Physics 11

Semester 1 Examination

Task 6

2021

Name: ______________________________

BB	Q 1 - 5
BD	Q 6 – 10
MM	Q 11 – 12
MP	Q 13 - 14

ANSWERS

TIME ALLOWED FOR THIS PAPER

Reading time before commencing work: 10 minutes
Working time for the paper: 2½ hours

MATERIALS REQUIRED/RECOMMENDED FOR THIS PAPER

To be provided by the supervisor:

- This Question/Answer Booklet; Formula and Constants sheet

To be provided by the candidate:

- Standard items: pens, pencils, eraser or correction fluid, ruler, highlighter.
- Special items: Calculators satisfying the conditions set by the SCSA for this subject.

IMPORTANT NOTE TO CANDIDATES

No other items may be taken into the examination room. It is **your** responsibility to ensure that you do not have any unauthorised notes or other items of a non-personal nature in the examination room. If you have any unauthorised material with you, hand it to the supervisor **before** reading any further.

Section 1	Section 2	Section 3	Total
/40	/72	/18	/130

Structure of this paper

Section	Number of questions available	Number of questions to be answered	Suggested working time (minutes)	Marks available	Percentage of exam
Section One: Short answer	8	8	46	40	31
Section Two: Problem solving	5	5	83	72	55
Section Three: Comprehension and data analysis	1	1	21	18	14
			Total	130	100

Instructions to candidates

1. The rules for the conduct of Western Australian external examinations are detailed in the *SCSA Information Handbook 2021.* Sitting this examination implies that you agree to abide by these rules.

2. Write your answers in this Question/Answer Booklet.

3. When calculating numerical answers, show your working or reasoning clearly. Give final answers to **three** significant figures and include appropriate units where applicable.

   When estimating numerical answers, show your working or reasoning clearly. Give final answers to a maximum of **two** significant figures and include appropriate units where applicable.

4. You must be careful to confine your responses to the specific questions asked and follow any instructions that are specific to a particular question.

5. Spare pages are included at the end of this booklet. They can be used for planning your responses and/or as additional space if required to continue an answer.
   - Planning: If you use the spare pages for planning, indicate this clearly.
   - Continuing an answer: If you need to use the space to continue an answer, indicate in the original answer space where the answer is continued, i.e. give the page number. Refer to the question(s) where you are continuing your work.

Section One: Short answer 31% (40 Marks)

This section has **eight (8)** questions. Answer **all** questions. Write your answers in the space provided.

When calculating numerical answers, show your working and reasoning clearly. Give final answers to **three** significant figures and include appropriate units where applicable.

When estimating numerical answers, show your working and reasoning clearly. Give final answers to a maximum of **two** significant figures and include appropriate units where applicable.

Supplementary pages for planning/continuing your answers to questions are provided at the end of the Question/Answer booklet. If you use these pages to continue an answer, indicate at the original answer where the answer is continued, ie – give the page number.

Suggested working time for this section is 46 minutes.

Question 1 (6 marks)

A 1.00 x 10^3 W electric water heater has an efficiency, η = 55.0%. The heater raises the temperature of 10.0 kg of water from 20.0 °C to 75.0 °C. Calculate the time (in seconds) taken for the electric water heater to complete this task.

$Q_{water} = mc\Delta T = 10.0 \times 4180 \times (75.0 - 20.0)$	1 mark
$= 2.30 \times 10^6 J$	1 mark
$\eta = \frac{\text{Energy output}}{\text{Energy input}} \times 100\%;\ \therefore \text{Energy input} = \frac{\text{Energy output}}{\eta} \times 100\%$	1 mark
$= \frac{2.30 \times 10^6}{55.0} \times 100$	
$= 4.18 \times 10^6 J$	1 mark
$P = \frac{Q}{t};\ \therefore t = \frac{Q}{P} = \frac{4.18 \times 10^6}{1.00 \times 10^3}$	1 mark
$= 4.18 \times 10^3 s$	1 mark

Question 2 **(6 marks)**

An ageing nuclear plant is being dismantled by some workers. During the dismantling process, one of the workers' hands comes into contact with an object that is emitting 24 000 alpha particles every 5 minutes. The worker's hand has a mass of 0.500 kg and absorbs 6.00 μJ of ionising radiation energy.

a) Calculate the activity of the sample in becquerels (Bq).
[Note: 1 Bq = 1 decay per second]

(2)

$A = \dfrac{24\,000}{(5 \times 60)}$	1 mark
$= 80.0 \text{ Bq}$	1 mark

b) Calculate:

(i) the absorbed dose received by the worker's hand.

(2)

$AD = \dfrac{6.00 \times 10^{-6}}{0.500}$	1 mark
$= 1.20 \times 10^{-5} \text{ Gy}$	1 mark

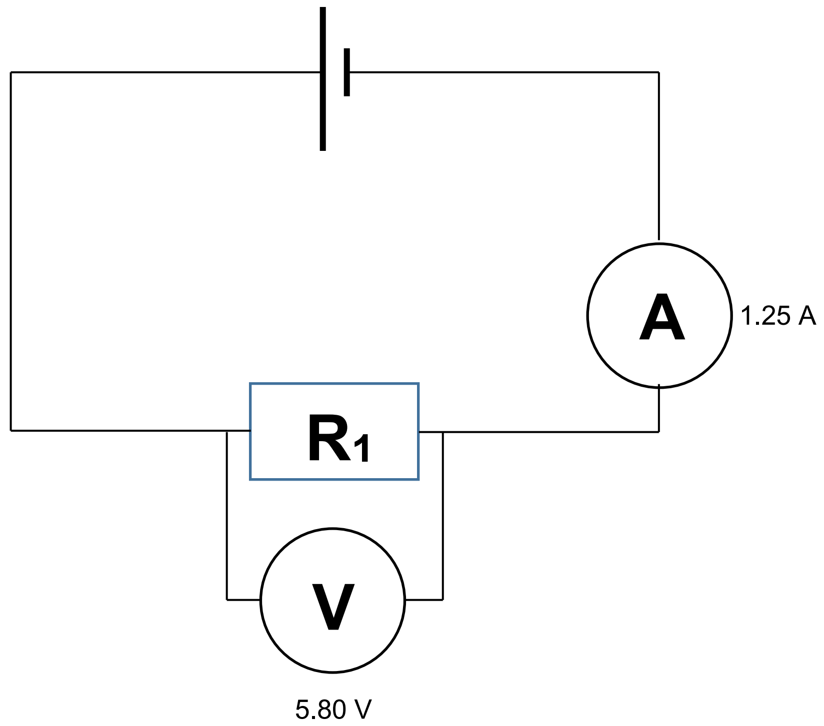
(ii) the dose equivalent received by the worker's hand.

