and kinetic energy (of particles)	B1	**Allow** ‘PE’ or ‘E_P’ for ‘potential energy’. **Allow** ‘KE’ or ‘E_K’ for ‘kinetic energy’. **Allow** ‘atoms’ or ‘molecules’ for ‘particles’. **Allow** ‘a particle’ for ‘particles’. **Do not allow** ‘system’ or ‘gas’ for ‘particles’.
	(total) energy of random motion of particles	B1	**Allow** ‘distribution’ for ‘motion’. **Allow** ‘random energy of particles’. **Allow** ‘atoms’ or ‘molecules’ for ‘particles’. **Do not allow** ‘system’ or ‘gas’ for ‘particles’. **Do not allow** ‘a particle’ for ‘particles’. **Ignore** any references to the first law of thermodynamics.
4(a)(ii)	potential energy of molecules (in an ideal gas) is zero	B1	
	kinetic energy of molecules is proportional to thermodynamic temperature, so internal energy of gas is proportional to thermodynamic temperature	B1	**Allow** ‘*T*’ for ‘thermodynamic temperature’. **Allow** ‘E_K = 3/2 kT so $U \propto T$’.
4(b)	cooling work done = **0**	B1	
	compression increase in internal energy = **+2*U***	B1	**Allow** ‘**2*U***’.
	cooling change in internal energy = **–*U***	B1	
	both rows thermal energy adds to work to give increase in internal energy (if all correct, compression = **2*U* – *W***; cooling = **–*U***) compression | +*W* | **2*U* – *W*** | **+2*U*** cooling | **0** | **–*U*** | **–*U***	B1	

Q22

3(a)	(thermal) energy per unit mass (to cause temperature change)	B1	<u>Both marking points:</u> Ratio must be clear. **Allow** ‘heat’ for ‘thermal’ or ‘thermal energy’. **Ignore** any symbols unless they are defined. **Ignore** any reference to units. **Do not allow** ‘work’ for ‘thermal energy’. **Do not allow** if context is state change.
	(thermal) energy per unit change in temperature	B1	
3(b)(i)	density = mass / volume mass = $2.700 \times 10^3 \times 3.612 \times 10^{-3}$	C1	
	= **9.752 kg**	A1	Correct to at least **3** significant figures. (**9.75** for AFC).
3(b)(ii)	*either*: volume = $3.612 \times 10^{-3} \times (2.700 / 2.620)$ = 3.722×10^{-3} m^3	A1	Full substitution and answer needed.
	or: volume = $9.752 / 2.620 \times 10^3$ = 3.722×10^{-3} m^3	(A1)	Full substitution and answer needed. No ECF from **(b)(i)**.
3(b)(iii)	$W = p\Delta V$ = $1.01 \times 10^5 \times (3.722 - 3.612) \times 10^{-3}$	C1	Correct to at least 3 significant figures. AFC. **Ignore** sign of answer.
	= **11.1 J**	A1	
3(b)(iv)	volume of block increases	B1	
	work is done against the atmosphere so work done (on block) is negative	B1	**Allow** ‘by block’ for ‘against the atmosphere’.
3(b)(v)	thermal energy = $(4.38 \times 10^6) + 11.1$	B1	Possible ECF form **(b)(iii)**.
	s.h.c. = $(4.38 \times 10^6) / (9.75 \times 500)$	C1	**Allow** comment that the work done is negligible.
	= **898 J kg^{-1} °C^{-1}**	A1	**Ignore** subtraction of 11.1 for the C1 mark. Must be to three significant figures. Unit needed with answer. **Allow** J kg^{-1} K^{-1}.

3(c)	work done is negligible compared with change in internal energy so specific heat capacity will be unchanged	B1	**Do not allow** if answer to **(b)(iii)** > 2000 J. Provided that answer to **(b)(iii)** < 200 J, **allow** an answer for a slightly increased s.h.c reasoned in terms of *W* being slightly greater.

Q23

(a)(i)	thermodynamic temperature	B1	**Allow** 'absolute', 'kelvin' or 'in K' for 'thermodynamic'. **Do not allow** just 'temperature'.
4(a)(ii)	molar gas constant	B1	**Allow** 'universal gas constant'.
4(b)(i)	*m*: mass of one molecule (of the gas) $<c^2>$: mean square speed (of molecules)	B1 B1	**Do not allow** 'mean square speed of the gas'. **Do not allow** 'root mean square' for 'mean square'. **Do not allow** 'mean speed squared'.
4(b)(ii)	$NBT / A = ⅓ Nm<c^2>$ clear use of $E_K = ½ m<c^2>$ leading to $\mathbf{E_K = 3BT / 2A}$	M1 A1	Completion of algebra must follow through clearly.
4(c)	sketch: line with positive gradient passing through the origin curve with decreasing positive gradient	B1 B1	

Q24

3(a)	gas that obeys the law $pV \propto T$ where T is thermodynamic temperature, p is pressure and V is volume	M1 A1	**Allow** 'gas that obeys 'pV = constant × T'. Allow any of N, n, R and/or k for 'constant'. Allow 'absolute' or 'Kelvin' for 'thermodynamic'.
3(b)(i)	r.m.s. speed $= \sqrt{<c^2>}$ $pV = ⅓ Nm <c^2>$ and $Nm / V = \rho$ so $p = ⅓ \rho <c^2>$ $1.6 \times 10^5 = ⅓ \times 1.9 \times (\text{r.m.s. speed})^2$ and so r.m.s. speed = 500 m s^{-1}	C1 C1 A1	The C1 marks are independent of each other. (Neither implies the other, and XP in one does not negate the other). This expression implies the second C1 mark. Full substitution and answer needed for the A1 mark. The A1 mark implies both C1 marks.
3(b)(ii)	method 1 $(pV =)\ ⅓ Nm <c^2> = NkT$ so $½ m<c^2> = (3/2)kT$ $½ \times 4.7 \times 10^{-26} \times 503^2 = (3/2) \times 1.38 \times 10^{-23} \times T$ T = **290 K** method 2 $pV = NkT$ and $Nm / V = \rho$ (so) $T = Pm / \rho k$ $= 1.6 \times 10^5 \times 4.7 \times 10^{-26} / (1.9 \times 1.38 \times 10^{-23})$ = **290 K**	C1 A1 (C1) (A1)	No ECF from **(b)(i)**. Correct to at least 2 significant figures. AFC. (287). Use of rounded c_{RMS} gives 280 (284) K (for AFC). Correct to at least 2 significant figures. AFC. (287).
3(c)	potential energy of molecules is zero	B1	Can be awarded from putting E_P = 0 into equation.

	$N = 6.0 \times 6.02 \times 10^{23}$ *either:* $U = N \times ½ m<c^2> = 6.0 \times 6.02 \times 10^{23} \times ½ \times 4.7 \times 10^{-26} \times 500^2$ *or:* $U = N \times (3/2)kT = 6.0 \times 6.02 \times 10^{23} \times (3/2) \times 1.38 \times 10^{-23} \times 280$ U = **21000 J**	C1 A1	C1 mark is for the working for N. Value does not need to be calculated, but $N = 3.6 \times 10^{24}$ implies C1. No ECF from **(b)(i)** for this method. Possible ECF from **(b)(ii)** for this method. Correct to at least 2 significant figures. AFC. 3SF answer depends on SFs carried through (but all values round to 21 kJ to 2SF).