



Oxford Cambridge and RSA

Thursday 15 June 2023 – Morning

A Level Physics A

H556/03 Unified physics

Time allowed: 1 hour 30 minutes



You must have:

- the Data, Formulae and Relationships Booklet

You can use:

- a scientific or graphical calculator
- a ruler (cm/mm)



Please write clearly in black ink. **Do not write in the barcodes.**

Centre number

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Candidate number

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First name(s)

Last name

StemUp Model Solution

INSTRUCTIONS

- Use black ink. You can use an HB pencil, but only for graphs and diagrams.
- Write your answer to each question in the space provided. If you need extra space use the lined pages at the end of this booklet. The question numbers must be clearly shown.
- Answer **all** the questions.
- Where appropriate, your answers should be supported with working. Marks might be given for a correct method, even if your answer is wrong.

INFORMATION

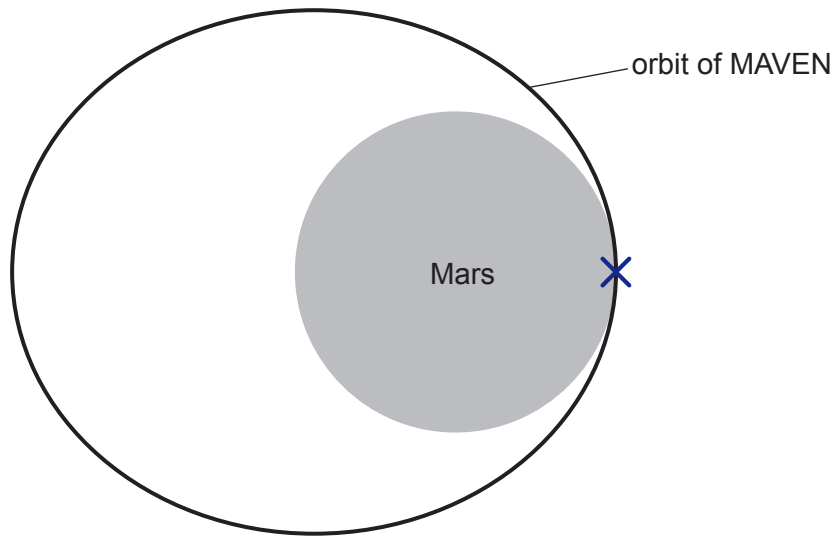
- The total mark for this paper is **70**.
- The marks for each question are shown in brackets [].
- Quality of extended response will be assessed in questions marked with an asterisk (*).
- This document has **24** pages.

ADVICE

- Read each question carefully before you start your answer.

1 The MAVEN spacecraft orbits Mars and studies its upper atmosphere.

(a) The diagram below shows the orbit of MAVEN around Mars.



(i) Mark an **X** on the diagram to show the point in the orbit where MAVEN has maximum acceleration. [1]

(ii) Explain how Kepler's 1st law applies to MAVEN's orbit around Mars.

*Kepler's 1st law: the orbit of MAVEN is an ellipse (elliptical orbit),
with (the centre of mass of) Mars at one focus of the ellipse.*

..... [2]

(b) The table shows data for four orbits around Mars.

Phobos and Deimos are moons of Mars.

An areostationary orbit for Mars is the equivalent of a geostationary orbit for Earth.

Orbit	Time period / hours	Average distance from centre of Mars / km
MAVEN	4.5	6 500
Phobos	7.7	9 400
Deimos	30	23 000
Areostationary	25	20 000

(i) Show that Kepler's 3rd law applies to this data.

Kepler's 3rd law: $T^2 \propto r^3$, so T^2/r^3 should be constant.

MAVEN: $4.5^2 \div 6500^3 = 7.4 \times 10^{-11} \text{ h}^2 \text{ km}^{-3}$

Phobos: $7.7^2 \div 9400^3 = 7.1 \times 10^{-11} \text{ h}^2 \text{ km}^{-3}$

Deimos: $30^2 \div 23\,000^3 = 7.4 \times 10^{-11} \text{ h}^2 \text{ km}^{-3}$

Areostationary: $25^2 \div 20\,000^3 = 7.8 \times 10^{-11} \text{ h}^2 \text{ km}^{-3}$

T^2/r^3 is (reasonably) constant for all four, so $T^2 \propto r^3$ and Kepler's 3rd law applies.

