BRIDGING PROBLEM RESISTIVITY, TEMPERATURE, AND POWER

SOLUTION

A toaster using a Nichrome heating element operates on 120 V. When it is switched on at 20°C, the heating element carries an initial current of 1.35 A. A few seconds later the current reaches the steady value of 1.23 A. (a) What is the final temperature of the element? The average value of the temperature coefficient of resistivity for Nichrome over the relevant temperature range is $4.5 \times 10^{-4}\ (\text{C}°)^{-1}$. (b) What is the power dissipated in the heating element initially and when the current reaches 1.23 A?

SOLUTION GUIDE

IDENTIFY and SET UP

1. A heating element acts as a resistor that converts electrical energy into thermal energy. The resistivity ρ of Nichrome depends on temperature, and hence so does the resistance $R = \rho L/A$ of the heating element and the current $I = V/R$ that it carries.
2. We are given $V = 120$ V and the initial and final values of I. Select an equation that will allow you to find the initial and final values of resistance, and an equation that relates resistance to temperature [the target variable in part (a)].
3. The power P dissipated in the heating element depends on I and V. Select an equation that will allow you to calculate the initial and final values of P.

EXECUTE

4. Combine your equations from step 2 to give a relationship between the initial and final values of I and the initial and final temperatures (20°C and T_{final}).
5. Solve your expression from step 4 for T_{final}.
6. Use your equation from step 3 to find the initial and final powers.

EVALUATE

7. Is the final temperature greater than or less than 20°C? Does this make sense?
8. Is the final resistance greater than or less than the initial resistance? Again, does this make sense?
9. Is the final power greater than or less than the initial power? Does this agree with your observations in step 8?

Problems

For assigned homework and other learning materials, go to MasteringPhysics®. MP

•, ••, •••: Difficulty levels. **CP**: Cumulative problems incorporating material from earlier chapters. **CALC**: Problems requiring calculus. **DATA**: Problems involving real data, scientific evidence, experimental design, and/or statistical reasoning. **BIO**: Biosciences problems.

DISCUSSION QUESTIONS

Q25.1 The definition of resistivity ($\rho = E/J$) implies that an electric field exists inside a conductor. Yet we saw in Chapter 21 that there can be no electrostatic electric field inside a conductor. Is there a contradiction here? Explain.

Q25.2 Why is copper preferred over aluminum for household wiring even though copper is more expensive?

Q25.3 A cylindrical rod has resistivity ρ. If we triple its length and diameter, what is its resistivity, in terms of ρ?

Q25.4 You are working in a physics laboratory where you have made a simple circuit with a battery and bulb. In which part of your circuit is the current flow maximum, through the bulb filament or through the battery? If you reverse the polarity, would there be any difference in the intensity of the bulb?

Q25.5 When is a 1.5-V AAA battery *not* actually a 1.5-V battery? That is, when do its terminals provide a potential difference of less than 1.5 V?

Q25.6 Can the potential difference between the terminals of a battery ever be opposite in direction to the emf ? If it can, give an example. If it cannot, explain why not.

Q25.7 A rule of thumb used to determine the internal resistance of a source is that it is the open-circuit voltage divided by the short-circuit current. Is this correct? Why or why not?

Q25.8 Batteries are always labeled with their emf; for instance, an AA flashlight battery is labeled "1.5 volts." Would it also be appropriate to put a label on batteries stating how much current they provide? Why or why not?

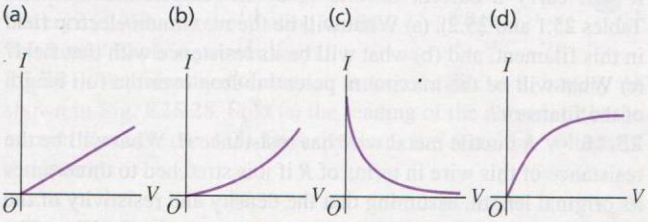
Q25.9 We have seen that a coulomb is an enormous amount of charge; it is virtually impossible to place a charge of 1 C on an object. Yet, a current of 10 A, 10 C/s, is quite reasonable. Explain this apparent discrepancy.

Q25.10 Electrons in an electric circuit pass through a resistor. The wire on either side of the resistor has the same diameter. (a) How does the drift speed of the electrons before entering the resistor compare to the speed after leaving the resistor? Explain your reasoning. (b) How does the potential energy for an electron before entering the resistor compare to the potential energy after leaving the resistor? Explain your reasoning.

Q25.11 Temperature coefficients of resistivity are given in Table 25.2. (a) If a copper heating element is connected to a source of constant voltage, does the electrical power consumed by the heating element increase or decrease as its temperature increases? Explain. (b) A resistor in the form of a carbon cylinder is connected to the voltage source. As the temperature of the cylinder increases, does the electrical power it consumes increase or decrease? Explain.

Q25.12 Which of the graphs in **Fig. Q25.12** best illustrates the current I in a real resistor as a function of the potential difference V across it? Explain.

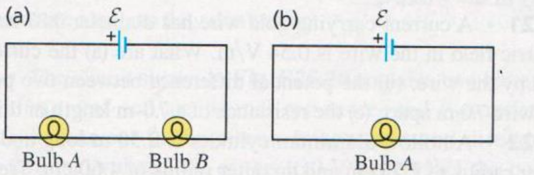
Figure **Q25.12**



Q25.13 Why is it a good idea to wear thick-soled shoe and to have dry hands when working with heavy electrical devices?

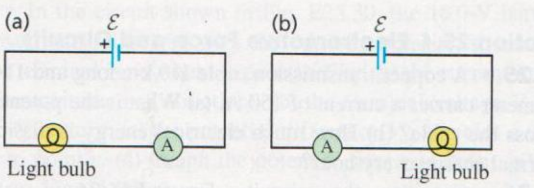
Q25.14 A light bulb glows because it has resistance. The brightness of a light bulb increases with the electrical power dissipated in the bulb. (a) In the circuit shown in **Fig. Q25.14a**, the two bulbs A and B are identical. Compared to bulb A, does bulb B glow more brightly, just as brightly, or less brightly? Explain your reasoning. (b) Bulb B is removed from the circuit and the circuit is completed as shown in Fig. Q25.14b. Compared to the brightness of bulb A in Fig. Q25.14a, does bulb A now glow more brightly, just as brightly, or less brightly? Explain your reasoning.