(2)

$DE = 1.20 \times 10^{-5} \times 20$	1 mark
$= 2.40 \times 10^{-4} \text{ Sv}$	1 mark

Question 3 **(5 marks)**

A student constructed the following circuit and measured the current and voltage flowing through a resistor.



a) Calculate the value of the resistor, R_1 (in ohms).

(2)

$R = \frac{V}{I} = \frac{5.80}{1.25}$	1 mark
$= 4.64\ \Omega$	1 mark

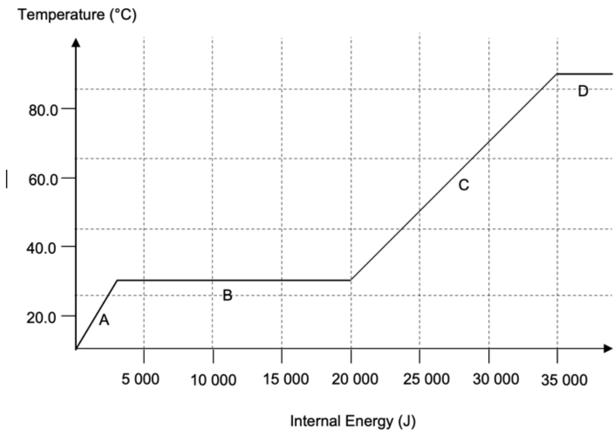
b) Calculate the number of electrons that flow through the resistor in one (1) minute.

(3)

$q = It = 1.25 \times 60 = 75.0\ C$	1 mark
$n = \frac{q}{q_e} = \frac{75.0}{1.60 \times 10^{-19}}$	1 mark
$= 4.69 \times 10^{20}$ electrons	1 mark

Question 4 **(6 marks)**

The graph below shows how the temperature of 0.500 kg of an unknown substance ‘X’ increases as thermal energy is added to it.



a) Circle the region where the particles in substance ‘X’ are moving the slowest. (1)

(A) B C D

b) Circle the region(s) where the kinetic energy of the particles in substance ‘X’ is increasing. (1)

(A) B (C) D. (both required)

c) Calculate the latent heat of fusion for substance ‘X’. Show working. (2)

$Q = mL; \therefore L = \frac{Q}{m} = \frac{20000 - 3000}{0.5}$	1 mark
$= 34\ 000\ Jkg^{-1}$ (range 34000 to 35000)	1 mark

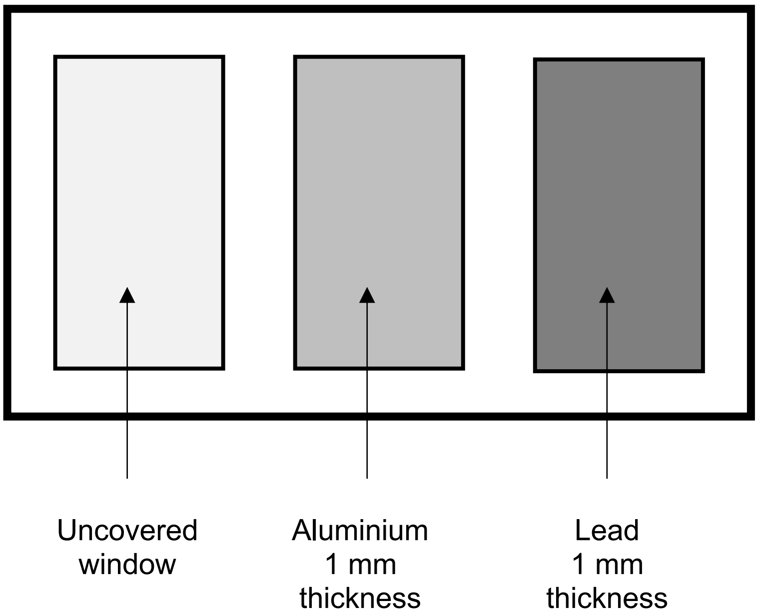
d) Using the particle model, describe one (1) difference between the arrangement of the particles in regions ‘A’ and ‘C’. (2)

One of the following:	
In region A, the particles are vibrating about a fixed position.	1 mark
In region C, the particles are free to move anywhere within the liquid.	1 mark
OR	
In region A, the particles are positioned very close together.	1 mark
In region C, the particles are further apart than in region A.	1 mark

Question 5 **(4 marks)**

A hospital physicist is working with some radioactive materials. As part of the safety procedures required when handling radioactive materials, the physicist wears a badge containing film which reacts to ionising radiation. The film is placed on the badge behind three filters (no cover, aluminium of 1 mm thickness and lead of 1 mm thickness).

The structure of the badge is shown below:



After working with the material, the film is developed. It is found that the film behind both the uncovered window and the aluminium window have turned black (the film has been exposed and has reacted to radiation). State which type of radiation could cause the film in **only** these areas to turn black. Explain your answer by commenting on the properties of alpha, beta and gamma radiation.

It is beta radiation.	1 mark
Alpha radiation will not penetrate through the air and expose any of the film.	1 mark
Beta radiation will penetrate through 1 mm of aluminium but NOT 1 mm of lead.	1 mark
Gamma radiation will penetrate through 1 mm of aluminium AND 1 mm of lead.	1 mark

Question 6 **(6 marks)**

Plutonium-239 is a fissile material used in fast-breeder nuclear reactors. One possible fission reaction involving this radioisotope is shown below. The nuclear reaction is incomplete.

a) Complete the equation (below) by determining the number of neutrons produced by this fission reaction.