[2]

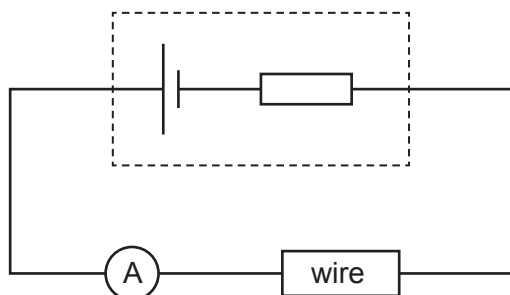
(ii) Suggest **two** reasons why MAVEN was **not** placed in an areostationary orbit.

1 *MAVEN needs to see the whole planet / atmosphere; an areostationary orbit stays above the same place, so it could only see one part of Mars.*

2 *MAVEN needs to be in / near the upper atmosphere to study it; the areostationary radius is so large it would not pass through the atmosphere.*

[2]

- 2 A student uses the circuit below to investigate the resistivity of a wire.



The cell has e.m.f. ε and internal resistance r . The wire has resistivity ρ and diameter d .

- (a) The student takes five measurements of the diameter of the wire, which are shown in the table below.

Diameter/mm	0.460	0.450	0.455	0.495	0.455
-------------	-------	-------	-------	-------	-------

- (i) Suggest how the student made these measurements.

Use a micrometer (screw gauge) or digital callipers to measure the diameter, taking readings at different positions along the wire and in different orientations (rotating the wire).

[2]

- (ii) The student calculates the value of the diameter as $d = 0.455 \pm 0.005$ mm.

Explain how the student calculated the value of the diameter, and its uncertainty, from the data in the table above.

The value 0.495 mm is an anomaly, so it is excluded.
 Mean of the remaining 4 values = $(0.460 + 0.450 + 0.455 + 0.455) \div 4 = 1.820 \div 4 = 0.455$ mm.
 Uncertainty = half the range of the remaining values = $(0.460 - 0.450) \div 2 = 0.005$ mm.

[3]

- (b) The student varies the length L of the wire in the circuit and records the current I using the ammeter.

- (i) Show that

$$\frac{1}{I} = \left(\frac{4\rho}{\pi \epsilon d^2} \right) L + \frac{r}{\epsilon}$$

$$\epsilon = I(R + r) \quad (\text{e.m.f.} = \text{terminal p.d.} + \text{lost volts})$$

$$R = \rho L/A \quad \text{and} \quad A = \pi d^2/4, \quad \text{so} \quad R = 4\rho L/(\pi d^2)$$

$$\epsilon = I(4\rho L/(\pi d^2) + r)$$

divide both sides by $I\epsilon$:

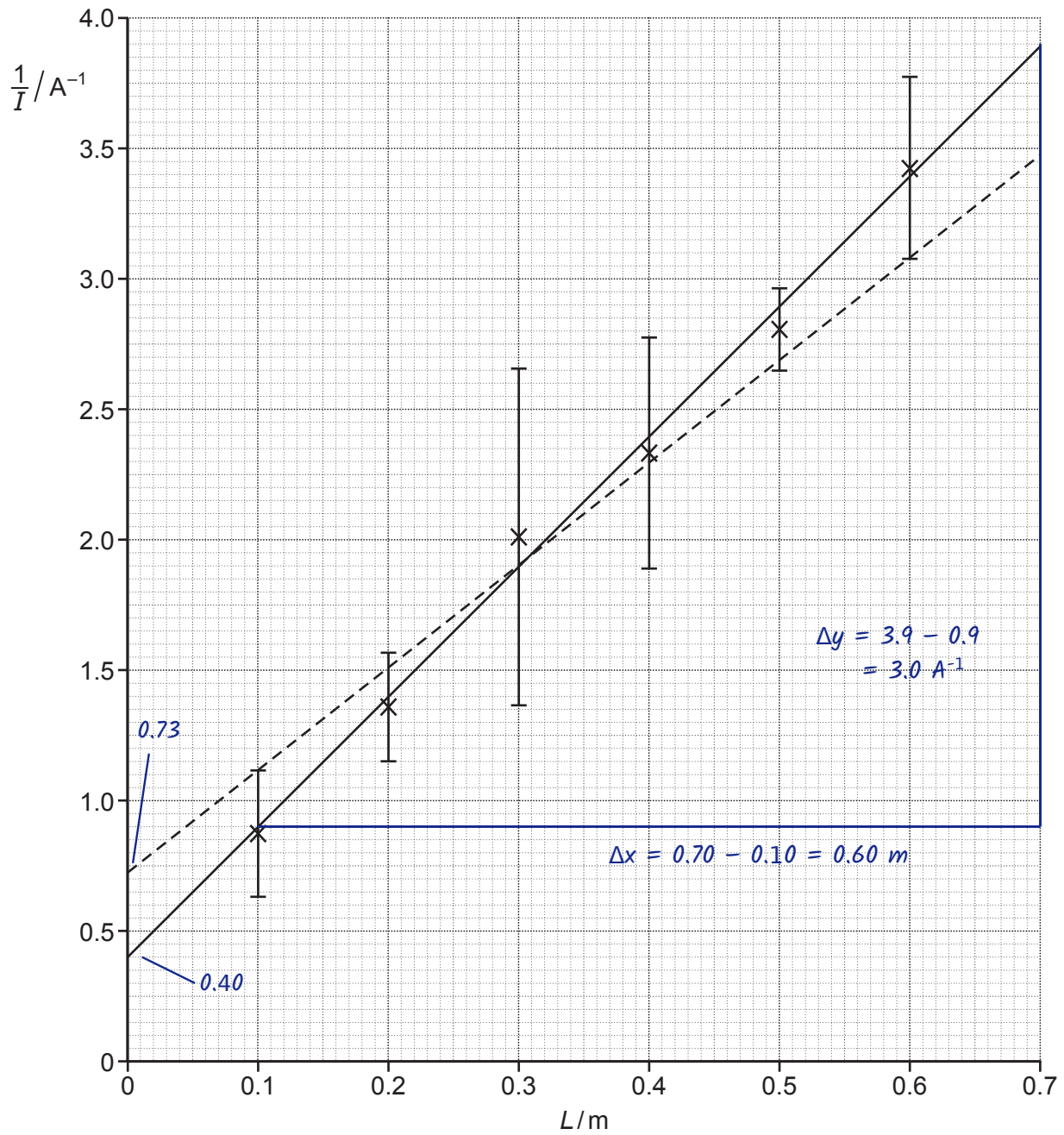
$$1/I = 4\rho L/(\pi \epsilon d^2) + r/\epsilon$$