Figure **Q25.14**



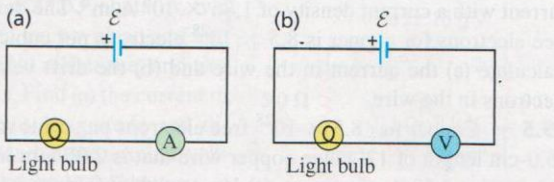
Q25.15 (See Discussion Question Q25.14.) An ideal ammeter A is placed in a circuit with a battery and a light bulb as shown in **Fig. Q25.15a**, and the ammeter reading is noted. The circuit is then reconnected as in Fig. Q25.15b, so that the positions of the ammeter and light bulb are reversed. (a) How does the ammeter reading in the situation shown in Fig. Q25.15a compare to the reading in the situation shown in Fig. Q25.15b? Explain your reasoning. (b) In which situation does the light bulb glow more brightly? Explain your reasoning.

Figure **Q25.15**



Q25.16 (See Discussion Question Q25.14.) Will a light bulb glow more brightly when it is connected to a battery as shown in **Fig. Q25.16a**, in which an ideal ammeter A is placed in the circuit, or when it is connected as shown in Fig. 25.16b, in which an ideal voltmeter V is placed in the circuit? Explain your reasoning.

Figure **Q25.16**



Q25.17 Why does a light bulb usually burn out the moment you turn it on and not after it is on for a while? Explain your answer.

Q25.18 Eight flashlight batteries in series have an emf of about 12 V, similar to that of a car battery. Could they be used to start a car with a dead battery? Why or why not?

Q25.19 When airplanes are in the air, does the electrical equipment onboard not have any "ground" connections? If not, what acts as a suitable ground for airplanes, or for that matter, any other thing which is not in direct contact with the ground? Explain.

Q25.20 Long-distance, electric-power, transmission lines always operate at very high voltage, sometimes as much as 750 kV. What are the advantages of such high voltages? What are the disadvantages?

Q25.21 Ordinary household electric lines in North America usually operate at 120 V. Why is this a desirable voltage, rather than a value considerably larger or smaller? On the other hand, automobiles usually have 12-V electrical systems. Why is this a desirable voltage?

Q25.22 Why does a bird not get electrocuted when it sits on a non-insulated high-tension power line? How and why could a bird actually get electrocuted?

Q25.23 High-voltage power supplies are sometimes designed intentionally to have rather large internal resistance as a safety precaution. Why is such a power supply with a large internal resistance safer than a supply with the same voltage but lower internal resistance?

Q25.24 What are the main considerations in the mind of an electrician when installing fuses in your home? Would it be dangerous if he used too large a value for the fuses?

EXERCISES

Section 25.1 Current

25.1 • **Lightning Strikes.** During lightning strikes from a cloud to the ground, currents as high as 25,000 A can occur and last for about 40 μs. How much charge is transferred from the cloud to the earth during such a strike?

25.2 • A silver wire 2.6 mm in diameter transfers a charge of 420 C in 80 min. Silver contains 5.8×10^{28} free electrons per cubic meter. (a) What is the current in the wire? (b) What is the magnitude of the drift velocity of the electrons in the wire?

25.3 • A 5.50-A current runs through a 12-gauge copper wire (diameter 2.05 mm) and through a light bulb. Copper has 8.5×10^{28} free electrons per cubic meter. (a) How many electrons pass through the light bulb each second? (b) What is the current density in the wire? (c) At what speed does a typical electron pass by any given point in the wire? (d) If you were to use wire of twice the diameter, which of the above answers would change? Would they increase or decrease?

25.4 • An 18-gauge copper wire (diameter 1.02 mm) carries a current with a current density of $1.86 \times 10^6\ \text{A/m}^2$. The density of free electrons for copper is 8.5×10^{28} electrons per cubic meter. Calculate (a) the current in the wire and (b) the drift velocity of electrons in the wire.

25.5 •• Copper has 8.5×10^{28} free electrons per cubic meter. A 66.0-cm length of 12-gauge copper wire that is 2.05 mm in diameter carries 4.50 A of current. (a) How much time does it take for an electron to travel the length of the wire? (b) Repeat part (a) for 6-gauge copper wire (diameter 4.12 mm) of the same length that carries the same current. (c) Generally speaking, how does changing the diameter of a wire that carries a given amount of current affect the drift velocity of the electrons in the wire?

25.6 •• You want to produce three 1.00-mm-diameter cylindrical wires, each with a resistance of 1.00 Ω at room temperature. One wire is gold, one is copper, and one is aluminum. Refer to Table 25.1 for the resistivity values. (a) What will be the length of each wire? (b) Gold has a density of $1.93 \times 10^4\ \text{kg/m}^3$. What will be the mass of the gold wire? If you consider the current price of gold, is this wire very expensive?

25.7 • CALC The current in a wire varies with time according to the relationship $I = 55\ \text{A} - (0.65\ \text{A/s}^2)t^2$. (a) How many coulombs of charge pass a cross section of the wire in the time interval between $t = 0$ and $t = 8.2$ s? (b) What constant current would transport the same charge in the same time interval?

25.8 • Current passes through a solution of sodium chloride. In 1.00 s, $2.68 \times 10^{16}\ Na^+$ ions arrive at the negative electrode and $3.92 \times 10^{16}\ Cl^-$ ions arrive at the positive electrode. (a) What is the current passing between the electrodes? (b) What is the direction of the current?

25.9 • BIO **Transmission of Nerve Impulses.** Nerve cells transmit electric signals through their long tubular axons. These signals propagate due to a sudden rush of Na^+ ions, each with charge $+e$, into the axon. Measurements have revealed that typically about $5.6 \times 10^{11}\ Na^+$ ions enter each meter of the axon during a time of 10 ms. What is the current during this inflow of charge in a meter of axon?

Section 25.2 Resistivity and Section 25.3 Resistance

25.10 • (a) At room temperature, what is the strength of the electric field in a 12-gauge copper wire (diameter 2.05 mm) that is needed to cause a 2.25-A current to flow? (b) What field would be needed if the wire were made of silver instead?

