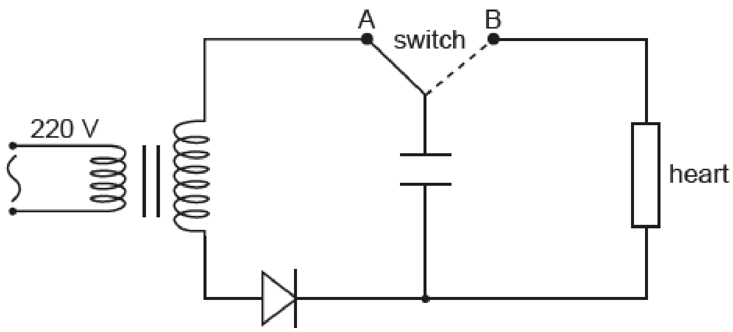
Yellow 3 [HL only] *[68 marks]*

A device sends an impulse of electrical energy to maintain a regular heartbeat in a person. The device is powered by an alternating current (ac) supply connected to a step-up transformer that charges a capacitor of capacitance 30 μF.



1a. Explain the role of the diode in the circuit when the switch is at position A. *[2 marks]*

Markscheme

to charge a capacitor current must be direct ✓

diode will only allow current to flow in one direction

OR

the diode provides half wave rectification ✓

The voltage across the primary coil of the transformer is 220 V. The number of turns on the secondary coil is 15 times greater than the number of turns on the primary coil.

1b. Show that the maximum energy stored by the capacitor is about 160 J. *[2 marks]*

Markscheme

$V_s = 15 \times 220 = «3300\ \text{V}»$ ✓

$E = \frac{1}{2}CV^2 = \frac{1}{2} \times 30 \times 10^{-6} \times 3300^2$

OR

163 «J» ✓

Allow use of 220 V as an RMS value to calculate V_s = 467 V and E = 327 J for full marks if appropriate work is provided.
Answer must be to 3 or more sf or working shown for ***MP2***

1c. Calculate the maximum charge Q_0 stored in the capacitor. *[1 mark]*

Markscheme

$Q_0 = 0.0989 \approx 0.1$ «C» ✓

Allow ***ECF*** *from (b)(i) (Q = 30 μF x V)*

1d. Identify, using the label + on the diagram, the polarity of the capacitor. *[1 mark]*

Markscheme

labels + on the lower side of the capacitor ✓

The switch is moved to position B.

1e. Describe what happens to the energy stored in the capacitor when the switch is moved to position B. *[1 mark]*

Markscheme

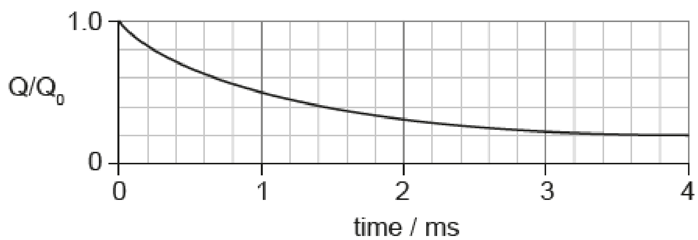
the energy stored in the capacitor is delivered to the resistor/heart ✓

1f. Show that the charge remaining in the capacitor after a time equal to one time constant τ of the circuit will be 0.37 Q_0. *[1 mark]*

Markscheme

use of $Q = Q_0 e^{-\frac{t}{\tau}}$ to show that $0.37 = \frac{1}{e}$ ✓

1g. The graph shows the variation with time of the charge in the capacitor as it is being discharged through the heart. *[2 marks]*



Determine the electrical resistance of the closed circuit with the switch in position B.

Markscheme

ALTERNATIVE 1

reads from the graph $\tau = 1.6$ ms ✓

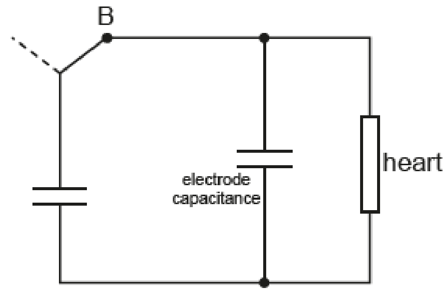
so $R = \frac{0.0016}{30 \times 10^{-6}} = 53$ «Ω» ✓

ALTERNATIVE 2

reads a correct value from the graph for $\frac{Q}{Q_0}$ and t ✓

so $R = \frac{t}{\ln\left(\frac{Q}{Q_0}\right)\left(3 \times 10^{-5}\right)}$ ✓

1h. In practice, two electrodes connect the heart to the circuit. These electrodes introduce an additional capacitance. *[2 marks]*



Explain the effect of the electrode capacitance on the discharge time.