$$1/I = (4\rho/(\pi \epsilon d^2)) L + r/\epsilon$$

[3]

Question 2 continues on page 6

- (ii) The student plots a graph of $\frac{1}{I}$ against L . The data points, error bars, line of best fit and a line of worst fit are shown in the graph below.



The cell has e.m.f. $\varepsilon = 1.45 \pm 0.05 \text{ V}$

The wire has diameter $d = 0.455 \pm 0.005 \text{ mm}$

- 1 Calculate the gradient of the best fit line and use this to determine a value for the resistivity ρ of the wire.

You are **not** required to determine an uncertainty.

$$\text{gradient} = \Delta y / \Delta x = (3.9 - 0.9) \div (0.70 - 0.10) = 3.0 \div 0.60 = 5.0 \text{ A}^{-1} \text{ m}^{-1}$$

$$\text{gradient} = 4\rho / (\pi \varepsilon d^2) \quad \text{so} \quad \rho = \text{gradient} \times \pi \varepsilon d^2 / 4$$

$$\rho = 5.0 \times \pi \times 1.45 \times (0.455 \times 10^{-3})^2 \div 4$$

$$\rho = 1.18 \times 10^{-6} \text{ } \Omega \text{ m}$$

$$\rho = \dots\dots\dots 1.2 \times 10^{-6} \dots\dots\dots \Omega \text{ m} \text{ [2]}$$

- 2 Determine a value for the internal resistance r of the cell **and** its absolute uncertainty.

$$y\text{-intercept (best fit)} = r/\varepsilon = 0.40 \text{ A}^{-1}$$

$$r = 0.40 \times 1.45 = 0.58 \text{ } \Omega$$

$$y\text{-intercept of worst fit line} = 0.73 \text{ A}^{-1}$$

$$\text{uncertainty in intercept} = 0.73 - 0.40 = 0.33 \text{ A}^{-1}$$

$$\text{fractional uncertainty in } r = 0.05/1.45 + 0.33/0.40$$

$$= 0.034 + 0.825 = 0.86$$

$$\text{absolute uncertainty} = 0.86 \times 0.58 = 0.50 \text{ } \Omega = 0.5 \text{ } \Omega \text{ (1 s.f.)}$$

$$\text{so } r = 0.6 \pm 0.5 \text{ } \Omega$$

$$r = \dots\dots\dots 0.6 \dots\dots\dots \pm \dots\dots\dots 0.5 \dots\dots\dots \Omega \text{ [4]}$$

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3 A pulsar is a rapidly rotating neutron star that emits radio waves.

(a) (i) Describe the formation of a neutron star.