25.11 •• A 1.50-m cylindrical rod of diameter 0.500 cm is connected to a power supply that maintains a constant potential difference of 17.0 V across its ends, while an ammeter measures the current through it. You observe that at room temperature (20.0°C) the ammeter reads 18.8 A, while at 92.0°C it reads 17.1 A. You can ignore any thermal expansion of the rod. Find (a) the resistivity at 20.0°C and (b) the temperature coefficient of resistivity at 20°C for the material of the rod.

25.12 • A copper wire has a square cross section 2.1 mm on a side. The wire is 4.3 m long and carries a current of 3.6 A. The density of free electrons is $8.5 \times 10^{28}/\text{m}^3$. Find the magnitudes of (a) the current density in the wire and (b) the electric field in the wire. (c) How much time is required for an electron to travel the length of the wire?

25.13 • A 14-gauge copper wire of diameter 1.628 mm carries a current of 12.5 mA. (a) What is the potential difference across a 2.00-m length of the wire? (b) What would the potential difference in part (a) be if the wire were silver instead of copper, but all else were the same?

25.14 •• A wire 6.20 m long with diameter of 2.25 mm has a resistance of 0.0350 Ω. What is the resistivity of the wire?

25.15 •• A cylindrical tungsten filament 13.0 cm long with a diameter of 1.00 mm is to be used in a machine for which the temperature will range from room temperature (20°C) up to 120°C. It will carry a current of 11.0 A at all temperatures (consult Tables 25.1 and 25.2). (a) What will be the maximum electric field in this filament, and (b) what will be its resistance with that field? (c) What will be the maximum potential drop over the full length of the filament?

25.16 •• A ductile metal wire has resistance R. What will be the resistance of this wire in terms of R if it is stretched to three times its original length, assuming that the density and resistivity of the material do not change when the wire is stretched? (*Hint:* The amount of metal does not change, so stretching out the wire will affect its cross-sectional area.)

25.17 • In household wiring, copper wire 2.05 mm in diameter is often used. Find the resistance of a 23.8-m length of this wire.

25.18 •• What diameter must a copper wire have if its resistance is to be the same as that of an equal length of aluminum wire with diameter 3.84 mm?

25.19 • A strand of wire has resistance 5.70 μΩ. Find the net resistance of 113 such strands if they are (a) placed side by side to form a cable of the same length as a single strand, and (b) connected end to end to form a wire 113 times as long as a single strand.

25.20 • You apply a potential difference of 4.50 V between the ends of a wire that is 2.50 m in length and 0.654 mm in radius. The resulting current through the wire is 17.6 A. What is the resistivity of the wire?

25.21 • A current-carrying gold wire has diameter 0.87 mm. The electric field in the wire is 0.54 V/m. What are (a) the current carried by the wire; (b) the potential difference between two points in the wire 7.0 m apart; (c) the resistance of a 7.0-m length of this wire?

25.22 • A hollow aluminum cylinder is 2.50 m long and has an inner radius of 2.75 cm and an outer radius of 4.60 cm. Treat each surface (inner, outer, and the two end faces) as an equipotential surface. At room temperature, what will an ohmmeter read if it is connected between (a) the opposite faces and (b) the inner and outer surfaces?

25.23 • (a) What is the resistance of a Nichrome wire at 0.0°C if its resistance is 180.0 Ω at 11.5°C? (b) What is the resistance of a carbon rod at 25.8°C if its resistance is 0.0140 Ω at 0.0°C?

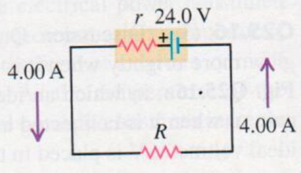
25.24 • A carbon resistor is to be used as a thermometer. On a winter day when the temperature is 4.0°C, the resistance of the carbon resistor is 217.8 Ω. What is the temperature on a spring day when the resistance is 215.5 Ω? (Take the reference temperature T_0 to be 4.0°C.)

Section 25.4 Electromotive Force and Circuits

25.25 • A copper transmission cable 110 km long and 11.0 cm in diameter carries a current of 150 A. (a) What is the potential drop across the cable? (b) How much electrical energy is dissipated as thermal energy every hour?

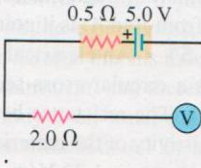
25.26 • Consider the circuit shown in **Fig. E25.26**. The terminal voltage of the 24.0-V battery is 21.2 V. What are (a) the internal resistance r of the battery and (b) the resistance R of the circuit resistor?

Figure E25.26



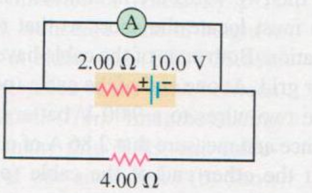
25.27 • An ideal voltmeter V is connected to a 2.0-Ω resistor and a battery with emf 5.0 V and internal resistance 0.5 Ω as shown in **Fig. E25.27**. (a) What is the current in the 2.0-Ω resistor? (b) What is the terminal voltage of the battery? (c) What is the reading on the voltmeter? Explain your answers.

Figure **E25.27**



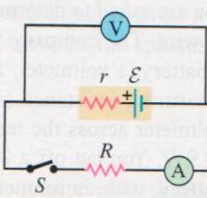
25.28 • An idealized ammeter is connected to a battery as shown in **Fig. E25.28**. Find (a) the reading of the ammeter, (b) the current through the 4.00-Ω resistor, (c) the terminal voltage of the battery.

Figure **E25.28**



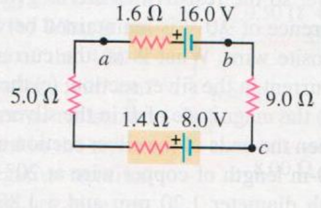
25.29 • When switch S in **Fig. E25.29** is open, the voltmeter V reads 3.14 V. When the switch is closed, the voltmeter reading drops to 2.93 V, and the ammeter A reads 1.67 A. Find the emf, the internal resistance of the battery, and the circuit resistance R. Assume that the two meters are ideal, so they don't affect the circuit.

