3.5 Electricity

AQA 7408 · Calculator allowed · about 200 minutes · Write-in edition

Total Marks

Name: _____ Date: ____ / ____ / _____

Answer ALL questions. Show all your working.

1 A student uses a data logger to measure the charge that flows through a filament lamp over a short period of time after it is switched on.

(a) State what is meant by electric current. **(1)**

(b) A charge of 480 C flows through the lamp in 4.0 minutes. Calculate the current in the lamp. Use Q = I t. **(3)**

(c) The charge on one electron is 1.60×10^{-19} C. Calculate the number of electrons that pass a point in the filament each second. **(3)**

(Total for Question 1 is 7 marks)

2 This question tests core definitions in electricity.

(a) Define the electromotive force (EMF) of a source. **(1)**

(b) Define the resistivity of a material. **(1)**

(c) State Kirchhoff's second law. **(1)**

(Total for Question 2 is 3 marks)

3 A wire in a circuit carries a steady current of 0.85 A for 12 minutes.

(a) Calculate the charge that flows through the wire in this time. **(2)**

(b) Calculate the number of electrons that pass a point in the wire during this time (charge of an electron = 1.60×10^{-19} C). **(2)**

(Total for Question 3 is 4 marks)

4 Compare and explain the I-V characteristics of three components: a metal wire resistor at constant temperature, a filament lamp, and a silicon diode. Your answer should refer to the effect of temperature (where relevant) and the behaviour of charge carriers in each case.

(Total for Question 4 is 6 marks)

5 A piece of copper wire used in a laboratory power supply has a cross-sectional area of 2.0 mm^2. The number density of free (charge-carrying) electrons in copper is 8.5×10^{28} m^{-3}.

(a) The current in the wire is 3.0 A. Calculate the mean drift velocity of the free electrons. Use I = n A v q, where q is the charge on an electron (1.60×10^{-19} C). **(3)**

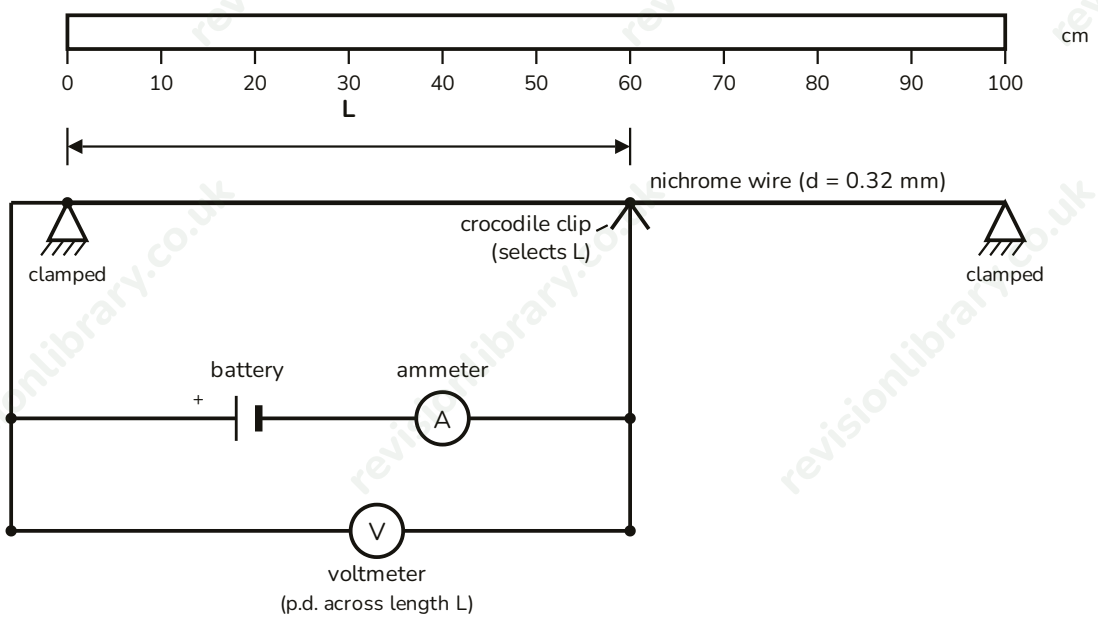
(b) Explain why the drift velocity of the electrons would be greater in a thinner wire of the same material carrying the same current. **(2)**

(c) A different copper wire is 5.0 m long and has a diameter of 0.60 mm. The resistivity of copper is 1.7×10^{-8} ohm metre. Calculate the resistance of the wire. Use R = resistivity x L / A. **(3)**

(Total for Question 5 is 8 marks)

6 Required practical: a student determines the resistivity of a sample of nichrome resistance wire of diameter 0.32 mm. The student measures the resistance R of different lengths L of the wire, using a crocodile clip to select each length, and plots a graph of R against L.