A massive red supergiant can no longer release enough energy by fusion, so its core collapses under gravity in a (Type II) supernova. Protons capture electrons to form neutrons; the core mass is above the Chandrasekhar limit (1.4 solar masses). [2]

(ii) State **one** characteristic of a neutron star.

It is extremely dense (about $10^{17} \text{ kg m}^{-3}$, similar to nuclear density). [1]

(b) A typical neutron star can be modelled as a sphere with mass $\approx 2 \times 10^{30} \text{ kg}$ and radius $\approx 10 \text{ km}$.

Show that the average density of a neutron star is similar to the average density of an atomic nucleus.

- radius of a nucleon $\approx 1 \text{ fm}$

$$\rho = m/V \quad \text{and} \quad V = (4/3)\pi r^3$$

$$\text{Neutron star: } V = (4/3)\pi(1.0 \times 10^4)^3 = 4.2 \times 10^{12} \text{ m}^3$$

$$\rho = 2 \times 10^{30} \div 4.2 \times 10^{12} = 4.8 \times 10^{17} \approx 5 \times 10^{17} \text{ kg m}^{-3}$$

$$\text{Nucleon: } m \approx 1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}, r \approx 1 \times 10^{-15} \text{ m}$$

$$V = (4/3)\pi(1 \times 10^{-15})^3 = 4.2 \times 10^{-45} \text{ m}^3$$

$$\rho = 1.66 \times 10^{-27} \div 4.2 \times 10^{-45} = 4.0 \times 10^{17} \approx 4 \times 10^{17} \text{ kg m}^{-3}$$

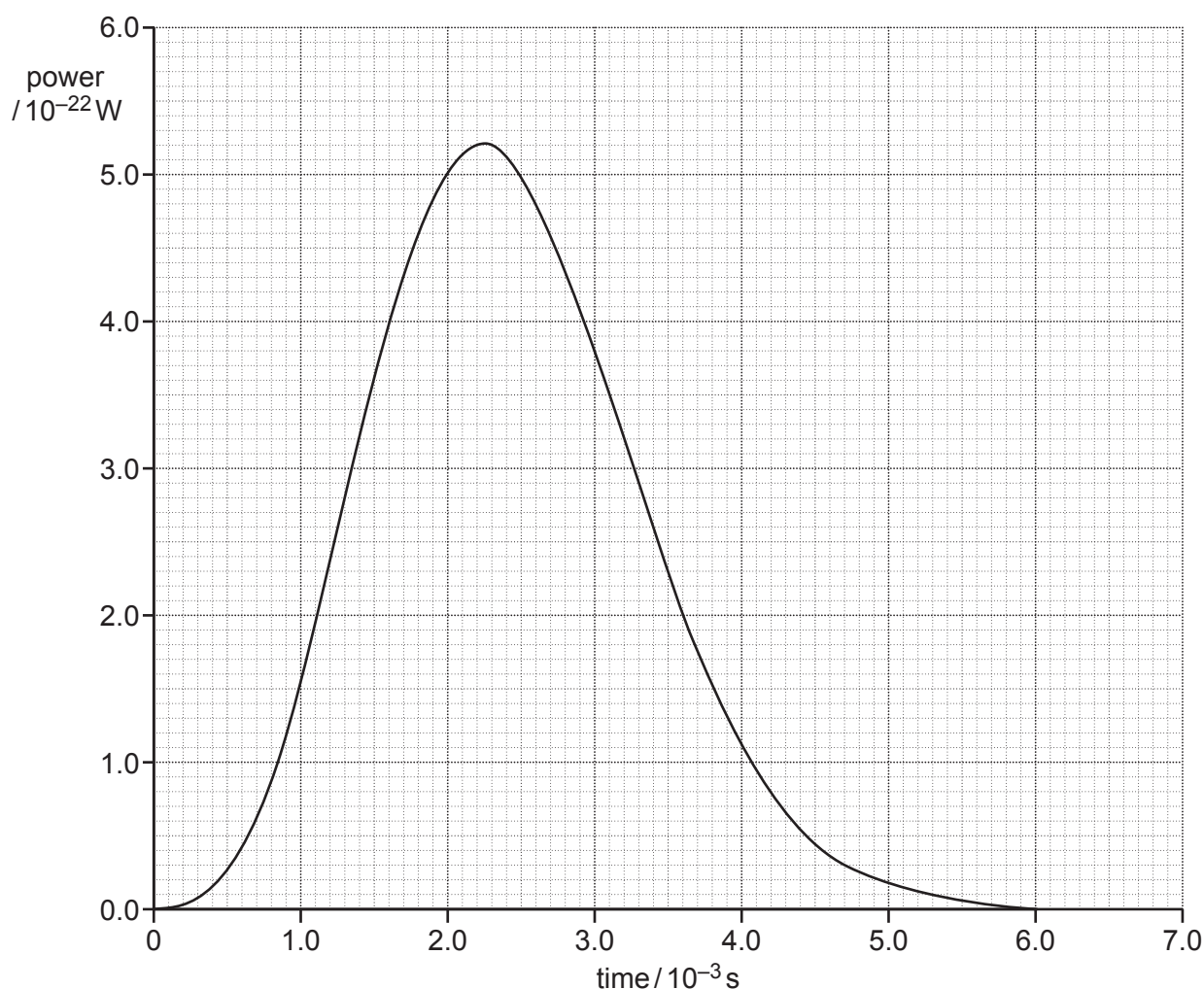
Both densities are about $10^{17} \text{ kg m}^{-3}$ (ratio ≈ 1.2), so the density of a neutron star is similar to that of a nucleus.