(1)

$$^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{142}_{56}Ba + ^{93}_{38}Sr + \_\_\_\_ ^{1}_{0}n$$

5 neutrons produced	1 mark

The masses of the particles involved in this fission reaction are in the table below.

Pu-239	**239.052163 u**
neutron	**1.00866 u**
Ba-142	**141.916343 u**
Sr-93	**92.91403 u**

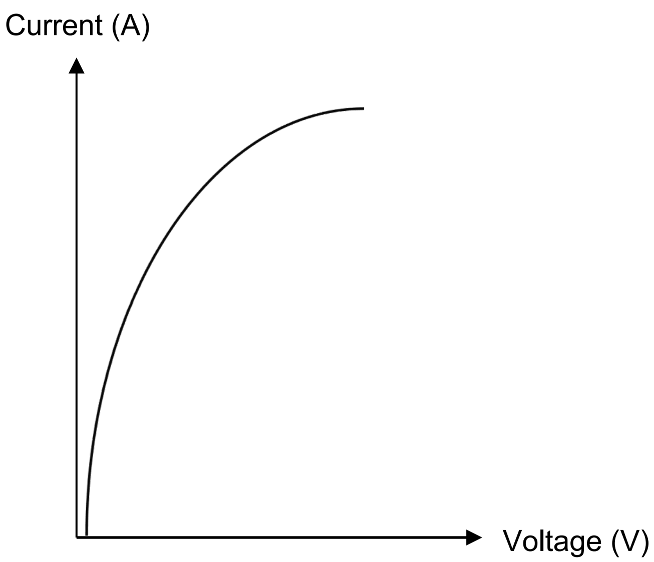
b) Calculate the energy released (in Joules) by this fission reaction.

(5)

$\text{Mass of reactants} = 239.052163 + 1.00866 = 240.060823 \text{ u}$	1 mark
$\text{Mass of products} = 141.916343 + 92.91403 + 5 \times 1.00866 = 239.873673 \text{ u}$	1 mark
$\text{Mass defect} = 240.060823 - 239.873673 = 0.18715 \text{ u}$	1 mark
$\therefore \text{Energy released} = 0.18715 \times 931 = 174.23665 \text{ MeV}$	1 mark
$= 174.23665 \times 1.60 \times 10^{-13} = 2.79 \times 10^{-11} \text{ J}$	1 mark

Question 7 **(4 marks)**

Some students gathered corresponding voltage and current data for an electrical conductor and plotted the results on a graph. This graph is shown below.



The conductor (above) is **ohmic** / **non-ohmic**? (circle the correct response) (1)

Non-ohmic.	1 mark

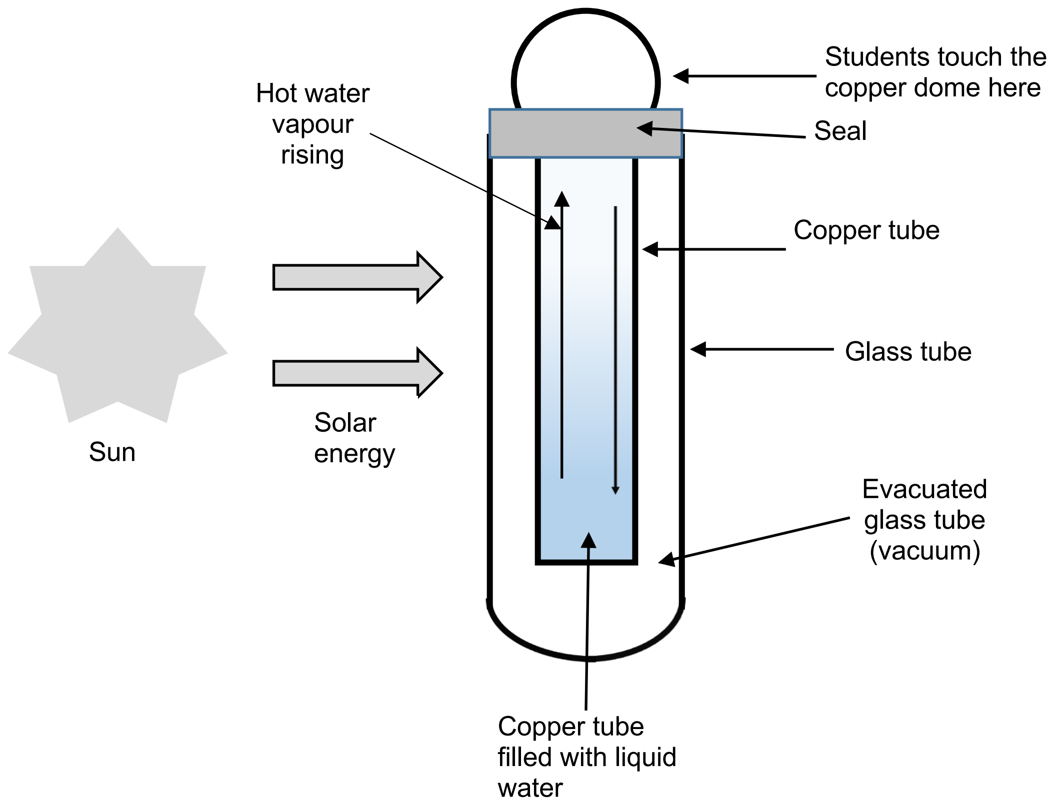
Using the terms **voltage**, **current** and **resistance**, explain what is occurring as an increasing voltage is applied across the conductor.

(3)

Ohmic conductors have a constant resistance; hence, for an ohmic conductor, the graph would have to be linear.	1 mark
In non-ohmic conductors, voltage and current are not directly proportional; hence, for an ohmic conductor, the graph would have to be linear.	1 mark
Given its curved shape, the ratio V/I – and, hence, R - is NOT constant and the conductor is non-ohmic.	1 mark

Question 8 **(3 marks)**

Some students conducted an experiment examining methods of heat transfer using the equipment shown below. A glass tube has all air evacuated from its interior creating a vacuum within it. A copper tube filled with water is placed inside the glass tube. The students are able to touch a copper dome located at the top of the copper tube and notice that after a certain time, it starts to get hotter.