Circuit for finding R at different lengths L of nichrome wire



(a) Describe how the student should carry out this experiment to obtain a reliable set of R and L measurements, including how the diameter of the wire is measured. **(5)**

(b) Two of the student's results are: at L = 0.200 m, R = 2.80 ohm; at L = 1.000 m, R = 13.60 ohm. Show that the gradient of the graph of R against L is approximately 13.5 ohm per metre. **(2)**

(c) Calculate the resistivity of the nichrome wire, using the gradient found in part (b) and the diameter of the wire (0.32 mm). The gradient of R against L is equal to resistivity/A, where A is the cross-sectional area of the wire. **(3)**

(d) Suggest two reasons why using the gradient of a graph of R against L gives a more accurate value of resistivity than calculating resistivity from a single pair of R and L readings. **(2)**

(Total for Question 6 is 12 marks)

7 A battery has EMF 6.0 V and internal resistance 0.50 ohm. It is connected to an external resistor of resistance 2.5 ohm. Use the equation EMF = I(R + r), where R is the external resistance and r is the internal resistance.

(a) Calculate the current in the circuit. **(3)**

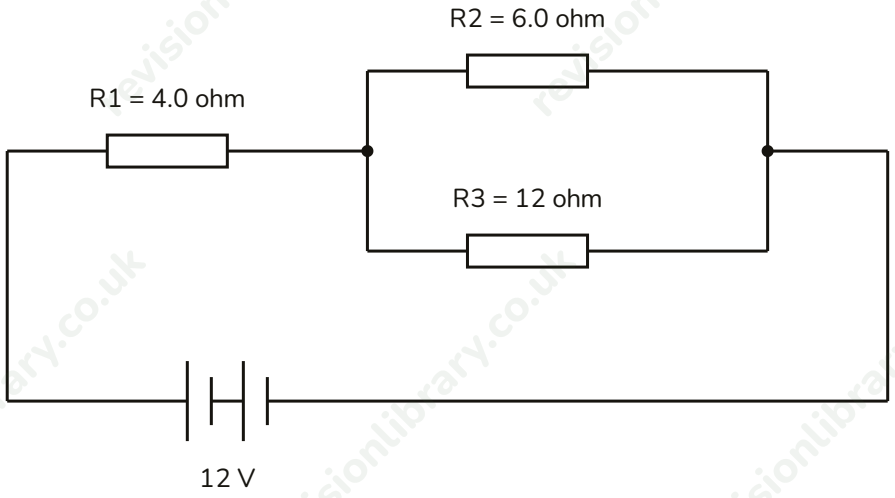
(b) Calculate the terminal potential difference of the battery. **(2)**

(c) Calculate the power dissipated inside the battery, in its internal resistance. **(2)**

(d) Explain what happens to the terminal potential difference of the battery if the external resistor is replaced with one of much smaller resistance, such as in a short circuit. **(3)**

(Total for Question 7 is 10 marks)

8 A battery of EMF 12 V with negligible internal resistance is connected in series with a resistor R1 = 4.0 ohm and a parallel combination of two resistors, R2 = 6.0 ohm and R3 = 12 ohm.



(a) Calculate the combined resistance of the parallel combination of R2 and R3. **(2)**

(b) Calculate the total resistance of the circuit. **(1)**

(c) Calculate the total current supplied by the battery. **(2)**

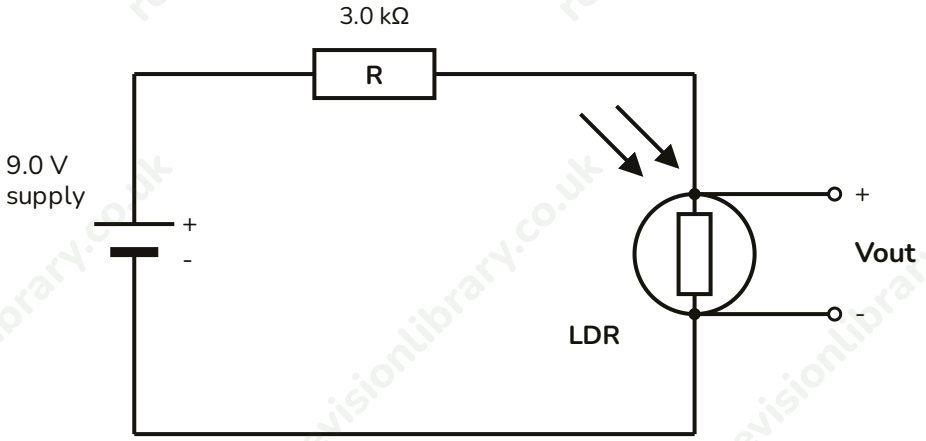
(d) Calculate the potential difference across the parallel combination. **(2)**

(e) Calculate the current in the R3 branch. **(2)**

(f) Use Kirchhoff's first law to show that the current in the R2 branch is 1.0 A, and confirm that the currents in R2 and R3 sum to the total current found in part (c). **(3)**

(Total for Question 8 is 12 marks)

9 A light-dependent resistor (LDR) is connected in series with a fixed resistor R = 3.0 kilohm across a 9.0 V supply, forming a potential divider. The output voltage, Vout, is taken across the LDR. Use Vout = Vin x R_{LDR} / (R + R_{LDR}).