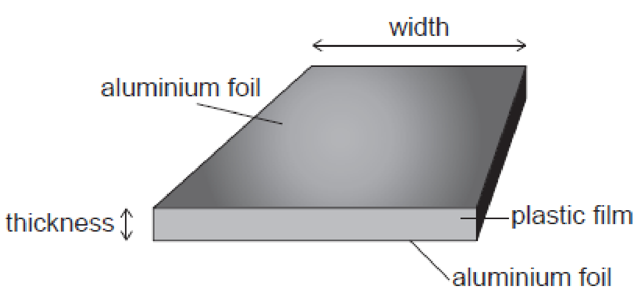
Markscheme

«the capacitors are in parallel hence» capacitances are added / more charge is stored
OR
C_{eq} is larger
OR
electrode capacitor charges and discharges ✓

«therefore» discharge takes longer/increases ✓

A student makes a parallel-plate capacitor of capacitance 68 nF from aluminium foil and plastic film by inserting one sheet of plastic film between two sheets of aluminium foil.

diagram not to scale



The aluminium foil and the plastic film are 450 mm wide.

The plastic film has a thickness of 55 μm and a permittivity of 2.5×10^{-11} C^2 N^{-1} m^{-2}.

2a. Calculate the total length of aluminium foil that the student will require. *[3 marks]*

Markscheme

length = $\frac{d \times C}{\text{width} \times \varepsilon}$ ✔

= 0.33 «m» ✔

so 0.66/0.67 «m» «as two lengths required» ✔

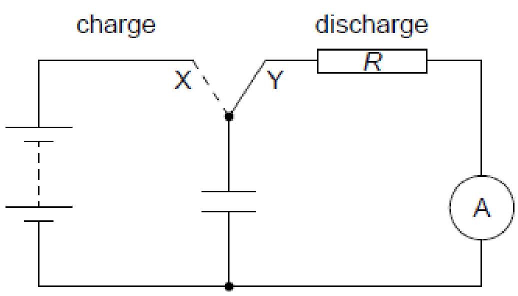
2b. The plastic film begins to conduct when the electric field strength in it exceeds 1.5 MN C^{-1}. Calculate the maximum charge that can be stored on the capacitor. *[2 marks]*

Markscheme

$1.5 \times 10^{6} \times 55 \times 10^{-6}$ = 83 «V» ✔

q «= CV»= 5.6×10^{-6} «C»✔

The student uses a switch to charge and discharge the capacitor using the circuit shown. The ammeter is ideal.



The emf of the battery is 12 V.

2c. The resistor *R* in the circuit has a resistance of 1.2 kΩ. Calculate the time taken for the charge on the capacitor to fall to 50 % of its fully charged value. *[3 marks]*

Markscheme

$0.5 = e^{-\frac{t}{RC}} = e^{-\frac{t}{1200 \times 6.8 \times 10^{-8}}}$

t = «−» 1200 × 6.8 × 10^{-8} × ln0.5 ✔

5.7 × 10^{-5} «s» ✔

OR

use of $t_{\frac{1}{2}} = RC \times \ln 2$ ✔

1200 × 6.8 × 10^{-8} × 0.693 ✔

5.7 × 10^{-5} «s» ✔

2d. The ammeter is replaced by a coil. Explain why there will be an induced emf in the coil while the capacitor is discharging. *[2 marks]*

Markscheme

mention of Faraday's law ✔

indicating that changing current in discharge circuit leads to change in flux in coil/change in magnetic field «and induced emf» ✔

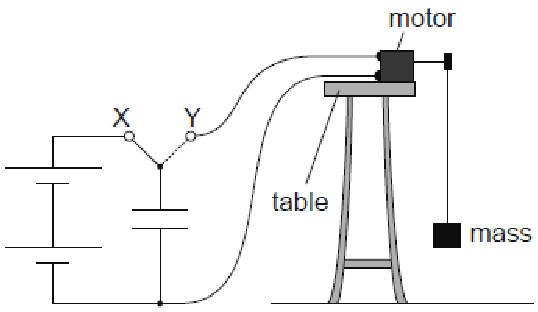
2e. Suggest **one** change to the discharge circuit, apart from changes to the coil, that will increase the maximum induced emf in the coil. *[2 marks]*

Markscheme

decrease/reduce ✔

resistance (R) ***OR*** capacitance (C) ✔

A small electric motor is used with a 12 mF capacitor and a battery in a school experiment.