Figure **E25.29**



25.30 • The circuit shown in **Fig. E25.30** contains two batteries, each with an emf and an internal resistance, and two resistors. Find (a) the current in the circuit (magnitude *and* direction); (b) the terminal voltage V_{ab} of the 16.0-V battery; (c) the potential difference V_{ac} of point a with respect to point c. (d) Using Fig. 25.20 as a model, graph the potential rises and drops in this circuit.

Figure **E25.30**

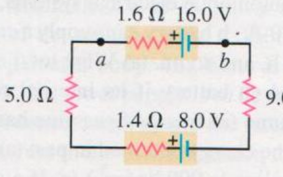


25.31 • In the circuit shown in Fig. E25.30, the 16.0-V battery is removed and reinserted with the opposite polarity, so that its negative terminal is now next to point a. Find (a) the current in the circuit (magnitude *and* direction); (b) the terminal voltage V_{ba} of the 16.0-V battery; (c) the potential difference V_{ac} of point a with respect to point c. (d) Graph the potential rises and drops in this circuit (see Fig. 25.20).

25.32 • In the circuit of Fig. E25.30, the 5.0-Ω resistor is removed and replaced by a resistor of unknown resistance R. When this is done, an ideal voltmeter connected across the points b and c reads 1.9 V. Find (a) the current in the circuit and (b) the resistance R. (c) Graph the potential rises and drops in this circuit (see Fig. 25.20).

25.33 •• The circuit shown in **Fig. E25.33** contains two batteries, each with an emf and an internal resistance, and two resistors. Find (a) the current in the circuit (magnitude and direction) and (b) the terminal voltage V_{ab} of the 16.0-V battery.

Figure **E25.33**



Section 25.5 Energy and Power in Electric Circuits

25.34 •• When a resistor with resistance R is connected to a 1.50-V flashlight battery, the resistor consumes 0.0625 W of electrical power. (Throughout, assume that each battery has negligible internal resistance.) (a) What power does the resistor consume if it is connected to a 12.6-V car battery? Assume that R remains constant when the power consumption changes. (b) The resistor is connected to a battery and consumes 5.00 W. What is the voltage of this battery?

25.35 • **Light Bulbs.** The power rating of a light bulb (such as a 100-W bulb) is the power it dissipates when connected across a 120-V potential difference. What is the resistance of (a) a 150-W bulb and (b) a 60-W bulb? (c) How much current does each bulb draw in normal use?

25.36 • If a "90-W" bulb (see Problem 25.35) is connected across a 220-V potential difference (as is used in Europe), how much power does it dissipate? Ignore the temperature dependence of the bulb's resistance.

25.37 • **European Light Bulb.** In Europe the standard voltage in homes is 220 V instead of the 120 V used in the United States. Therefore a "100-W" European bulb would be intended for use with a 220-V potential difference (see Problem 25.36). (a) If you bring a "100-W" European bulb home to the United States, what should be its U.S. power rating? (b) How much current will the 100-W European bulb draw in normal use in the United States?

25.38 • A battery-powered global positioning system (GPS) receiver operating on 9.5 V draws a current of 0.14 A. How much electrical energy does it consume during 1.7 h?

25.39 • Consider the circuit of Fig. E25.30. (a) What is the total rate at which electrical energy is dissipated in the 5.0-Ω and 9.0-Ω resistors? (b) What is the power output of the 16.0-V battery? (c) At what rate is electrical energy being converted to other forms in the 8.0-V battery? (d) Show that the power output of the 16.0-V battery equals the overall rate of consumption of electrical energy in the rest of the circuit.

25.40 • BIO **Electric Eels.** Electric eels generate electric pulses along their skin that can be used to stun an enemy when they come into contact with it. Tests have shown that these pulses can be up to 502 V and produce currents of 79 mA (or even larger). A typical pulse lasts for 10 ms. What power and how much energy are delivered to the unfortunate enemy with a single pulse, assuming a steady current?

25.41 • BIO **Treatment of Heart Failure.** A heart defibrillator is used to enable the heart to start beating if it has stopped. This is done by passing a large current of 12 A through the body at 25 V for a very short time, usually about 3.0 ms. (a) What power does the defibrillator deliver to the body, and (b) how much energy is transferred?

25.42 •• The battery for a certain cell phone is rated at 3.70 V. According to the manufacturer it can produce 3.15×10^4 J of electrical energy, enough for 5.25 h of operation, before needing to be recharged. Find the average current that this cell phone draws when turned on.

25.43 •• The capacity of a storage battery, such as those used in automobile electrical systems, is rated in ampere-hours $(A \cdot h)$. A $50\text{-}A \cdot h$ battery can supply a current of 50 A for 1.0 h, or 25 A for 2.0 h, and so on. (a) What total energy can be supplied by a 12-V, $50\text{-}A \cdot h$ battery if its internal resistance is negligible? (b) What volume (in liters) of gasoline has a total heat of combustion equal to the energy obtained in part (a)? (See Section 17.6; the density of gasoline is 900 kg/m^3.) (c) If a generator with an average electrical power output of 0.55 kW is connected to the battery, how much time will be required for it to charge the battery fully?

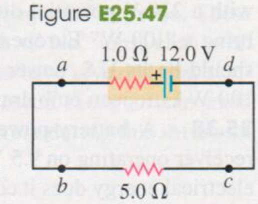
25.44 • An idealized voltmeter is connected across the terminals of a 15.0-V battery, and a $75.0\text{-}\Omega$ appliance is also connected across its terminals. If the voltmeter reads 11.9 V, (a) how much power is being dissipated by the appliance, and (b) what is the internal resistance of the battery?

25.45 •• A $28.0\text{-}\Omega$ bulb is connected across the terminals of a 12.0-V battery having $2.50 \ \Omega$ of internal resistance. What percentage of the power of the battery is dissipated across the internal resistance and hence is not available to the bulb?

25.46 •• A typical small flashlight contains two batteries, each having an emf of 1.5 V, connected in series with a bulb having resistance $15 \ \Omega$. (a) If the internal resistance of the batteries is negligible, what power is delivered to the bulb? (b) If the batteries last for 6.0 h, what is the total energy delivered to the bulb? (c) The resistance of real batteries increases as they run down. If the initial internal resistance is negligible, what is the combined internal resistance of both batteries when the power to the bulb has decreased to half its initial value? (Assume that the resistance of the bulb is constant. Actually, it will change somewhat when the current through the filament changes, because this changes the temperature of the filament and hence the resistivity of the filament wire.)