Explain all of the heating processes that occur within the apparatus that cause the students to detect an increase in temperature in the copper dome.

Heating Process	Explanation
Conduction	The heated copper tube transfers heat to the water via conduction. Heat is conducted from the hot water vapour to the students' fingers via conduction through the copper tube
Convection	Hot water vapour rises to the top of the tube and cooler water at the top of the tube falls to the bottom via convection.
Radiation	Solar energy heats the copper tube by travelling through the vacuum via radiation.

Section Two: Problem-solving 55% (72 Marks)

This section has **five (5)** questions. You must answer **all** questions. Write your answers in the space provided.

When calculating numerical answers, show your working and reasoning clearly. Give final answers to **three** significant figures and include appropriate units where applicable.

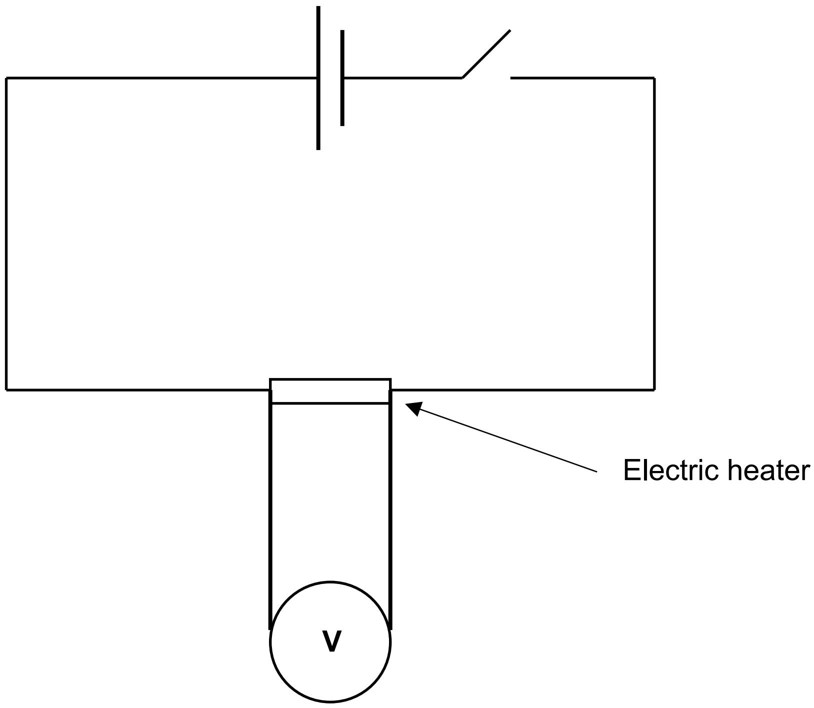
When estimating numerical answers, show your working and reasoning clearly. Give final answers to a maximum of **two** significant figures and include appropriate units where applicable.

Supplementary pages for planning/continuing your answers to questions are provided at the end of the Question/Answer booklet. If you use these pages to continue an answer, indicate at the original answer where the answer is continued, ie – give the page number.

Suggested working time for this section is 83 minutes.

Question 9 (14 marks)

A group of Year 11 Physics students conducted an experiment to find the mass of some water. They set up the electrical equipment shown below:



During the experiment, the students used the electric heater to heat up a known mass of water for 100.0 seconds in the calorimeter. They gradually increased the voltage (V) supplied to the electric heater (measured by the voltmeter) and then measured the change in temperature of the water (ΔT) after this time using the thermometer.

The calorimeter is a perfect insulator. The resistance of the connecting wires, voltage supply and the switch are negligible. The heater is an ohmic conductor and has an efficiency of 100%.

Values are listed in the tables below.

Table 1

Resistance of the electric heater	**1.50 Ω**
Specific heat capacity	**4180 J kg^{-1} °C^{-1}**
Heating time	**100.0 s**

Table 2

V (V)	**V^2 (V^2)**	**ΔT (°C)**
2.90	**8.41**	**5.40**
4.20	**17.6**	**11.2**
5.00	**25.0**	**15.9**
5.90		**22.2**
7.10	**50.4**	**32.1**
8.00	**64.0**	**40.8**

After collecting this data, the students then proceeded to analyse the data and find the mass of water used in this experiment.

a) Complete **Table 2** by writing the missing value in the second column (shaded box).

(1)

34.8	1 mark

QUESTION 9 is continued on page 13

b) The students know that the rate at which electrical energy is supplied to the electric heater can be calculated using the following formulae:

$$\mathbf{P = VI = I^2R = \frac{V^2}{R} = \frac{Q}{t}}$$

The students also know that the electrical energy supplied (Q) to the water is converted into thermal energy that increases its temperature.

By combining appropriate formulae for electric power (see above), and information from the first data table (Table 1) on the previous page, derive the equation show below.

$$\mathbf{\Delta T = \frac{V^2}{m \times 62.7}}$$

where 'm' equals the unknown mass of the water.