(a) In bright light the resistance of the LDR is 500 ohm. Calculate Vout. **(3)**

(b) In darkness the resistance of the LDR increases to 12 kilohm. Calculate the new value of Vout. **(2)**

(c) Explain how this potential divider circuit, together with a transistor switch connected to Vout via a suitable switching interface, could be used to switch a garden lamp on automatically at night. **(3)**

(d) State and explain what would happen to Vout in darkness (R_{LDR} = 12 kilohm) if the positions of R and the LDR in the circuit were swapped, so that Vout is now taken across R instead. **(3)**

(Total for Question 9 is 11 marks)

10 A cylindrical graphite rod is used as a fixed resistor. It has length 55 mm and diameter 2.0 mm. The resistivity of the graphite is 6.5×10^{-5} ohm m.

(a) Calculate the cross-sectional area of the rod. **(1)**

(b) Calculate the resistance of the rod. **(3)**

(c) Using the equation I = nAvq (where n is the number density of charge carriers, A is cross-sectional area, v is drift velocity and q is charge), explain why the resistance of a typical metal wire increases as its temperature rises. **(3)**

(Total for Question 10 is 7 marks)

11 A cell of EMF E and internal resistance r is connected in series with a variable resistor. The current I and the terminal potential difference V are recorded for three settings.

I (A): 0.20, 0.50, 0.80

V (V): 1.44, 1.20, 0.96

(a) State the equation relating the terminal pd V, the EMF E, the current I and the internal resistance r. **(1)**

(b) Using the first and third data pairs, calculate the internal resistance of the cell. **(3)**

(c) Calculate the EMF of the cell. **(2)**

(d) Calculate the power dissipated inside the cell (due to its internal resistance) when the current is 0.80 A. **(2)**

(Total for Question 11 is 8 marks)

12 REQUIRED PRACTICAL. A student investigates the I-V characteristic of a silicon diode. The results are given below.

V (V): 0.00, 0.40, 0.50, 0.55, 0.60, 0.65

I (mA): 0.0, 0.0, 0.1, 0.8, 4.5, 18.0

(a) Describe the shape of the I-V graph for the diode and relate this to its behaviour as a circuit component. **(3)**

(b) Calculate the resistance of the diode at V = 0.65 V. **(2)**

(c) Explain why the diode does not obey Ohm's law, referring to the gradient of the I-V graph. **(2)**

(Total for Question 12 is 7 marks)

13 A thermistor and a fixed resistor of resistance 1.2 kilohm form a potential divider connected across a 6.0 V supply. The output voltage is taken across the fixed resistor. At room temperature the thermistor has a resistance of 3.6 kilohm.

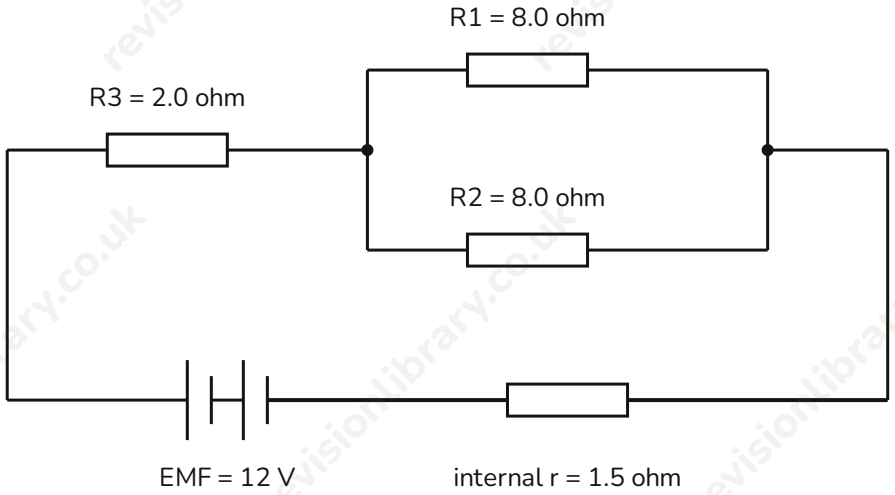
(a) Calculate the output voltage at room temperature. **(3)**

(b) As the temperature rises, the thermistor's resistance falls to 0.80 kilohm. Calculate the new output voltage. **(2)**

(c) Explain, referring to your answers above, how this circuit could be used as the basis of a temperature-operated warning circuit that switches on as temperature rises. **(2)**

(Total for Question 13 is 7 marks)

14 A battery of EMF 12 V and internal resistance 1.5 ohm is connected to an external circuit made from two resistors, R1 = 8.0 ohm and R2 = 8.0 ohm, connected in parallel with each other. This parallel combination is connected in series with a third resistor, R3 = 2.0 ohm.