25.47 • In the circuit in **Fig. E25.47**, find (a) the rate of conversion of internal (chemical) energy to electrical energy within the battery; (b) the rate of dissipation of electrical energy in the battery; (c) the rate of dissipation of electrical energy in the external resistor.

Figure **E25.47**



25.48 • A "570-W" electric heater is designed to operate from 120-V lines. (a) What is its operating resistance? (b) What current does it draw? (c) If the line voltage drops to 110 V, what power does the heater take? (Assume that the resistance is constant. Actually, it will change because of the change in temperature.) (d) The heater coils are metallic, so that the resistance of the heater decreases with decreasing temperature. If the change of resistance with temperature is taken into account, will the electrical power consumed by the heater be larger or smaller than what you calculated in part (c)? Explain.

Section 25.6 Theory of Metallic Conduction

25.49 •• Pure silicon at room temperature contains approximately 1.0×10^{16} free electrons per cubic meter. (a) Referring to Table 25.1, calculate the mean free time τ for silicon at room temperature. (b) Your answer in part (a) is much greater than the mean free time for copper given in Example 25.11. Why, then, does pure silicon have such a high resistivity compared to copper?

PROBLEMS

25.50 •• In an ionic solution, a current consists of Ca^{2+} ions (of charge $+2e$) and Cl^- ions (of charge $-e$) traveling in opposite directions. If 5.11×10^{18} Cl^- ions go from A to B every 0.50 min, while 3.24×10^{18} Ca^{2+} ions move from B to A, what is the current (in mA) through this solution, and in which direction (from A to B or from B to A) is it going?

25.51 • An electrical conductor designed to carry large currents has a circular cross section 2.00 mm in diameter and is 14.6 m long. The resistance between its ends is $0.110 \ \Omega$. (a) What is the resistivity of the material? (b) If the electric-field magnitude in the conductor is 1.22 V/m, what is the total current? (c) If the material has 8.5×10^{28} free electrons per cubic meter, find the average drift speed under the conditions of part (b).

25.52 •• An overhead transmission cable for electrical power is 2000 m long and consists of two parallel copper wires, each encased in insulating material. A short circuit has developed somewhere along the length of the cable where the insulation has worn thin and the two wires are in contact. As a power-company employee, you must locate the short so that repair crews can be sent to that location. Both ends of the cable have been disconnected from the power grid. At one end of the cable (point A), you connect the ends of the two wires to a 9.00-V battery that has negligible internal resistance and measure that 2.86 A of current flows through the battery. At the other end of the cable (point B), you attach those two wires to the battery and measure that 1.65 A of current flows through the battery. How far is the short from point A?

25.53 •• On your first day at work as an electrical technician, you are asked to determine the resistance per meter of a long piece of wire. The company you work for is poorly equipped. You find a battery, a voltmeter, and an ammeter, but no meter for directly measuring resistance (an ohmmeter). You put the leads from the voltmeter across the terminals of the battery, and the meter reads 12.9 V. You cut off a 20.0-m length of wire and connect it to the battery, with an ammeter in series with it to measure the current in the wire. The ammeter reads 6.90 A. You then cut off a 40.0-m length of wire and connect it to the battery, again with the ammeter in series to measure the current. The ammeter reads 4.20 A. Even though the equipment you have available to you is limited, your boss assures you of its high quality: The ammeter has very small resistance, and the voltmeter has very large resistance. What is the resistance of 1 meter of wire?

25.54 • A 2.0-m length of wire is made by welding the end of a 120-cm-long silver wire to the end of an 80-cm-long copper wire. Each piece of wire is 0.60 mm in diameter. The wire is at room temperature, so the resistivities are as given in Table 25.1. A potential difference of 9.0 V is maintained between the ends of the 2.0-m composite wire. What is (a) the current in the copper section; (b) the current in the silver section; (c) the magnitude of $\vec{E}$ in the copper; (d) the magnitude of $\vec{E}$ in the silver; (e) the potential difference between the ends of the silver section of wire?

25.55 • A 3.00-m length of copper wire at 20° C has a 1.20-m-long section with diameter 1.20 mm and a 1.80-m-long section with diameter 0.60 mm. There is a current of 2.0 mA in the 1.20-mm-diameter section. (a) What is the current in the 0.60-mm-diameter section? (b) What is the magnitude of $\vec{E}$ in the 1.20-mm-diameter section? (c) What is the magnitude of $\vec{E}$ in the 0.60-mm-diameter section? (d) What is the potential difference between the ends of the 3.00-m length of wire?

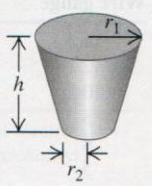
25.56 •• A heating element made of tungsten wire is connected to a large battery that has negligible internal resistance. When the heating element reaches 80.0° C, it consumes electrical energy at a rate of 480 W. What is its power consumption when its temperature is 150.0° C? Assume that the temperature coefficient of resistivity has the value given in Table 25.2 and that it is constant over the temperature range in this problem. In Eq. (25.12) take T_0 to be 20.0° C.

25.57 •• CP BIO **Struck by Lightning.** Lightning strikes can involve currents as high as 25,000 A that last for about 40 μs. If a person is struck by a bolt of lightning with these properties, the current will pass through his body. We shall assume that his mass is 71.0 kg, that he is wet (after all, he is in a rainstorm) and therefore has a resistance of 1.50 kΩ, and that his body is all water (which is reasonable for a rough, but plausible, approximation). (a) By how many degrees Celsius would this lightning bolt increase the temperature of 71 kg of water? (b) Given that the internal body temperature is about 37°C, would the person's temperature actually increase that much? Why not? What would happen first?

25.58 •• A resistor with resistance R is connected to a battery that has emf 16.0 V and internal resistance $r = 0.370\ \Omega$. For what two values of R will the power dissipated in the resistor be 81.0 W?

25.59 • CALC A material of resistivity ρ is formed into a solid, truncated cone of height h and radii r_1 and r_2 at either end (**Fig. P25.59**). (a) Calculate the resistance of the cone between the two flat end faces. (*Hint:* Imagine slicing the cone into very many thin disks, and calculate the resistance of one such disk.) (b) Show that your result agrees with Eq. (25.10) when $r_1 = r_2$.