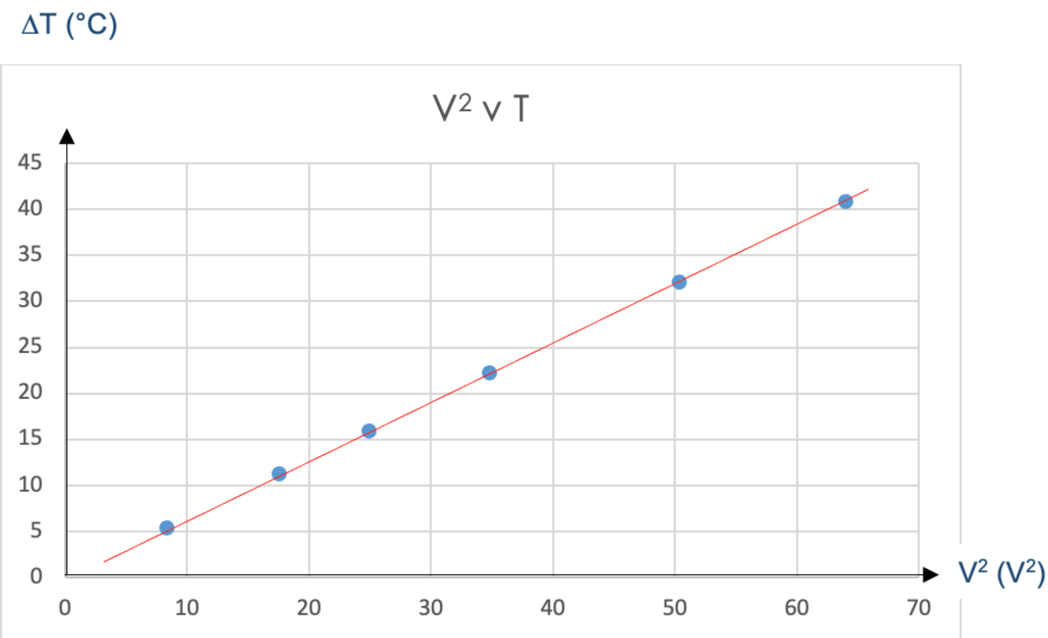
This equation displays the relationship between the voltage supplied to the electric heater (V) and the resultant change in temperature (ΔT). Use the space (below) to show your working.

(3)

Uses the formulae $\mathrm{P = \frac{V^2}{R}; P = \frac{Q}{t}}$; and $\mathrm{Q = mc\Delta T}$ to derive: $\mathrm{\frac{V^2}{R} = \frac{mc\Delta T}{t}}$	1 mark
$\therefore \mathrm{\frac{V^2}{1.50} = \frac{m \times 4180 \times \Delta T}{100.0}}$	1 mark
$\mathrm{V^2 = m \times 62.7\, \Delta T;\ \therefore \Delta T = \frac{V^2}{m \times 62.7}}$	1 mark

c) Using the grid (on the next page), plot a graph of 'ΔT' against 'V^2'. Place 'ΔT' on the vertical axis. Draw a line of best fit for the data.

(4)



Points are plotted correctly.	1 mark
Line of best fit drawn correctly.	1 mark
Axes are labelled correctly (ΔT on the y-axis).	1 mark
Units are correctly displayed.	1 mark

d) Calculate the gradient of the line of best fit. Clearly show how you did this by drawing construction lines. State the units.

(3)

Uses two points from the graph; eg – (10, 6) and (60, 38).	1 mark
$\text{Slope} = \frac{(38-6)}{(60-10)} = 0.64$	1 mark
Units: °C V^{-2}	1 mark

e) Use the gradient you calculated in part d) to calculate the unknown mass 'm' of the water in the experiment.

(3)

$\text{Slope} = \frac{\Delta T}{V^2} = \frac{1}{m \times 62.7}$	1 mark
$\therefore 0.620 = \frac{1}{m \times 62.7}$	1 mark
$m = \frac{1}{0.64 \times 62.7} = 0.025 \text{ kg}$	1 mark

Question 10 **(18 marks)**

Lead sinkers used in fishing are made by heating masses of the lead to its melting point and then placing it in a mould to achieve the required shape. The lead is then cooled down and solidified by plunging the sinkers into a cool bucket of water.

In one such example of sinker production, 500.0 g of lead is heated to its melting point of 327.5 °C. While it is at this temperature, the lead is moulded into the required shape and then dropped into a bucket of water at 25.0 °C. The mass of the plastic bucket is 200.0 g and it contains 2.00 L of water.

The extra data required to answer the questions that follow is contained in the table below. Other data can be found in the Formulae and Data booklet if required.

Specific heat capacity of lead	**130 J kg^{-1} °C^{-1}**
Latent heat of fusion of lead	**23 000 J kg^{-1}**
Specific heat capacity of the plastic bucket	**1900 J kg^{-1} °C^{-1}**
Mass of one (1) litre of water	**1.00 kg**

The lead, water and the plastic bucket reach thermal equilibrium and achieve a final common temperature of 'T'. For parts a) to d), assume no energy is lost to the surroundings.

a) Show that the quantity of internal energy lost by the lead as it freezes at its melting point is equal to 11500 J.

(2)

$Q = mL_f = 0.5 \times 23\,000$	1 mark
$= 11500\text{ J}$	1 mark

b) Derive an expression (in terms of ‘T’) for the **total** internal energy lost by the lead as it achieves a final temperature of ‘T’.

(3)

$Q = 11500 + 0.5 \times 130 \times (327.5 - T)$	1 mark
$= 11500 + 21287.5 - 65T$	1 mark
$= 32787.5 - 65T$	1 mark

c) Derive an expression (in terms of ‘T’) for the **total** internal energy gained by the water and the plastic bucket as they achieve a final temperature of ‘T’.

(4)

$Q = 2.00 \times 4180 \times (T - 25) + 0.2 \times 1900 \times (T - 25)$	1 mark
$= 8360 \times (T - 25) + 380 \times (T - 25)$	1 mark
$= 8360T - 209000 + 380T - 9500$	1 mark
$= 8740T - 218500$	1 mark

d) Hence, use the expressions you derived in parts b) and c) to show that the final temperature ‘T’ is approximately 28.5 °C.

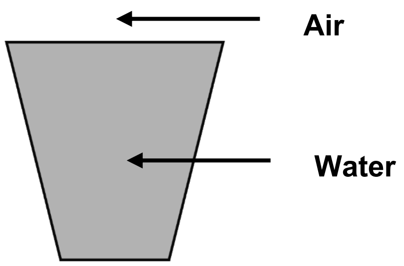
(3)

$32787.5 - 65T = 8740T - 218500$	1 mark
$8805T = 251287.5; \therefore T = \frac{251287.5}{8805}$	1 mark
$= 28.5\ °C$	1 mark

In reality, some thermal energy is lost to the atmosphere by the lead/water/plastic bucket system.

e) Describe the roles that conduction and convection play in transferring heat from the bucket of water to the air above.