(a) Calculate the combined resistance of R1 and R2 in parallel. **(2)**

(b) Calculate the total resistance of the complete circuit, including the internal resistance of the battery. **(2)**

(c) Calculate the current supplied by the battery. **(2)**

(d) Calculate the terminal potential difference of the battery. **(2)**

(e) Show that the efficiency of energy transfer from the battery to the external circuit is 80%. Efficiency = useful power delivered to the external circuit / total power supplied by the battery, which is equal to the external resistance divided by the total resistance. **(3)**

(f) Calculate the current in resistor R1. **(2)**

(Total for Question 14 is 13 marks)

15 Some materials become superconductors when cooled below a critical temperature, at which their electrical resistance drops suddenly to zero.

(a) State what is meant by the critical temperature of a superconductor. **(1)**

(b) State two practical applications that make use of superconductors. **(2)**

(c) A superconducting cable and a copper cable each carry a current of 150 A. The copper cable has a resistance of 0.40 ohm per kilometre. Calculate the power dissipated per kilometre of the copper cable. Use $P = I^2 R$. **(2)**

(d) Explain why using a superconducting cable rather than a copper cable to transmit electrical power over long distances is more efficient, and suggest one practical difficulty in using superconducting cables for this purpose. **(3)**

(Total for Question 15 is 8 marks)

16 A 2.0 kW immersion heater, rated at 230 V, is used to heat 2.5 kg of water in a well-insulated tank. Over 285 seconds (4.75 minutes) of operation, the water temperature rises from 15°C to 65°C. The specific heat capacity of water is 4200 J/(kg °C). Evaluate whether all of the electrical energy supplied by the heater is transferred usefully to raising the temperature of the water, using appropriate calculations to support your answer, and discuss possible physical reasons for any discrepancy you find. In your answer, connect the electrical energy transfer equations to the thermal energy equation for the water.

(Total for Question 16 is 6 marks)

17 A student determines the resistivity of a sample of wire. The length is measured as 0.850 ± 0.001 m, the diameter as 0.32 ± 0.01 mm (an average of several micrometer readings), and the resistance as 4.55 ± 0.05 ohm.

(a) Calculate the cross-sectional area of the wire. **(2)**

(b) Calculate the resistivity of the wire. **(3)**

(c) Calculate the percentage uncertainty in the resistivity, explaining why the percentage uncertainty in the diameter must be doubled before being combined with the others. **(4)**

(d) State the final result for the resistivity with its absolute uncertainty, to an appropriate number of significant figures. **(1)**

(Total for Question 17 is 10 marks)

Mark scheme · 3.5 Electricity

Question 1

(a) the rate of flow of (positive) charge, oe **B1**

(a) Answer: Current is the rate of flow of charge.

(b) convert time to seconds: 4.0 min = 240 s **B1**

(b) correct rearrangement I = Q/t and substitution **M1**

(b) I = 2.0 A, cao **A1**

(b) Answer: 2.0 A

(c) recognise that the number per second n = I / e, oe, ft from (b) **M1**

(c) correct substitution: n = 2.0 / (1.60 x 10^{-19}) **M1**

(c) 1.25 x 10^{19} electrons per second, awrt, cao **A1**

(c) Answer: 1.25 x 10^{19} electrons per second

Question 2

(a) the (total) energy transferred (from chemical or other forms) to electrical energy per unit charge that passes through the source oe **B1**

(a) Answer: The energy transferred to electrical energy per unit charge that passes through the source.

(b) a property of a material equal to RA/L, the resistance of a sample per unit cross-sectional area per unit length oe **B1**

(b) Answer: Resistivity is a property of a material, defined by resistivity = RA/L, where R is resistance, A is cross-sectional area and L is length.

(c) the sum of the EMFs around any closed loop in a circuit equals the sum of the potential differences (voltage drops) around that loop oe **B1**

(c) Answer: The sum of the EMFs around any closed loop equals the sum of the potential differences around that loop.