When the switch is connected to X, the capacitor is charged using the battery. When the switch is connected to Y, the capacitor fully discharges through the electric motor that raises a small mass.

3a. The battery has an emf of 7.5 V. Determine the charge that flows through the motor when the mass is raised. *[1 mark]*

Markscheme

charge stored on capacitor = $12 \times 10^{-3} \times 7.5 = 0.09$ «C» ✔

3b. The motor can transfer one-third of the electrical energy stored in the capacitor into gravitational potential energy of the mass. Determine the maximum height through which a mass of 45 g can be raised. *[2 marks]*

Markscheme

energy stored in capacitor «$\frac{1}{2}CV^2$ or $\frac{1}{2}QV$ =» $\frac{1}{2} \times 12 \times 10^{-3} \times 7.5^2$ «= 0.338 J» ✔

height = «$\frac{1}{3} \times \frac{0.338}{9.81 \times 4.5 \times 10^{-2}} =$» 0.25/0.26 «m»

Allow use of $g = 10\,m\,s^{-2}$ which gives 0.25 «m»

3c. An additional identical capacitor is connected in series with the first capacitor and the charging and discharging processes are repeated. Comment on the effect this change has on the height and time taken to raise the 45 g mass. *[3 marks]*

Markscheme

C <u>halved</u> ✔

so energy stored is halved/reduced so rises «less than» half height ✔

discharge time/raise time less as RC halved/reduced ✔

Allow 6 mF

A capacitor consists of two parallel square plates separated by a vacuum. The plates are 2.5 cm × 2.5 cm squares. The capacitance of the capacitor is 4.3 pF.

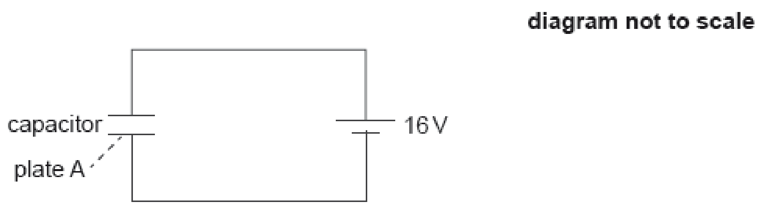
4a. Calculate the distance between the plates. *[1 mark]*

Markscheme

$d =$ «$\frac{8.85\times10^{-12}\times0.025^{2}}{4.3\times10^{-12}}$ =» 1.3×10^{-3} «m»

[1 mark]

4b. The capacitor is connected to a 16 V cell as shown. *[2 marks]*



Calculate the magnitude and the sign of the charge on plate A when the capacitor is fully charged.

Markscheme

6.9×10^{-11} «C»

negative charge/sign

[2 marks]

4c. The capacitor is fully charged and the space between the plates is then filled with a dielectric of permittivity $\varepsilon = 3.0\varepsilon_0$. *[2 marks]*

Explain whether the magnitude of the charge on plate A increases, decreases or stays constant.

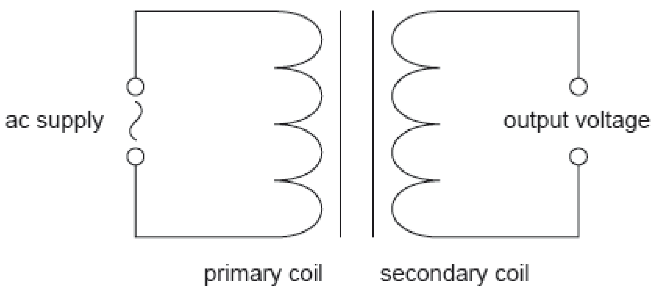
Markscheme

charge increases

because capacitance increases ***AND*** pd remains the same.