(3)



Hotter water particles will collide with air particles. Hence, heat is conducted from the water to the air.	1 mark
The hotter air expands and the particles move apart.	1 mark
Hence, the hotter air undergoes convection and rises carrying heat away from the water.	1 mark

f) When calculating the final temperature in part d), heat lost to the atmosphere and surroundings was not included. In words, explain the effect that including this energy loss would have had on this final temperature.

(3)

The heat gained by the water and the bucket would have been less than calculated in part c).	1 mark
Hence, the temperature rise experienced by the water and the bucket would have been less than calculated.	1 mark
Therefore, the final temperature of the water and the bucket would have been less than 28.5 °C.	1 mark

Question 11 **(14 marks)**

The radioisotope most widely used in medicine is an isotope of Technetium, Tc-99. It is employed in some 80% of all nuclear medicine procedures. Tc-99 has almost the ideal characteristics for a nuclear medicine scan. These are:

- It has a half-life of 6 hours.
- It mainly emits gamma rays.
- The chemistry of technetium is so versatile it can form tracers by being incorporated into a range of biologically-active substances that ensure it concentrates in the tissue or organ of interest.

Technetium generators, consisting of a lead pot enclosing a glass tube containing the radioisotope, are supplied to hospitals from the nuclear reactor where the isotopes are made. They contain molybdenum-99 (Mo-99), with a half-life of 66 hours, which progressively decays to Tc-99.

The Tc-99 is washed out of the lead pot by saline solution when it is required. After two weeks or less the generator is returned for recharging.

a) As stated, Tc-99 is gained from the decay of Mo-99 atoms. Identify the type of decay that occurs in Mo-99 by writing a balanced nuclear equation for this transmutation.

(3)

${}^{99}_{42}Mo \rightarrow {}^{99}_{43}Tc + {}^{0}_{-1}e$ (if positron -1)	
All species identified with correct chemical/particle symbols.	1 mark
Mass numbers and atomic numbers balanced.	1 mark
Identifies Mo-99 as a beta-emitter.	1 mark

b) Tc-99 mainly emits gamma rays. This also makes it very useful for medical scans. State two (2) reasons for this.

(2)

Gamma has high penetrating ability so they can penetrate organs and tissues **and escape easily from the human body and can be captured for external scans.** (teaching point)	1 mark
Gamma rays have the least ionising power of the three most common types of radiation and, therefore, will do less damage to the human body.	1 mark

c) Explain why the half-life of Tc-99 makes it an ideal radioisotope to use for a medical scan.

(2)

The short half-life(6 hours) ensures that Tc-99 decays **to very low levels of radioactivity in a very short time**. (teaching point)	1 mark
Hence, in the longer run, less damage is inflicted on the human body by the radioisotope.	1 mark

A 50.0 g sample of solid Tc-99 arrives at a hospital.

d) (i) Calculate the mass of solid, radioactive Tc-99 that remains after 15 hours. Show working.

(3)

$N = N_0(1/2)^n$; where $N_0 = 50.0$ g; $n = \frac{15}{6} = 2.5$ half lives	1 mark
$N = 50.0\,(1/2)^{2.5}$	1 mark
$\therefore N = 8.84$ g or 8.84 x 10^{-3} kg	1 mark

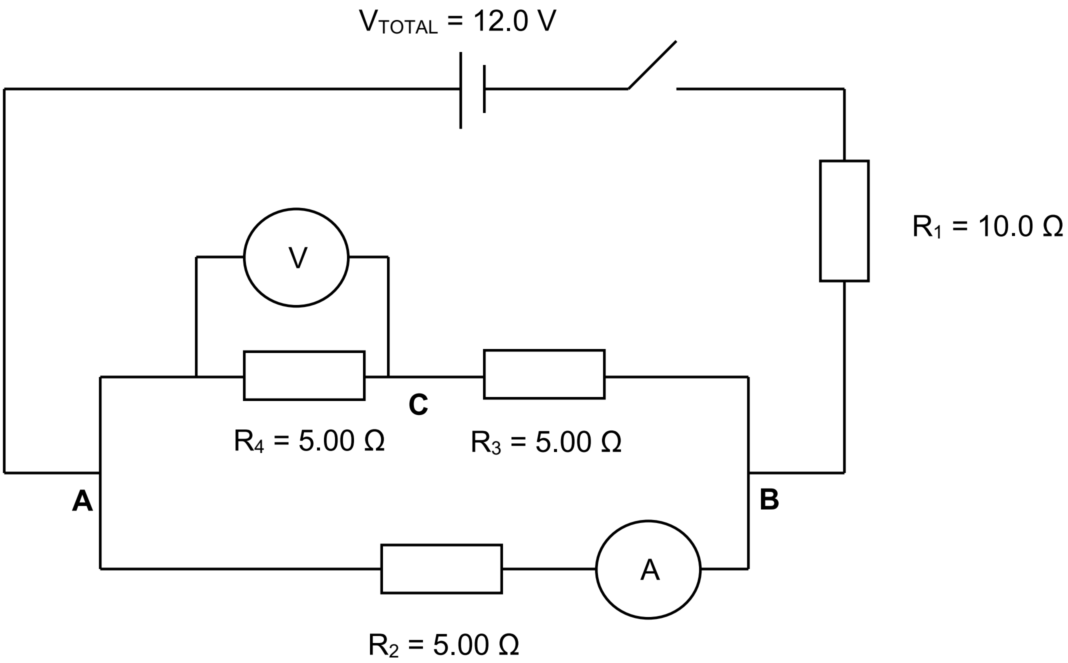
(ii) Once the mass of a sample of Tc-99 drops below 5.00 g, a new sample of Tc-99 needs to be brought in to the hospital. Calculate how long (in hours) it will take for this sample of Tc-99 to drop below this mass.