Figure **P25.59**



25.60 • CALC The region between two concentric conducting spheres with radii a and b is filled with a conducting material with resistivity ρ. (a) Show that the resistance between the spheres is given by

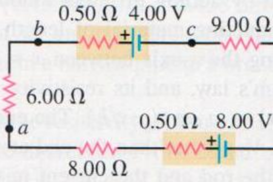
$$R = \frac{\rho}{4\pi}\left(\frac{1}{a} - \frac{1}{b}\right)$$

(b) Derive an expression for the current density as a function of radius, in terms of the potential difference V_{ab} between the spheres. (c) Show that the result in part (a) reduces to Eq. (25.10) when the separation $L = b - a$ between the spheres is small.

25.61 • The potential difference across the terminals of a battery is 8.10 V when there is a current of 1.54 A in the battery from the negative to the positive terminal. When the current is 3.44 A in the reverse direction, the potential difference becomes 9.1 V. (a) What is the internal resistance of the battery? (b) What is the emf of the battery?

25.62 • (a) What is the potential difference V_{ad} in the circuit of **Fig. P25.62**? (b) What is the terminal voltage of the 4.00-V battery? (c) A battery with emf 10.30 V and internal resistance 0.50 Ω is inserted in the circuit at d, with its negative terminal connected to the negative terminal of the 8.00-V battery. What is the difference of potential V_{bc} between the terminals of the 4.00-V battery now?

Figure **P25.62**



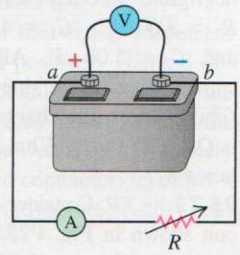
25.63 • BIO The average bulk resistivity of the human body (apart from surface resistance of the skin) is about 5.0 $\Omega \cdot$m. The conducting path between the hands can be represented approximately as a cylinder 1.6 m long and 0.10 m in diameter. The skin resistance can be made negligible by soaking the hands in salt water. (a) What is the resistance between the hands if the skin resistance is negligible? (b) What potential difference between the hands is needed for a lethal shock current of 100 mA? (Note that your result shows that small potential differences produce dangerous currents when the skin is damp.) (c) With the current in part (b), what power is dissipated in the body?

25.64 •• BIO A person with body resistance between his hands of 11 kΩ accidentally grasps the terminals of a 13-kV power supply. (a) If the internal resistance of the power supply is 1500 Ω, what is the current through the person's body? (b) What is the power dissipated in his body? (c) If the power supply is to be made safe by increasing its internal resistance, what should the internal resistance be for the maximum current in the above situation to be 1.00 mA or less?

25.65 • A typical cost for electrical power is \$0.120 per kilowatt-hour. (a) Some people leave their porch light on all the time. What is the yearly cost to keep a 90-W bulb burning day and night? (b) Suppose your refrigerator uses 300 W of power when it's running, and it runs 8 hours a day. What is the yearly cost of operating your refrigerator?

25.66 •• In the circuit shown in **Fig. P25.66**, R is a *variable resistor* whose value ranges from 0 to ∞, and a and b are the terminals of a battery that has an emf $\mathcal{E} = 15.0$ V and an internal resistance of 4.00 Ω. The ammeter and voltmeter are idealized meters. As R varies over its full range of values, what will be the largest and smallest readings of (a) the voltmeter and (b) the ammeter? (c) Sketch qualitative graphs of the readings of both meters as functions of R.

Figure **P25.66**



25.67 •• **A Nonideal Ammeter.** Unlike the idealized ammeter described in Section 25.4, any real ammeter has a nonzero resistance. (a) An ammeter with resistance R_A is connected in series with a resistor R and a battery of emf $\mathcal{E}$ and internal resistance r. The current measured by the ammeter is I_A. Find the current through the circuit if the ammeter is removed so that the battery and the resistor form a complete circuit. Express your answer in terms of I_A, r, R_A, and R. The more "ideal" the ammeter, the smaller the difference between this current and the current I_A. (b) If $R = 3.80\ \Omega$, $\mathcal{E} = 7.50$ V, and $r = 0.45\ \Omega$, find the maximum value of the ammeter resistance R_A so that I_A is within 1.0% of the current in the circuit when the ammeter is absent. (c) Explain why your answer in part (b) represents a *maximum* value.

25.68 •• A cylindrical copper cable 1.20 km long is connected across a 220.0-V potential difference. (a) What should be its diameter so that it produces heat at a rate of 30.0 W? (b) What is the electric field inside the cable under these conditions?

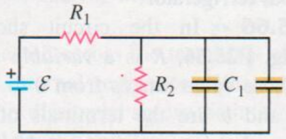
25.69 • CALC A 1.50-m cylinder of radius 1.10 cm is made of a complicated mixture of materials. Its resistivity depends on the distance x from the left end and obeys the formula $\rho(x) = a + bx^2$, where a and b are constants. At the left end, the resistivity is $2.25 \times 10^{-8}\ \Omega \cdot$m, while at the right end it is $8.50 \times 10^{-8}\ \Omega \cdot$m. (a) What is the resistance of this rod? (b) What is the electric field at its midpoint if it carries a 1.75-A current? (c) If we cut the rod into two 75.0-cm halves, what is the resistance of each half?

25.70 •• **Compact Fluorescent Bulbs.** Compact fluorescent bulbs are much more efficient at producing light than are ordinary incandescent bulbs. They initially cost much more, but they last far longer and use much less electricity. According to one study of these bulbs, a compact bulb that produces as much light as a 100-W incandescent bulb uses only 23 W of power. The compact bulb lasts 10,000 hours, on the average, and costs \$11.00, whereas the incandescent bulb costs only \$0.75, but lasts just 750 hours. The study assumed that electricity costs \$0.080 per kilowatt-hour and that the bulbs are on for 4.0 h per day. (a) What is the total cost (including the price of the bulbs) to run each bulb for 3.0 years? (b) How much do you save over 3.0 years if you use a compact fluorescent bulb instead of an incandescent bulb? (c) What is the resistance of a "100-W" fluorescent bulb? (Remember, it actually uses only 23 W of power and operates across 120 V.)