[2 marks]

4d. In a different circuit, a transformer is connected to an alternating current (ac) supply. *[3 marks]*



The transformer has 100 turns in the primary coil and 1200 turns in the secondary coil. The peak value of the voltage of the ac supply is 220 V. Determine the root mean square (rms) value of the output voltage.

Markscheme

ALTERNATIVE 1

$\varepsilon_s = \frac{1200}{100} \times 220$

= 2640 «V»

$V_{rms} = \frac{2640}{\sqrt{2}}$ = 1870 «V»

ALTERNATIVE 2

(Primary) $V_{rms} = \frac{220}{\sqrt{2}}$ = 156 «V»

(Secondary) $V_{rms} = \frac{156 \times 1200}{100}$

V_{rms} = 1870 «V»

Allow ECF from MP1 and MP2.

*Award **[2]** max for 12.96 V (reversing N_p and N_s).*

[3 marks]

4e. Describe the use of transformers in electrical power distribution. *[3 marks]*

Markscheme

step-up transformers increase voltage/step-down transformers decrease voltage

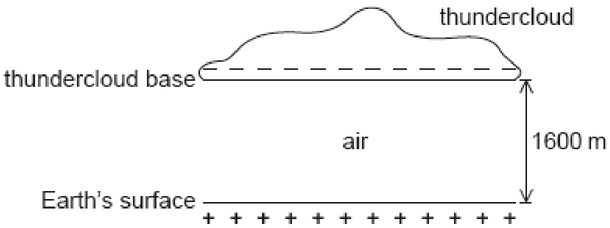
(step-up transformers increase voltage) from plants to transmission lines / (step-down transformers decrease voltage) from transmission lines to final utilizers

this decreases current (in transmission lines)

to minimize energy/power losses in transmission

[3 marks]

A negatively charged thundercloud above the Earth's surface may be modelled by a parallel plate capacitor.



The lower plate of the capacitor is the Earth's surface and the upper plate is the base of the thundercloud.

The following data are available.

Area of thundercloud base	$= 1.2 \times 10^8 \text{m}^2$
Charge on thundercloud base	$= -25\text{C}$
Distance of thundercloud base from Earth's surface	$= 1600\text{m}$
Permittivity of air	$= 8.8 \times 10^{-12} \text{Fm}^{-1}$

5a. Show that the capacitance of this arrangement is $C = 6.6 \times 10^{-7}$ F. *[1 mark]*

Markscheme

$C =$ «$\varepsilon \frac{A}{d} =$» $8.8 \times 10^{-12} \times \frac{1.2 \times 10^8}{1600}$

«$C = 6.60 \times 10^{-7}$ F»

[1 mark]

5b. Calculate in V, the potential difference between the thundercloud and the Earth's surface. *[2 marks]*

Markscheme

$V =$ «$\frac{Q}{C} =$» $\frac{25}{6.6 \times 10^{-7}}$

$V = 3.8 \times 10^7$ «V»

*Award **[2]** for a bald correct answer*

[2 marks]

5c. Calculate in J, the energy stored in the system. *[2 marks]*

Markscheme

ALTERNATIVE 1

E = «$\frac{1}{2}QV$ =» $\frac{1}{2}$ × 25 × 3.8 × 10^7

E = 4.7 × 10^8 «J»

ALTERNATIVE 2

E = «$\frac{1}{2}CV^2$ =» $\frac{1}{2}$ × 6.60 × 10^{-7} × (3.8 × 10^7)^2

E = 4.7 × 10^8 «J» / 4.8 × 10^8 «J» if rounded value of V used

*Award **[2]** for a bald correct answer*

Allow ECF from (b)(i)

[2 marks]

Lightning takes place when the capacitor discharges through the air between the thundercloud and the Earth's surface. The time constant of the system is 32 ms. A lightning strike lasts for 18 ms.