Question 3

(a) Q = I t = 0.85 x (12 x 60) **M1**

(a) Q = 612 C cao **A1**

(a) Answer: 612 C

(b) n = Q / e = 612 / (1.60 x 10^{-19}) **M1**

(b) n = 3.83 x 10^{21} cao **A1**

(b) Answer: 3.83 x 10^{21}

Question 4

Level 3 A full, coherent comparison of all three components, correctly describing each I-V characteristic (straight line through the origin for the resistor; curve of decreasing gradient for the lamp; negligible current until a threshold voltage then a rapid rise for the diode) and explaining the underlying physics for each (constant lattice vibration/collision rate at constant temperature; increased lattice vibration and collision rate with the drift electrons as the filament heats up; charge carriers only crossing the p-n junction in significant numbers once forward biased beyond the threshold voltage), using accurate specialist terminology throughout. **5-6**

Level 2 A correct description of the I-V behaviour of at least two of the three components, with a partial physical explanation (for example, linking temperature change to resistance change for the lamp, or describing the diode's threshold behaviour) for at least one. The answer has some logical structure and is mostly clear. **3-4**

Level 1 Basic, largely descriptive statements about the shape of one or two of the I-V graphs, with little or no physical explanation in terms of charge carriers or lattice vibration. The answer may lack clarity. **1-2**

Level 0 No relevant content, or the answer does not relate to the question. **0**

Indicative content:

- A metal wire resistor kept at constant temperature gives a straight-line I-V graph through the origin, showing that current is directly proportional to pd (Ohm's law); resistance is constant because temperature is constant, so the lattice ions vibrate with the same amplitude and the collision rate with drifting electrons does not change.
- A filament lamp gives a curve whose gradient decreases as I and V increase, so resistance increases with current; as current increases, the filament's temperature rises, the lattice ions vibrate with greater amplitude, and this increases the rate of collision between the ions and the drifting electrons, increasing resistance.
- A silicon diode carries almost no current in reverse bias, and negligible current in forward bias until a threshold (turn-on) voltage of around 0.6-0.7 V is reached; beyond this threshold, current increases very rapidly for a small further increase in pd.
- The diode's behaviour arises because charge carriers only cross the p-n junction in significant numbers once the forward bias is large enough to overcome the potential barrier at the junction; below threshold, effectively no charge carriers have enough energy to cross, so almost no current flows.
- Unlike the resistor and the lamp, the diode's I-V characteristic is not symmetrical about the origin, reflecting the fact that it allows current to flow easily in only one direction.

Question 5

(a) convert area to m^2: 2.0 mm^2 = 2.0 x 10^{-6} m^2 **M1**

(a) correct rearrangement v = I / (n A q) and substitution **M1**

(a) v = 1.1 x 10^{-4} m/s, awrt 2 sf, cao **A1**

(a) Answer: 1.1 x 10^{-4} m/s

(b) a thinner wire has a smaller cross-sectional area A, with n and q unchanged (same material, same charge carrier) **B1**

(b) since I = n A v q and I is the same, a smaller A means v must be larger to keep I constant, oe **B1**

(b) Answer: The drift velocity increases because A is smaller; since I = nAvq is fixed and n and q are unchanged, v must increase to compensate.

(c) correct area from diameter: A = $\pi(d/2)^2$ = 2.8 x 10^{-7} m^2 **M1**

(c) correct substitution into R = resistivity x L / A **M1**

(c) R = 0.30 ohm, awrt 2 sf, cao **A1**

(c) Answer: 0.30 ohm

Question 6

(a) measure the diameter of the wire using a micrometer (or digital calliper) at several points along the wire and at different orientations, then calculate a mean, oe **B1**

(a) clamp the wire straight along a metre ruler so it is taut but not stretched, to allow accurate length measurement **B1**

(a) use a crocodile clip to select each length L of wire in the circuit, with an ammeter (in series) and voltmeter (in parallel across the length in circuit) to find R at each L **B1**

(a) keep the current low, or switch off the circuit between readings, so the wire does not heat up (which would change its resistance/resistivity) **B1**

(a) repeat each measurement of R (at each L) and calculate a mean to reduce random error / improve reliability **B1**

(a) Answer: Measure the wire's diameter with a micrometer (mean of several readings); clamp it taut against a ruler; use a crocodile clip and ammeter/voltmeter to find R at each L; keep current low to avoid heating; repeat readings for reliability.

(b) gradient = (13.60 - 2.80)/(1.000 - 0.200), oe **M1**

(b) cso: gradient = 10.80/0.800 = 13.5 ohm/m **A1**

(b) Answer: 13.5 ohm per metre (shown)

(c) correct area from diameter: A = $\pi(0.16 \times 10^{-3})^2$ = 8.0 x 10^{-8} m^2 **M1**

(c) resistivity = gradient x A, ft from (b) **M1**

(c) 1.1 x 10^{-6} ohm metre, awrt 2 sf, cao (ft) **A1**

(c) Answer: 1.1 x 10^{-6} ohm metre

(d) using the gradient removes the effect of a constant systematic error, such as contact resistance at the crocodile clip, because this appears as a y-intercept rather than affecting the gradient, oe **B1**

(d) plotting several points and drawing a line of best fit averages out random errors in individual readings, oe **B1**

(d) Answer: The gradient method removes constant systematic errors (e.g. contact resistance, which shows up as an intercept), and averaging several points via a line of best fit reduces the effect of random error.