[3]

Question 3 continues on page 10

- (c) An astronomer uses a radio telescope to observe a pulsar.

The graph below shows the power that the telescope receives due to the radio waves from one full rotation of a pulsar.



- (i) By calculating the area between the curve and the horizontal axis, estimate the total energy received by the telescope in one full rotation of the pulsar.

number of large squares under the curve ≈ 11

area of 1 large square = $1.0 \times 10^{-22} \text{ W} \times 1.0 \times 10^{-3} \text{ s} = 1.0 \times 10^{-25} \text{ J}$

energy = $11 \times 1.0 \times 10^{-25} = 1.1 \times 10^{-24} \text{ J}$

total energy received = ... 1.1×10^{-24} J [2]

- (ii) The surface area of the telescope is about 3000 m^2 .

The distance to the pulsar is about 300 pc.

By assuming that the radiation from the pulsar is emitted equally in all directions, estimate the total energy emitted in one full rotation.

$$d = 300 \text{ pc} = 300 \times 3.1 \times 10^{16} = 9.3 \times 10^{18} \text{ m}$$

energy spreads over a sphere of area $4\pi d^2$

$$4\pi d^2 = 4\pi \times (9.3 \times 10^{18})^2 = 1.09 \times 10^{39} \text{ m}^2$$

$$\text{ratio of areas} = 1.09 \times 10^{39} \div 3000 = 3.6 \times 10^{35}$$

energy emitted = ratio $\times$ energy received

$$= 3.6 \times 10^{35} \times 1.1 \times 10^{-24}$$

$$= 4.0 \times 10^{11} \text{ J}$$

energy emitted = ... 4.0×10^{11} J [3]

4 A cloud is made up of droplets of water falling at terminal velocity.

(a) Describe and explain the motion of an object falling at terminal velocity.

The object moves at a constant velocity, so its acceleration is zero.

The weight (downwards) is equal to the drag (+ upthrust) acting upwards,

so the resultant (net) force on the object is zero (Newton's 1st law), and its

velocity does not change.

[3]

(b) (i) The terminal velocity v of a small sphere of density ρ_s and radius r falling through a fluid of density ρ_f is given by the formula:

$$v = \frac{2gr^2(\rho_s - \rho_f)}{9\eta}$$

where η is a constant for the fluid and g is the acceleration of free fall.

Water droplets of rain fall to the ground whereas water droplets in mist appear to float.

Use the formula above to suggest why.

$v \propto r^2$, so droplets with a smaller radius have a much smaller terminal

velocity.

Water droplets in mist have a much smaller radius than raindrops, so

their v is so small that they appear to float.

[2]

- *(ii)** A student models water droplets falling through air using small solid spheres in a liquid.

The table shows properties of the materials available to the student.

Material	Solid density, $\rho_s / \text{kg m}^{-3}$	Liquid density, $\rho_f / \text{kg m}^{-3}$	Approximate value of $\eta / 10^{-3} \text{ kg m}^{-1} \text{ s}^{-1}$
Water (liquid)		1000	1
Sunflower oil (liquid)		920	50
Steel (solid sphere)	7 800		
Lead (solid sphere)	11 300		

Describe an experiment to verify the expression given in **(i)** as accurately as possible. As part of your answer, estimate the **lowest** terminal velocity if the student uses a solid sphere of diameter = 1 mm.