5d. Show that about –11 C of charge is delivered to the Earth's surface. *[3 marks]*

Markscheme

Q = «$Q_0 e^{-\frac{t}{\tau}}$ =» 25 × $e^{-\frac{18}{32}}$

Q = 14.2 «C»

charge delivered = Q = 25 – 14.2 = 10.8 «C»

«≈ –11 C»

Final answer must be given to at least 3 significant figures

[3 marks]

5e. Calculate, in A, the average current during the discharge. *[1 mark]*

Markscheme

I «$= \frac{\Delta Q}{\Delta t} = \frac{11}{18 \times 10^{-3}}$» ≈ 610 «A»

Accept an answer in the range 597 − 611 «A»

[1 mark]

5f. State **one** assumption that needs to be made so that the Earth-thundercloud system may be modelled by a parallel plate capacitor. *[1 mark]*

Markscheme

the base of the thundercloud must be parallel to the Earth surface

OR

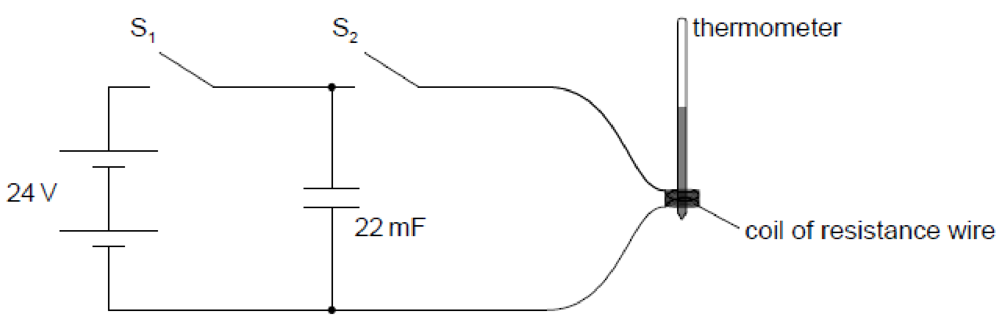
the base of the thundercloud must be flat

OR

the base of the cloud must be very long «compared with the distance from the surface»

[1 mark]

The electrical circuit shown is used to investigate the temperature change in a wire that is wrapped around a mercury-in-glass thermometer.



A power supply of emf (electromotive force) 24 V and of negligible internal resistance is connected to a capacitor and to a coil of resistance wire using an arrangement of two switches. Switch S_1 is closed and, a few seconds later, opened. Then switch S_2 is closed.

6a. The capacitance of the capacitor is 22 mF. Calculate the energy stored in the capacitor when it is fully charged. *[1 mark]*

Markscheme

«$\frac{1}{2}CV^2 = \frac{1}{2} \times 0.22 \times 24^2$» = «J»

6b. The resistance of the wire is 8.0 Ω. Determine the time taken for the capacitor to discharge through the resistance wire. Assume that the capacitor is completely discharged when the potential difference across it has fallen to 0.24 V. *[3 marks]*

Markscheme

$\frac{1}{100} = e^{-\frac{t}{8.0 \times 0.022}}$

$\ln 0.01 = -\frac{t}{8.0 \times 0.022}$

0.81 «s»

6c. The mass of the resistance wire is 0.61 g and its observed temperature rise is 28 K. Estimate the specific heat capacity of the wire. Include an appropriate unit for your answer. *[2 marks]*

Markscheme

$c = \frac{Q}{m \times \Delta T}$

OR

$\frac{6.3}{0.00061 \times 28}$

370 J kg^{-1} K^{-1}

Allow ECF from 3(a) for energy transferred.

Correct answer only to include correct unit that matches answer power of ten.

Allow use of g and kJ in unit but must match numerical answer, eg: 0.37 J kg^{-1} K^{-1} receives ***[1]***

6d. Suggest **one** other energy loss in the experiment and the effect it will have on the value for the specific heat capacity of the wire. *[2 marks]*

Markscheme

ALTERNATIVE 1

some thermal energy will be transferred to surroundings/along connecting wires/to thermometer