25.71 • A lightning bolt strikes one end of a steel lightning rod, producing a 15,200-A current burst that lasts for 65 μs. The rod is 1.7 m long and 2.1 cm in diameter, and its other end is connected to the ground by 33 m of 7.8-mm-diameter copper wire. (a) Find the potential difference between the top of the steel rod and the lower end of the copper wire during the current burst. (b) Find the total energy deposited in the rod and wire by the current burst.

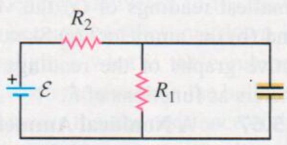
25.72 •• **CP** Consider the circuit shown in **Fig. P25.72**. The battery has emf 52.0 V and negligible internal resistance. $R_2 = 3.00\ \Omega$, $C_1 = 4.00\ \mu$F, and $C_2 = 5.00\ \mu$F. After the capacitors have attained their final charges, the charge on C_1 is $Q_1 = 18.0\ \mu$C. What is (a) the final charge on C_2; (b) the resistance R_1?

Figure **P25.72**



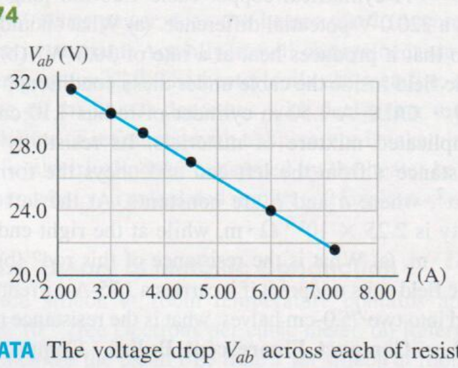
25.73 •• **CP** Consider the circuit shown in **Fig. P25.73**. The emf source has negligible internal resistance. The resistors have resistances $R_1 = 7.00\ \Omega$ and $R_2 = 4.00\ \Omega$. The capacitor has capacitance $C = 6.00\ \mu$F. When the capacitor is fully charged, the magnitude of the charge on its plates is $Q = 35.0\ \mu$C. Calculate the emf $\mathcal{E}$.

Figure **P25.73**



25.74 •• **DATA** An external resistor R is connected between the terminals of a battery. The value of R varies. For each R value, the current I in the circuit and the terminal voltage V_{ab} of the battery are measured. The results are plotted in **Fig. P25.74**, a graph of V_{ab} versus I that shows the best straight-line fit to the data. (a) Use the graph in Fig. P25.74 to calculate the battery's emf and internal resistance. (b) For what value of R is V_{ab} equal to 80.0% of the battery emf?

Figure **P25.74**



25.75 •• **DATA** The voltage drop V_{ab} across each of resistors A and B was measured as a function of the current I in the resistor. The results are shown in the table:

Resistor A

I (A)	0.50	1.00	2.00	4.00
V_{ab} (V)	2.55	3.11	3.77	4.58

Resistor B

I (A)	0.50	1.00	2.00	4.00
V_{ab} (V)	1.94	3.88	7.76	15.52

(a) For each resistor, graph V_{ab} as a function of I and graph the resistance $R = V_{ab}/I$ as a function of I. (b) Does resistor A obey Ohm's law? Explain. (c) Does resistor B obey Ohm's law? Explain. (d) What is the power dissipated in A if it is connected to a 4.00-V battery that has negligible internal resistance? (e) What is the power dissipated in B if it is connected to the battery?

25.76 •• **DATA** According to the U.S. National Electrical Code, copper wire used for interior wiring of houses, hotels, office buildings, and industrial plants is permitted to carry no more than a specified maximum amount of current. The table shows values of the maximum current I_{max} for several common sizes of wire with varnished cambric insulation. The "wire gauge" is a standard used to describe the diameter of wires. Note that the larger the diameter of the wire, the *smaller* the wire gauge.

Wire gauge	Diameter (cm)	I_{max} (A)
14	0.163	18
12	0.205	25
10	0.259	30
8	0.326	40
6	0.412	60
5	0.462	65
4	0.519	85

(a) What considerations determine the maximum current-carrying capacity of household wiring? (b) A total of 4200 W of power is to be supplied through the wires of a house to the household electrical appliances. If the potential difference across the group of appliances is 120 V, determine the gauge of the thinnest permissible wire that can be used. (c) Suppose the wire used in this house is of the gauge found in part (b) and has total length 42.0 m. At what rate is energy dissipated in the wires? (d) The house is built in a community where the consumer cost of electrical energy is \$0.11 per kilowatt-hour. If the house were built with wire of the next larger diameter than that found in part (b), what would be the savings in electricity costs in one year? Assume that the appliances are kept on for an average of 12 hours a day.

CHALLENGE PROBLEMS

25.77 ••• **CALC** The resistivity of a semiconductor can be modified by adding different amounts of impurities. A rod of semiconducting material of length L and cross-sectional area A lies along the x-axis between $x = 0$ and $x = L$. The material obeys Ohm's law, and its resistivity varies along the rod according to $\rho(x) = \rho_0 \exp(-x/L)$. The end of the rod at $x = 0$ is at a potential V_0 greater than the end at $x = L$. (a) Find the total resistance of the rod and the current in the rod. (b) Find the electric-field magnitude $E(x)$ in the rod as a function of x. (c) Find the electric potential $V(x)$ in the rod as a function of x. (d) Graph the functions $\rho(x)$, $E(x)$, and $V(x)$ for values of x between $x = 0$ and $x = L$.

25.78 ••• An external resistor with resistance R is connected to a battery that has emf $\mathcal{E}$ and internal resistance r. Let P be the electrical power output of the source. By conservation of energy, P is equal to the power consumed by R. What is the value of P in the limit that R is (a) very small; (b) very large? (c) Show that the power output of the battery is a maximum when $R = r$. What is this maximum P in terms of $\mathcal{E}$ and r? (d) A battery has $\mathcal{E} = 64.0$ V and $r = 4.00\ \Omega$. What is the power output of this battery when it is connected to a resistor R, for $R = 2.00\ \Omega$, $R = 4.00\ \Omega$, and $R = 6.00\ \Omega$? Are your results consistent with the general result that you derived in part (b)?