Lowest v : steel (lowest ρ_s) in sunflower oil (largest η), $r = 0.50 \times 10^{-3} \text{ m}$

$$v = 2 \times 9.81 \times (0.50 \times 10^{-3})^2 \times (7800 - 920) \div (9 \times 50 \times 10^{-3})$$

$$v = 0.075 \text{ m s}^{-1} \quad (\text{steel in water: } v \approx 3.7 \text{ m s}^{-1}, \text{ too fast to time})$$

Analysis: plot v against r^2 ; a straight line through the origin shows $v \propto r^2$.

$$\text{gradient} = 2g(\rho_s - \rho_f)/9\eta, \text{ so } g = 9\eta \times \text{gradient} \div 2(\rho_s - \rho_f); \text{ compare with } 9.81.$$

..Fill a long, clear tube with sunflower oil and check it is vertical with a spirit level.....
 ..or plumb line. Measure the diameter of each steel sphere with a micrometer at.....
 ..several orientations, take the mean and use $r = d/2$
 ..Fix rubber bands around the tube at marks 10 cm apart, starting well below the.....
 ..surface so the sphere has reached terminal velocity. Drop the sphere gently at the.....
 ..centre of the tube. Time the fall between bands with a stopwatch (or film it.....
 ..next to a metre rule and step through the video frame by frame), with the eye.....
 ..level with each band to avoid parallax.....
 ..Check terminal velocity has been reached: the times for successive equal 10 cm.....
 ..intervals must be the same. Then $v = \text{distance} \div \text{time}$. Repeat each measurement.....
 ..three times and average.....
 ..Repeat with spheres of several different radii (and with lead spheres). Plot v [6]

Additional answer space if required

Q4(b)(ii) continued
against r^2 : if the points lie on a straight line through the origin, $v \propto r^2$ is
verified. Calculate g from the gradient using the values of η , ρ_s and ρ_f and check
it is close to 9.81 m s^{-2} , or compare each measured v with the value predicted by
the formula.
The lowest v (0.075 m s^{-1} , steel in sunflower oil) is slow enough to time
accurately, so steel and sunflower oil are the best choice.

15
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5 Large power stations generate an electrical power of about 1 GW.

Current methods of energy production that use nuclear fusion are unable to produce enough energy for large-scale energy production. A proposed method of controlling nuclear fusion is inertial confinement fusion (ICF). ICF uses a large number of powerful lasers to create the high temperatures required for nuclear fusion to occur.

One ICF experiment uses a network of capacitors to store the energy needed to power the lasers. When the network is fully charged:

- potential difference across the network = 24 kV
- total energy stored in the network = 400 MJ

(a) (i) Calculate the total capacitance, C , of the network.

$$W = \frac{1}{2} CV^2$$

$$400 \times 10^6 = 0.5 \times C \times (24 \times 10^3)^2$$

$$C = 2 \times 400 \times 10^6 \div (24 \times 10^3)^2 = 1.39 \text{ F}$$

$$C = \dots\dots\dots 1.4 \dots\dots\dots \text{ F [2]}$$

(ii) Explain why the individual capacitors in the network should be connected in parallel in order to produce this total capacitance.

Capacitors in parallel add ($C_T = C_1 + C_2 + \dots$), so this increases the total capacitance to 1.4 F. [1]

(b) The total stored energy must be released in a time of less than 1 millisecond.

Explain, using a calculation, why the lasers are powered by the network of capacitors instead of being connected directly to the mains electricity supply.

Power = $E/t = 400 \times 10^6 \div 1 \times 10^{-3} = 4.0 \times 10^{11} \text{ W}$ (400 GW).

This is about 400 times the output of a large (1 GW) power station, so the mains supply could not provide this power; the capacitors store the energy slowly and release it in under 1 ms. [2]

(c) The fusion reaction in the ICF experiment is

deuterium + tritium $\rightarrow$ alpha particle + neutron

Calculate the number of fusion reactions that must occur for the energy released by fusion to be equal to the electrical energy stored in the network of capacitors.

- mass of deuterium = 2.014102 u
- mass of tritium = 3.016049 u
- mass of alpha particle = 4.002603 u
- mass of neutron = 1.008665 u

$$\begin{aligned} \text{mass defect} &= (2.014102 + 3.016049) - (4.002603 + 1.008665) \\ &= 0.018883 \text{ u} \end{aligned}$$

$$\text{in kg: } 0.018883 \times 1.661 \times 10^{-27} = 3.1365 \times 10^{-29} \text{ kg}$$

$$\begin{aligned} \text{energy per reaction} &= \Delta mc^2 = 3.1365 \times 10^{-29} \times (3.00 \times 10^8)^2 \\ &= 2.82 \times 10^{-12} \text{ J} \end{aligned}$$

$$\begin{aligned} \text{number of reactions} &= \text{energy needed} \div \text{energy per reaction} \\ &= 400 \times 10^6 \div 2.82 \times 10^{-12} \\ &= 1.4 \times 10^{20} \end{aligned}$$

$$\text{number of fusion reactions} = \dots\dots\dots 1.4 \times 10^{20} \dots\dots\dots [4]$$

- 6 A 3D printer can manufacture small objects.