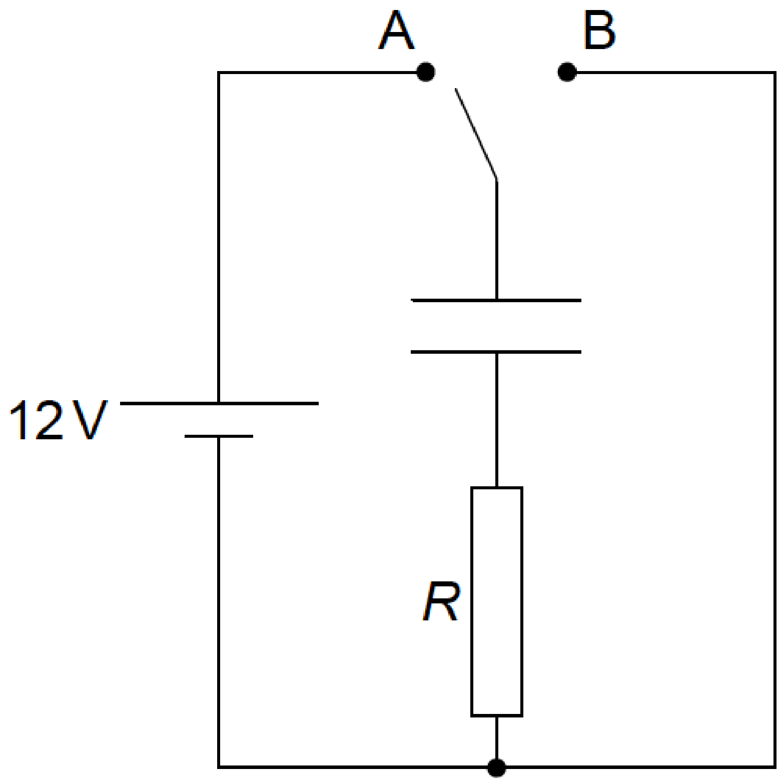
estimate «of specific heat capacity by student» will be larger «than accepted value»

ALTERNATIVE 2

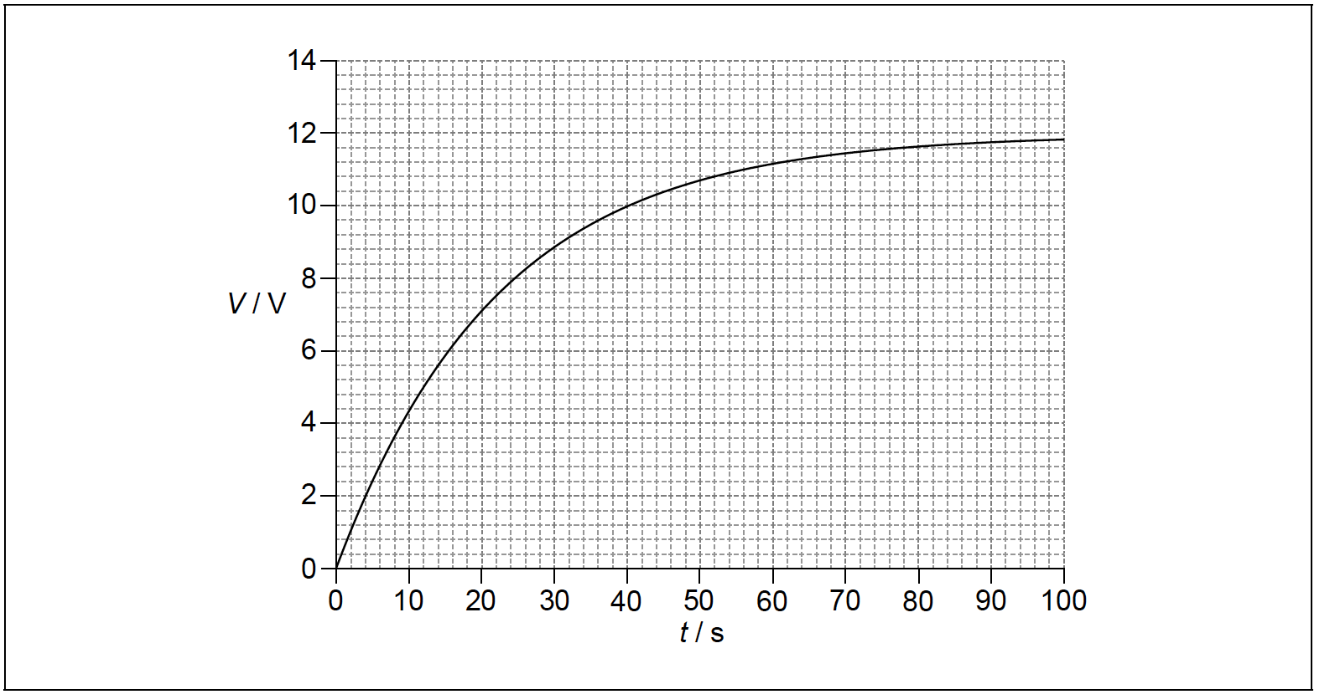
not all energy transferred as capacitor did not fully discharge

so estimate «of specific heat capacity by student» will be larger «than accepted value»

An uncharged capacitor in a vacuum is connected to a cell of emf 12V and negligible internal resistance. A resistor of resistance *R* is also connected.