Question 7

(a) correct substitution: 6.0 = I(2.5 + 0.50) **M1**

(a) correct rearrangement I = 6.0/3.0 **M1**

(a) I = 2.0 A, cao **A1**

(a) Answer: 2.0 A

(b) correct method: V = IR (or V = EMF - Ir), ft from (a) **M1**

(b) 5.0 V, cao (ft) **A1**

(b) Answer: 5.0 V

(c) correct substitution into P = I^2 r, ft from (a) **M1**

(c) 2.0 W, cao (ft) **A1**

(c) Answer: 2.0 W

(d) a smaller external resistance R means a smaller total resistance (R + r), so the current I increases, oe **B1**

(d) the pd across the internal resistance (the 'lost volts', Ir) therefore increases **B1**

(d) since terminal pd = EMF - Ir, the terminal pd decreases, approaching zero as R approaches zero (short circuit), oe **B1**

(d) Answer: As R decreases, current increases, so the lost volts (Ir) increase; since terminal pd = EMF - Ir, the terminal pd falls, tending to zero in a short circuit.

Question 8

(a) correct substitution: 1/Rp = 1/6.0 + 1/12 **M1**

(a) Rp = 4.0 ohm, cao **A1**

(a) Answer: 4.0 ohm

(b) 8.0 ohm, cao (ft from (a): R1 + Rp) **B1**

(b) Answer: 8.0 ohm

(c) correct substitution I = V/Rtotal, ft from (b) **M1**

(c) 1.5 A, cao (ft) **A1**

(c) Answer: 1.5 A

(d) correct substitution V = I Rp, ft from (a) and (c) **M1**

(d) 6.0 V, cao (ft) **A1**

(d) Answer: 6.0 V

(e) correct substitution I3 = V/R3, ft from (d) **M1**

(e) 0.50 A, cao (ft) **A1**

(e) Answer: 0.50 A

(f) I2 = V/R2 = 6.0/6.0, ft from (d) **M1**

(f) cso: I2 = 1.0 A **A1**

(f) 1.0 + 0.50 = 1.5 A, equal to the total current in (c), confirming Kirchhoff's first law (current entering a junction equals current leaving it) **B1**

(f) Answer: I2 = 1.0 A; 1.0 + 0.50 = 1.5 A, matching the total current in part (c).

Question 9

(a) total resistance R + R_{LDR} = 3000 + 500 = 3500 ohm **M1**

(a) correct substitution into Vout = 9.0 x 500/3500 **M1**

(a) 1.3 V, awrt 2 sf, cao **A1**

(a) Answer: 1.3 V

(b) correct substitution into Vout = 9.0 x 12000/15000 **M1**

(b) 7.2 V, cao **A1**

(b) Answer: 7.2 V

(c) as it gets dark, R_{LDR} increases, so Vout (taken across the LDR) increases, as shown in parts (a) and (b), oe **B1**

(c) a high-input-resistance switching interface has an effective threshold between the bright and dark Vout values, so it drives the transistor on only when Vout rises above that threshold, oe **B1**

(c) the transistor then allows current to flow in the output circuit (e.g. via a relay), switching on the lamp **B1**

(c) Answer: As darkness falls, R_{LDR} and Vout increase. A high-input-resistance switching interface with an effective threshold between the bright and dark Vout values drives the transistor on in darkness, switching on the lamp circuit.

(d) Vout would now be small in darkness (rather than large), because it is taken across R rather than the LDR, oe **B1**

(d) reasoning: as R_{LDR} increases, the larger share of the supply pd is now across the LDR, leaving a smaller share across R (Vout), oe **B1**

(d) correct supporting calculation: Vout = 9.0 x 3000/15000 = 1.8 V (ecf from correct method) **B1**

(d) Answer: Vout would fall to about 1.8 V in darkness (rather than rising), because Vout is now across the fixed resistor R, and R's share of the total pd decreases as R_{LDR} increases.

Question 10

(a) A = π $(1.0 \times 10^{-3})^2$ = 3.14×10^{-6} m^2 cao **B1**

(a) Answer: 3.14×10^{-6} m^2

(b) quote R = ρ L / A **M1**

(b) substitute R = $(6.5 \times 10^{-5} \times 0.055) / (3.14 \times 10^{-6})$ **M1**

(b) R = 1.14 ohm cao **A1**

(b) Answer: 1.14 ohm

(c) as temperature rises, the amplitude of vibration of the (fixed) positive ions in the lattice increases **B1**

(c) this causes more frequent collisions between the conduction electrons and the vibrating ions **B1**

(c) so, for a given current, the drift velocity (and hence the ease of electron flow) is reduced, meaning the wire's resistance increases oe **B1**

(c) Answer: Increased temperature increases the vibration amplitude of the lattice ions, causing more frequent collisions with conduction electrons; this reduces the drift velocity attainable for a given current, so the wire's resistance increases.