(4)

$N = N_0(1/2)^n$; where $N_0 = 50.0$ g; $N = 5.00$g	
$5.00 = 50.0\,(1/2)^n$; $(1/2)^n = 0.100$	1 mark
$\therefore n = \frac{\log 0.100}{\log 0.5}$	1 mark
$= 3.32$ half lives	1 mark
$\therefore t = 3.32 \times 6 = 19.9$ hours	1 mark

Question 12 **(17 marks)**

A Physics student built the circuit shown below:



When the switch is closed:

a) Calculate the total resistance between the points 'A' and 'B' (R_{AB}) in the circuit. Show working.

(3)

$\frac{1}{R_{AB}} = \frac{1}{(5+5)} + \frac{1}{5} = \frac{1}{10} + \frac{1}{5}$	1 mark
$\frac{1}{R_{AB}} = \frac{3}{10}$	1 mark
$R_{AB} = \frac{10}{3} = 3.33\ \Omega$	1 mark

b) Hence, calculate the total resistance in the entire circuit (R_T).

(2)

$R_T = 10 + 3.33$	1 mark
$= 13.3\ \Omega$	1 mark

c) Calculate the total current flowing in the circuit (I_T).

(2)

$I_T = \frac{V_T}{R_T} = \frac{12.0}{13.3}$	1 mark
$= 0.900/0.902\ A$	1 mark

d) Calculate the reading on the ammeter.

(3)

$V_{10\Omega} = 0.900 \times 10.0 = 9.00\ V$	1 mark
$\therefore V_{AB} = 12.0 - 9.0 = 3.0\ V$	1 mark
$\therefore I_{AMMETER} = \frac{V}{R} = \frac{3.00}{5} = 0.600\ A$	1 mark

e) Calculate the reading on the voltmeter (V_V).

(3)

$I_{5\Omega} = 0.900 - 0.600$	1 mark
$= 0.300\ A$	1 mark
$V_V = IR = 0.300 \times 5 = 1.50\ V$	1 mark

f) The student creates a break in the circuit at point ‘C’. Does the power at the 10.0 Ω resistor (R_1) change? Explain using calculations.

(4)

Before break at 'C': $P_{10} = VI = 9.00 \times 0.900 = 8.10\ W$	1 mark
After break at 'C': $R_T = 10.0 + 5.00 = 15.0\ \Omega$	0.5 mark
Hence, $I_T = \frac{12.0}{15.0} = 0.800\ A$	0.5 mark
$P_{10} = I^2R = 0.800^2 \times 10 = 6.40\ W$ or $P = VI = (0.800 \times 10) \times 0.800 = 6.40\ W$ (1 mark) decreases(1 mark)	2 marks

Question 13 **(9 marks)**

A **fast breeder reactor** - unlike other 'conventional' reactors - is a nuclear fission reactor that generates more fissile material than it consumes. Breeder reactors achieve this by irradiation of a 'fertile material' (ie – a radioisotope that can be turned into a fissile material by capturing bombarding neutrons). An example of a 'fertile material' is uranium-238 and this is loaded into the reactor along with fissile fuel (eg – U-235). Modern nuclear weapons adopt the same 'fast-breeding' principle.

The extra fissile material that is produced by irradiation of U-238 with neutrons is an isotope of Plutonium, Pu-239. The initial neutron bombardment of U-238 produces U-239. This radioisotope of Uranium is a beta emitter and transmutes into fissile Pu-239. The extra fissile
Neutron capture in a nuclear reactor or weapon can only occur with slow-moving neutrons.

a) Name the feature within a nuclear fission reactor that is responsible for reducing the speed of fast-moving neutrons. Explain how this material works.

(3)

Moderator.	1 mark
The neutrons undergo inelastic collisions with the moderator particles without being captured by them.	1 mark
Hence, the lost kinetic energy of the neutrons results in their reduced speeds.	1 mark

The chain reaction that occurs in the fast breeder reactor is a 'controlled' chain reaction. This contrasts with the 'uncontrolled' chain reaction which occurs when a nuclear weapon is detonated.

b) (i) Name the structure in the nuclear fission reactor that is responsible for 'controlling' the chain reaction. Explain how this structure achieves this.

(3)

Control rods.	1 mark
The rods are made of material that is able to absorb or capture neutrons.	1 mark
Hence, the control rods absorb 'excess neutrons' and the rate at which the chain reaction occurs decreases.	1 mark

(ii) Explain why the chain reaction in a nuclear reactor must be 'controlled' – but is **not** 'controlled' in the same way in a nuclear weapon.

(3)

In an uncontrolled chain reaction, all nuclei undergo fission in an extremely short period of time.	1 mark
Hence, all available nuclear energy in the fissile fuel is released at a very high rate resulting in an explosion.	1 mark
In a nuclear reactor, energy must be released far more slowly and safely; hence, the reaction must be controlled and slowed down.	1 mark

Section Three: Comprehension and data analysis 14% (18 Marks)

This section contains **one (1)** question. Write your answers in the spaces provided.

When calculating numerical answers, show your working and reasoning clearly. Give final answers to **three** significant figures and include appropriate units where applicable.

When estimating numerical answers, show your working and reasoning clearly. Give final answers to a maximum of **two** significant figures and include appropriate units where applicable.

Supplementary pages for planning/continuing your answers to questions are provided at the end of the Question/Answer booklet. If you use these pages to continue an answer, indicate at the original answer where the answer is continued, i.e. – give the page number.

Suggested working time for this section is 21 minutes.

Question 15 **(18 marks)**

The Space Shuttle's Thermal Protection System

The Space Shuttle Orbiter was an amazing technological achievement that remained in service for thirty years between 1976 and 2006. It was the world's first reusable spacecraft.

One of the most visible aspects of the Orbiter was its external tiles (seen above as both black and white in colour). These tiles formed part of the Orbiter's Thermal Protection System (TPS), which worked to protect both the spacecraft and its human occupants from the extreme temperatures created by friction during its re-entry into the Earth's atmosphere.

Early vehicles that had to re-enter the Earth's atmosphere used a variety of techniques to avoid combusting. Two examples included heat sinks that absorbed the enormous heat that would have been absorbed by the vehicle itself and ablative materials that actually ignited, burned and charred as they absorbed the heat created by re-entry.