Some 3D printers use polylactic acid (PLA). PLA is supplied in the form of long filaments. The 3D printer melts the PLA and builds up the shape of the desired object in layers.

The electrical supply to the heater in the printer has an e.m.f., $\mathcal{E}$, of 12 V. The power of the heater is 40 W.

- (a) Calculate the resistance, R , of the heater.

$$P = V^2/R \quad \text{so} \quad R = V^2/P$$

$$R = 12^2 \div 40 = 144 \div 40 = 3.6 \, \Omega$$

$$R = \dots\dots\dots 3.6 \dots\dots\dots \Omega \quad [2]$$

- (b) The specific latent heat of fusion of PLA is $9.4 \times 10^4 \text{ J kg}^{-1}$ and its melting point is 160°C .

- (i) Define **specific latent heat of fusion**.

The (thermal) energy required per unit mass to change a substance from solid to liquid at constant temperature.

..... [1]

- (ii) Calculate the **maximum** mass m of PLA that the heater could melt in one minute.

$$\text{energy} = Pt = mL$$

$$m = 40 \times 60 \div 9.4 \times 10^4 = 2400 \div 94\,000 = 2.55 \times 10^{-2} \text{ kg}$$

$$m = \dots\dots\dots 2.6 \times 10^{-2} \dots\dots\dots \text{ kg} \quad [2]$$

- (iii) Explain why the printing process is slower in practice than your answer to (ii) suggests.

Some energy / time is first needed to raise the temperature of the PLA from 20°C up to its melting point of 160°C .

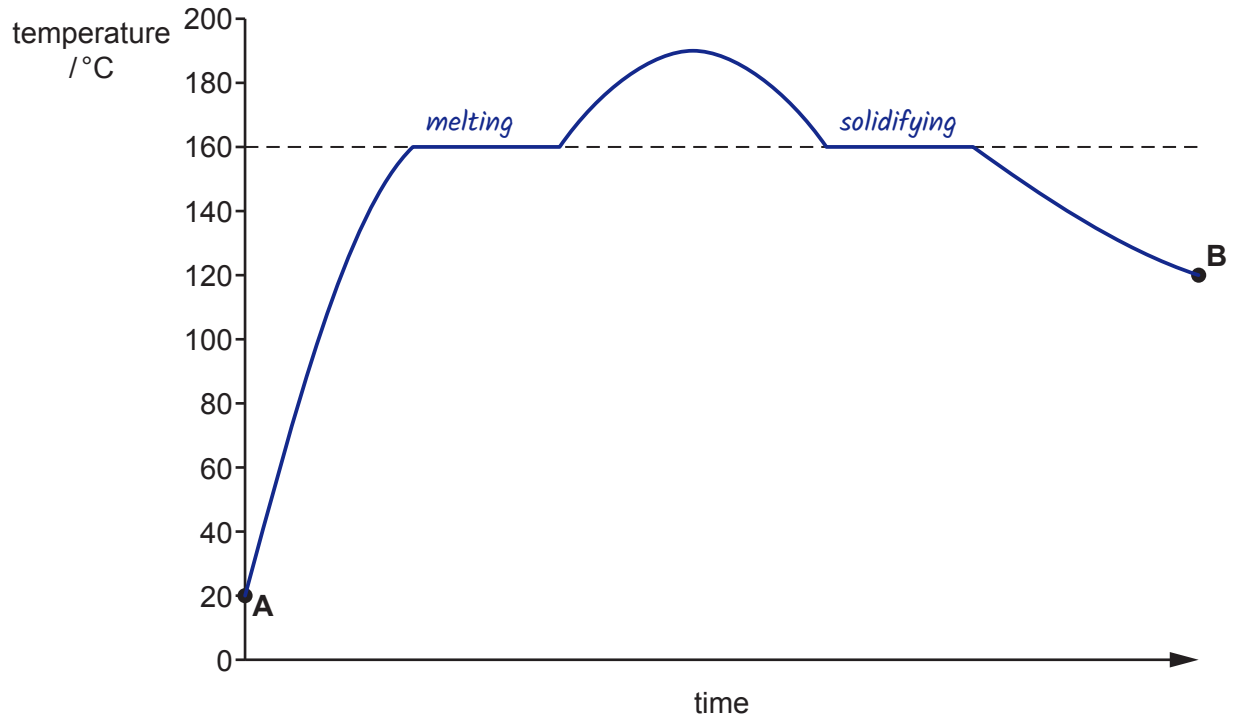
Not all the heat is used to melt PLA: some is lost to the surroundings (printer nozzle, air).