Question 11

(a) V = E - I r cao **B1**

(a) Answer: V = E - Ir

(b) gradient of V against I = -r = (0.96 - 1.44) / (0.80 - 0.20) **M1**

(b) gradient = -0.80, so r = 0.80 **M1**

(b) r = 0.80 ohm cao **A1**

(b) Answer: 0.80 ohm

(c) substitute E = V + Ir using I = 0.20, V = 1.44, r = 0.80 **M1**

(c) E = 1.60 V cao **A1**

(c) Answer: 1.60 V

(d) use P = I^2 r = 0.80^2 x 0.80 **M1**

(d) P = 0.51 W cao **A1**

(d) Answer: 0.51 W

Question 12

(a) little or no current flows until the pd reaches a threshold (turn-on) voltage of approximately 0.5-0.6 V **B1**

(a) above the threshold, the current rises very steeply (rapidly increasing gradient) with only small further increases in pd **B1**

(a) this shows the diode is non-ohmic (does not obey Ohm's law) and conducts easily in the forward direction only once the threshold pd is exceeded oe **B1**

(a) Answer: Below about 0.5-0.6 V almost no current flows; above this threshold voltage the current rises very steeply for small further increases in voltage, showing non-ohmic behaviour typical of a forward-biased diode.

(b) R = V/I = 0.65 / (18.0×10^{-3}) **M1**

(b) R = 36 ohm cao **A1**

(b) Answer: 36 ohm

(c) Ohm's law requires current to be directly proportional to pd, i.e. a constant gradient (constant resistance) through the origin **B1**

(c) the diode's I-V graph has a gradient (1/R) that changes markedly with V (near zero below threshold, very large above it), so its resistance is not constant oe **B1**

(c) Answer: Ohm's law requires a constant ratio V/I (constant gradient); the diode's gradient changes sharply once past the threshold voltage, so its resistance is not constant and it does not obey Ohm's law.

Question 13

(a) quote V(out) = V(in) x R(fixed) / (R(fixed) + R(thermistor)) **M1**

(a) substitute V(out) = 6.0 x 1.2 / (1.2 + 3.6) **M1**

(a) V(out) = 1.5 V cao **A1**

(a) Answer: 1.5 V

(b) substitute V(out) = 6.0 x 1.2 / (1.2 + 0.80) **M1**

(b) V(out) = 3.6 V cao **A1**

(b) Answer: 3.6 V

(c) as temperature rises, thermistor resistance falls, so the output voltage across the fixed resistor increases (as shown by the rise from 1.5 V to 3.6 V) **B1**

(c) this rising output voltage can be fed to a switching device (e.g. a transistor or comparator) that turns on a warning output (lamp/alarm) once the output voltage exceeds a set threshold oe **B1**

(c) Answer: As temperature rises the thermistor's resistance falls, so the output voltage across the fixed resistor rises; feeding this rising voltage to a transistor or comparator circuit allows the warning device to switch on once the output exceeds a preset threshold voltage.

Question 14

(a) correct substitution: Rp = (8.0 x 8.0)/(8.0 + 8.0), oe **M1**

(a) 4.0 ohm, cao **A1**

(a) Answer: 4.0 ohm

(b) Rtotal = Rp + R3 + r, ft from (a) **M1**

(b) 7.5 ohm, cao (ft) **A1**

(b) Answer: 7.5 ohm

(c) correct substitution I = EMF/Rtotal, ft from (b) **M1**

(c) 1.6 A, cao (ft) **A1**

(c) Answer: 1.6 A

(d) correct method: terminal pd = EMF - I r, ft from (c) **M1**

(d) 9.6 V, cao (ft) **A1**

(d) Answer: 9.6 V

(e) identify external resistance = Rp + R3 = 4.0 + 2.0 = 6.0 ohm, ft from (a) **M1**

(e) efficiency = 6.0/7.5, ft from (b) **M1**

(e) cso: = 0.80 = 80% **A1**

(e) Answer: 80% (shown)

(f) pd across parallel section = I x Rp = 1.6 x 4.0, ft from (a) and (c) **M1**

(f) I1 = 6.4/8.0 = 0.80 A, cao (ft) **A1**

(f) Answer: 0.80 A

Question 15

(a) the temperature below which a material's electrical resistance becomes (suddenly) zero, oe **B1**

(a) Answer: The temperature below which a material's resistance suddenly becomes zero.

(b) any one valid application, e.g. superconducting magnets in MRI scanners (produce very strong magnetic fields without resistive energy loss) **B1**

(b) any second valid application, e.g. powerful electromagnets in particle accelerators, or superconducting cables for (loss-free) power transmission, oe **B1**

(b) Answer: Any two of: MRI scanner magnets; particle accelerator electromagnets; superconducting power transmission cables.