However, none of these early vehicles were reusable. Hence, the materials used to protect these vehicles were rendered essentially unusable after the space flight. Reusable vehicles posed a different challenge. Scientists figured that a combination of metals and ceramic materials could not only withstand but also survive the high temperatures of re-entry.

In the case of the Orbiter, scientists chose the conventional aluminium for the main body due to its low density and light mass. A TPS that essentially coated the main body with a layer of heat resistant materials was then added to the exterior.

The properties of aluminium demanded that the maximum temperature of the Orbiter's structure remained lower than 175 °C. At this temperature, the aluminium begins to soften and its shape can be permanently distorted by the extreme heat. The temperatures experienced by the Orbiter during re-entry were, however, much higher than the melting point of aluminium (660 °C).

During the 1960's, NASA developed a silica-based insulation material (silicon dioxide). NASA designers constructed tiles made from this material to coat the Orbiter's aluminium body.

The part of the Orbiter that experienced the highest temperatures during re-entry was on the underside of its body. This part of the Orbiter was covered with about 20 000 black High-Temperature Reusable Surface Insulation (or HRSI tiles) made from the silica-based insulation material. These tiles experienced maximum surface temperatures of between 650 °C and 1260 °C.

These tiles have very different thermal properties to the aluminium. Some of these are shown in the table below:

	ALUMINIUM	SILICON DIOXIDE
MELTING POINT	660 °C	1710 °C
SPECIFIC HEAT CAPACITY	900 $Jkg^{-1}°C^{-1}$	628 $Jkg^{-1}°C^{-1}$
THERMAL CONDUCTIVITY	180 $Wm^{-1}°C^{-1}$	0.0485 $Wm^{-1}°C^{-1}$

As can be seen from the table, the thermal conductivity of silicon dioxide is vastly lower than that of aluminium. Thermal conductivity (often denoted by 'k') refers to the intrinsic ability of a material to transfer heat by conduction. It is also defined as the amount of heat per unit time (ie, Joules per second), per unit area (in square metres) that can be conducted through a flat surface of unit length or thickness of a given material (ie - per metre), the faces of the plate differing by one unit of temperature (per degree Celsius). Thermal conductivity can be calculated using the equation below:

$$k = \frac{Q}{t} \cdot \frac{L}{A\,(T_2 - T_1)} \qquad (Equation\ 1)$$

where:
k = thermal conductivity ($Wm^{-1}°C^{-1}$)
$^{Q}/_{t}$ = rate of flow of thermal energy (W)
L = length or thickness of the conducting material (m)
A = surface area of the material (m^2)
$T_2 - T_1$ = temperature difference across the length of the material (°C)

a) Identify two (2) thermal properties that materials used as 'heat sinks' would need to have when protecting a spacecraft during re-entry.

(2)

High melting point.	1 mark
High specific heat capacity.	1 mark

b) Use the particle model to describe what is happening to the aluminium as its temperature increases from below 175 °C to above its melting point of 660 °C.

(4)

Below 660 °C, as thermal energy is added, the average kinetic energy of the particles increases.	1 mark
The particles, therefore, move faster and further causing expansion and a softening of the aluminium.	1 mark
At 660 °C, any further added thermal energy increases the potential energy of the particles without changing the kinetic energy of the particles.	1 mark
This changes the force of attraction from strong to weak and causes a change of phase from solid to liquid.	1 mark

A typical HRSI tile has the following specifications:

mass = 1.02 kg; dimensions = 15 cm x 15 cm; thickness = 2.54 cm

c) (i) Calculate the energy required to raise the temperature of an HRSI tile from 650 °C to 1260 °C.

(3)

$Q = mc\Delta T$	1 mark
$= 1.02 \times 628 \times (1260 - 650)$	1 mark
3.91×10^5 J	1 mark

(ii) During re-entry, an HRSI tile will typically experience a temperature gradient of 1260 °C on its exterior to about 170 °C on its interior. Using ***Equation 1*** (above), determine how much heat energy is passed through the tile every second during re-entry.

(4)

k = 0.0485 $Wm^{-1}°C^{-1}$; L = 0.0254 m; A = 0.15 x 0.15 = 2.25 x 10^{-2} m^2; $T_2 - T_1$ = 1260 – 170 = 1.09 x 10^3 °C	1 mark
$k = \frac{Q}{t} \cdot \frac{L}{A\,(T_2 - T_1)}$; $\therefore 0.0485 = \frac{Q}{t} \cdot \frac{0.0254}{2.25 \times 10^{-2} \times 1.09 \times 10^3}$	1 mark
$\frac{Q}{t} = \frac{0.0485 \times 24.5}{0.0254}$	1 mark
$= 46.8\ W$ (or 46.8 Js^{-1})	1 mark

(iii) A human can hold an HRSI tile in their bare hands even if it has been raised to temperatures similar to those experienced during re-entry. This certainly could not be done with an aluminium object. Using data from the table, explain why.

(3)

Silicon dioxide's low thermal conductivity means that the rate it conducts thermal energy into human skin is very slow and would not raise its temperature markedly.	1 mark
Aluminium has a thermal conductivity that is much higher than silicon dioxide (~3700 times larger).	1 mark
Hence, aluminium would conduct thermal energy into skin far quicker than silicon dioxide and would cause a rapid and significant increase in temperature.	1 mark

d) The HRSI tiles are black in colour. Explain why this colour also assists with protecting the aluminium Orbiter body from absorbing excessive amounts of heat.

(2)

Black objects are excellent absorbers and emitters of thermal radiation.	1 mark
The tiles will, therefore, absorb much more of the radiant energy than that absorbed by the aluminium.	1 mark

End of Questions

Additional working space

Additional working space

Spare grid for graph

Acknowledgements

“Nuclear astrophysics: nucleosynthesis in the Universe”; International Journal of Astrobiology (Lepine-Szily & Descouvemnont, 2012).

https://www.centennialofflight.net/essay/Evolution_of_Technology/TPS/Tech41.htm

https://www.azom.com/article.aspx?ArticleID=11443