[2]

(iv) **Fig. 6.1** shows the initial and final temperature of the PLA during the printing process.

Initially (point **A**), the solid PLA is at 20 °C and is just entering the heater. Later (point **B**), the PLA has been added to the object and is solid again.

Fig. 6.1



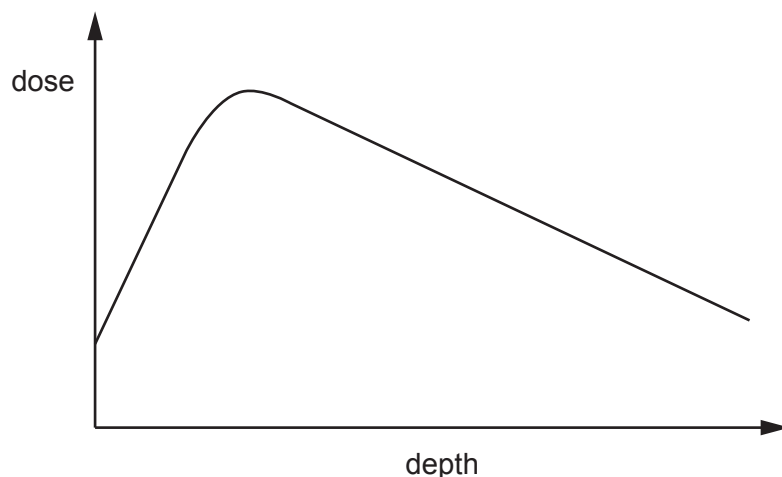
Complete **Fig. 6.1** to show how the temperature of the PLA changes between **A** and **B**. You are **not** required to label the time axis. **[3]**

- (c) High-energy X-ray photons can destroy living cells. In radiotherapy, these photons are targeted at cancer cells.

The radiation **dose** is the amount of energy that a patient's body absorbs from the high-energy X-ray photons.

Fig. 6.2 shows how this dose changes with depth below the surface of the skin.

Fig. 6.2



The dose initially rises with depth because the high-energy X-ray photons produce electrons and positrons as they pass through the body. These electrons and positrons are quickly absorbed, increasing the dose.

- (i) Explain why high-energy X-ray photons produce electrons **and** positrons as they pass through the body.

The photon interacts with (travels close to) a nucleus and its energy is transformed into matter and antimatter: pair production.
A positron is the antiparticle of the electron, so a particle and antiparticle pair is produced. [2]

- *(ii) A 3D object called a **bolus** is used in radiotherapy for patients with skin cancer. A bolus targets the maximum radiation dose near the surface of the skin. So using a bolus makes the radiotherapy more effective.

A bolus can be made from PLA using a 3D printer. The bolus must fit the shape of the patient's body exactly. This shape is found beforehand by giving the patient either a CAT scan or a PET scan.

- Explain how CAT scans and PET scans work.
- Discuss the advantages and disadvantages of having a scan to produce a bolus for radiotherapy.

CAT scan: a thin, fan-shaped beam of X-rays is passed through the patient while the X-ray tube and a ring of detectors rotate around them. Each rotation gives an image of a thin slice; the patient moves through the ring so many 2D slices are taken, and a computer combines them into a 3D image of the body shape.

PET scan: a positron-emitting tracer (e.g. fluorine-18 in FDG) is injected. Each positron annihilates with an electron, producing two gamma photons that travel in opposite directions. A ring of gamma detectors detects the pair, and the difference in arrival times locates the annihilation; a computer builds a 3D image.

Disadvantages: both scans give a dose of ionising radiation to healthy tissue (increased cancer risk); they are expensive and use NHS resources, and can be long, uncomfortable or scary for the patient.

Advantages: the bolus fits the body exactly, so the maximum dose is at the skin surface where the cancer is. Less radiotherapy and a lower total dose to deeper healthy tissue are needed, saving cost and discomfort. The more effective treatment may save the patient's life, so overall the benefits outweigh the extra risk of the scan. [6]

Additional answer space if required

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END OF QUESTION PAPER

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