(c) correct substitution into $P = I^2 R = (150)^2 \times 0.40$ **M1**

(c) 9.0×10^3 W (9.0 kW), cao **A1**

(c) Answer: 9.0×10^3 W (9.0 kW)

(d) below its critical temperature the superconducting cable has zero resistance, so by $P = I^2 R$ no power is dissipated as heat in the cable, unlike the copper cable which continuously loses energy (e.g. 9.0 kW per km, as in part (c)), oe **B1**

(d) so a greater proportion of the generated electrical power reaches the consumer / less energy is wasted as heat, oe **B1**

(d) practical difficulty: the cable must be cooled continuously to below its critical temperature (e.g. using liquid nitrogen or liquid helium), which requires energy and specialist equipment, adding cost, oe **B1**

(d) Answer: The superconducting cable has zero resistance so no power is lost as heat (unlike the 9.0 kW/km lost in the copper cable), meaning more power reaches the consumer; however, the cable must be continuously cooled below its critical temperature, which is costly and requires specialist cryogenic equipment.

Question 16

Level 3 Correctly calculates the electrical energy supplied (E = Pt = 2000 x 285 = 570,000 J) and the thermal energy gained by the water (Q = mcT = 2.5 x 4200 x 50 = 525,000 J), correctly compares them to find an efficiency of about 92%, and gives at least two plausible, well-explained physical reasons for the shortfall (e.g. heat capacity of the tank/heating element itself absorbing some energy, heat lost to the surroundings despite insulation, energy used to heat surrounding air/fittings), clearly linking the electrical power equation to the thermal energy equation. **5-6**

Level 2 Correctly calculates both the electrical energy supplied and the thermal energy gained by the water (or makes only a minor numerical slip), identifies that not all energy is usefully transferred, and gives at least one reasonable physical reason for the discrepancy, with some link between the electrical and thermal equations. **3-4**

Level 1 Attempts one of the two energy calculations, or states qualitatively that some energy is lost without supporting calculation or a valid physical reason. **1-2**

Indicative content:

- Electrical energy supplied: E = Pt = 2000 W x 285 s = 570,000 J (0.57 MJ).
- Thermal energy gained by the water: Q = mcT = 2.5 kg x 4200 J/(kg °C) x (65-15) °C = 525,000 J (0.525 MJ).
- Efficiency = useful energy output / total energy input = 525,000/570,000 x 100 = about 92%, so not all electrical energy is transferred to the water; about 8% is unaccounted for by the simple water-only calculation.
- Possible reasons: the heating element and container also have significant heat capacity and must themselves be warmed, absorbing some of the supplied energy; despite insulation, some heat is still conducted/convected/radiated to the surroundings over the 285 s; energy may be used heating trapped air or the tank lid/fittings; the water may not be perfectly uniformly heated (temperature gradients) at the moment of measurement.
- Linking equations: the electrical power equation P = IV = I^2R gives the rate of electrical energy transfer, which should in principle all appear as thermal energy transferred to the water (Q = mcT) in a perfectly insulated, ideal system; the calculated efficiency shows the real system deviates from this ideal because of the additional heat capacities and loss pathways not included in the simple mcT calculation for the water alone.
- A valid evaluation must include a numerical efficiency figure derived from both energy calculations, not just a qualitative statement that losses occur.

Question 17

(a) $A = \pi d^2 / 4$ with $d = 0.32 \times 10^{-3}$ m **M1**

(a) $A = 8.04 \times 10^{-8}$ m^2 cao **A1**

(a) Answer: 8.04×10^{-8} m^2

(b) quote $\rho = RA/L$ **M1**

(b) substitute $\rho = (4.55 \times 8.04 \times 10^{-8}) / 0.850$ **M1**

(b) $\rho = 4.31 \times 10^{-7}$ ohm m cao **A1**

(b) Answer: 4.31×10^{-7} ohm m

(c) percentage uncertainty in L = 0.001/0.850 x 100 = 0.12%; in R = 0.05/4.55 x 100 = 1.10% **M1**

(c) percentage uncertainty in d = 0.01/0.32 x 100 = 3.13%; since A depends on d^2 ($A = \pi d^2/4$), the percentage uncertainty in A (and hence its contribution to ρ) is doubled to 6.25% **M1**

(c) sum all three contributions: 0.12% + 6.25% + 1.10% **M1**

(c) total percentage uncertainty = 7.5% cao **A1**

(c) Answer: 7.5%

(d) $\rho = (4.3 \pm 0.3) \times 10^{-7}$ ohm m cao (absolute uncertainty = 7.5% of $4.31 \times 10^{-7} = 0.32 \times 10^{-7}$) **B1**

(d) Answer: $(4.3 \pm 0.3) \times 10^{-7}$ ohm m