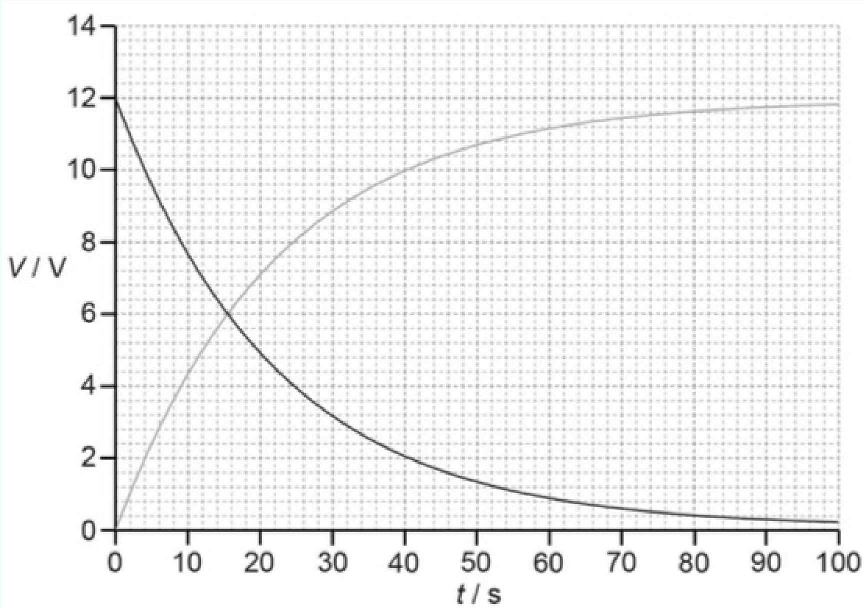


At *t*=0 the switch is placed at position A. The graph shows the variation with time *t* of the voltage *V* across the capacitor. The capacitor has capacitance 4.5μF in a vacuum.



7a. On the axes, draw a graph to show the variation with time of the voltage across the resistor. *[2 marks]*

Markscheme



general shape starting at 12 V
crosses at 6 V

Line must not touch time axis for MP2.

Allow tolerance of one square in 12 V (start) and 6 V (crossing).

7b. (i) The time constant of this circuit is 22s. State what is meant by the time constant. *[2 marks]*

(ii) Calculate the resistance *R*.

Markscheme

(i)
the time for the voltage/charge/current «in circuit» to drop to $\frac{1}{e}$ ***or*** 37% of its initial value

«as the capacitor discharges»

OR

time for voltage/charge/current «in circuit» to increase to $\left(1-\frac{1}{e}\right)$ ***or*** 63% of its final value

«as the capacitor charges»

(ii)
$R = \ll \frac{22}{4.5\times10^{-6}} = \gg 4.9\times10^{6}\Omega$

7c. A dielectric material is now inserted between the plates of the fully charged capacitor. State the effect, if any, on *[2 marks]*

(i) the potential difference across the capacitor.

(ii) the charge on one of the capacitor plates.

Markscheme

(i)
no change
OR
«remains at» 12 V

(ii)
increases
OR
doubles

Allow "doubles" in the light of (d).

7d. (i) The permittivity of the dielectric material in (c) is twice that of a vacuum. Calculate the energy stored in the capacitor when it is fully charged. *[3 marks]*

(ii) The switch in the circuit is now moved to position B and the fully charged capacitor discharges. Describe what happens to the energy in (d)(i).

Markscheme

(i)
recognises that new capacitance is 9.0 μF
$E = \ll \frac{1}{2}CV^2 = \frac{1}{2} \times 9.0 \times 10^{-6} \times 12^2 \gg = 0.65\text{mJ}$ or 6.5×10^{-4}J

Allow 11.8 V (value on graph at t=100s).

(ii)
energy goes into the resistor/surroundings
OR
«energy transferred» into thermal/internal energy form

Do not accept "dissipated" without location or form.
Do not allow "heat".

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