PASSAGE PROBLEMS

BIO SPIDERWEB CONDUCTIVITY. Some types of spiders build webs that consist of threads made of dry silk coated with a solution of a variety of compounds. This coating leaves the threads, which are used to capture prey, *hygroscopic*—that is, they attract water from the atmosphere. It has been hypothesized that this aqueous coating makes the threads good electrical conductors. To test the electrical properties of coated thread, researchers placed a 5-mm length of thread between two electrical contacts.* The researchers stretched the thread in 1-mm increments to more than twice its original length, and then allowed it to return to its original length, again in 1-mm increments. Some of the resistance measurements are shown in the table:

Resistance of thread ($10^9\ \Omega$)	9	19	41	63	102	76	50	24
Length of thread (mm)	5	7	9	11	13	9	7	5

*Based on F. Vollrath and D. Edmonds, "Consequences of electrical conductivity in an orb spider's capture web," *Naturwissenschaften* (100:12, December 2013, pp. 1163–69).

25.79 What is the best explanation for the behavior exhibited in the data? (a) Longer threads can carry more current than shorter threads do and so make better electrical conductors. (b) The thread stops being a conductor when it is stretched to 13 mm, due to breaks that occur in the thin coating. (c) As the thread is stretched, the coating thins and its resistance increases; as the thread is relaxed, the coating returns nearly to its original state. (d) The resistance of the thread increases with distance from the end of the thread.

25.80 If the conductivity of the thread results from the aqueous coating only, how does the cross-sectional area A of the coating compare when the thread is 13 mm long versus the starting length of 5 mm? Assume that the resistivity of the coating remains constant and the coating is uniform along the thread. $A_{13\text{ mm}}$ is about (a) $\frac{1}{10}A_{5\text{ mm}}$; (b) $\frac{1}{4}A_{5\text{ mm}}$; (c) $\frac{2}{5}A_{5\text{ mm}}$; (d) the same as $A_{5\text{ mm}}$.

25.81 What is the maximum current that flows in the thread during this experiment if the voltage source is a 9-V battery? (a) about 1 A; (b) about 0.1 A; (c) about 1 μA; (d) about 1 nA.

25.82 In another experiment, a piece of the web is suspended so that it can move freely. When either a positively charged object or a negatively charged object is brought near the web, the thread is observed to move toward the charged object. What is the best interpretation of this observation? The web is (a) a negatively charged conductor; (b) a positively charged conductor; (c) either a positively or negatively charged conductor; (d) an electrically neutral conductor.

Answers

Chapter Opening Question ?

(iii) The current out equals the current in. In other words, charge must enter the bulb at the same rate as it exits the bulb. It is not "used up" or consumed as it flows through the bulb.

Test Your Understanding Questions

25.1 (v) Doubling the diameter increases the cross-sectional area A by a factor of 4. Hence the current-density magnitude $J = I/A$ is reduced to $\frac{1}{4}$ of the value in Example 25.1, and the magnitude of the drift velocity $v_d = J/n|q|$ is reduced by the same factor. The new magnitude is $v_d = (0.15\text{ mm/s})/4 = 0.038\text{ mm/s}$. This behavior is the same as that of an incompressible fluid, which slows down when it moves from a narrow pipe to a broader one (see Section 12.4).

25.2 (ii) Figure 25.6b shows that the resistivity ρ of a semiconductor increases as the temperature decreases. From Eq. (25.5), the magnitude of the current density is $J = E/\rho$, so the current density decreases as the temperature drops and the resistivity increases.

25.3 (iii) Solving Eq. (25.11) for the current shows that $I = V/R$. If the resistance R of the wire remained the same, doubling the voltage V would make the current I double as well. However, we saw in Example 25.3 that the resistance is *not* constant: As the current increases and the temperature increases, R increases as well. Thus doubling the voltage produces a current that is *less* than double the original current. An ohmic conductor is one for which $R = V/I$ has the same value no matter what the voltage, so the wire is *nonohmic*. (In many practical problems the temperature change of the wire is so small that it can be ignored, so we can safely regard the wire as being ohmic. We do so in almost all examples in this book.)

25.4 (iii), (ii), (i) For circuit (i), we find the current from Eq. (25.16): $I = \mathcal{E}/(R + r) = (1.5\text{ V})/(1.4\ \Omega + 0.10\ \Omega) = 1.0\text{ A}$. For circuit (ii), we note that the terminal voltage $v_{ab} = 3.6\text{ V}$ equals the voltage IR across the 1.8-Ω resistor: $V_{ab} = IR$, so $I = V_{ab}/R = (3.6\text{ V})/(1.8\ \Omega) = 2.0\text{ A}$. For circuit (iii), we use Eq. (25.15) for the terminal voltage: $V_{ab} = \mathcal{E} - Ir$, so $I = (\mathcal{E} - V_{ab})/r = (12.0\text{ V} - 11.0\text{ V})/(0.20\ \Omega) = 5.0\text{ A}$.

25.5 (iii), (ii), (i) These are the same circuits that we analyzed in Test Your Understanding of Section 25.4. In each case the net power output of the battery is $P = V_{ab}I$, where V_{ab} is the battery terminal voltage. For circuit (i), we found that $I = 1.0\text{ A}$, so $V_{ab} = \mathcal{E}\ \ Ir = 1.5\text{ V} - (1.0\text{ A})(0.10\ \Omega) = 1.4\text{ V}$, so $P = (1.4\text{ V})(1.0\text{ A}) = 1.4\text{ W}$. For circuit (ii), we have $V_{ab} = 3.6\text{ V}$ and found that $I = 2.0\text{ A}$, so $P = (3.6\text{ V})(2.0\text{ A}) = 7.2\text{ W}$. For circuit (iii), we have $V_{ab} = 11.0\text{ V}$ and found that $I = 5.0\text{ A}$, so $P = (11.0\text{ V})(5.0\text{ A}) = 55\text{ W}$.

25.6 (i) The difficulty of producing a certain amount of current increases as the resistivity ρ increases. From Eq. (25.24), $\rho = m/ne^2\tau$, so increasing the mass m will increase the resistivity. That's because a more massive charged particle will respond more sluggishly to an applied electric field and hence drift more slowly. To produce the same current, a greater electric field would be needed. (Increasing n, e, or τ would decrease the resistivity and make it easier to produce a given current.)

Bridging Problem

(a) 237°C **(b)** 162 W initially, 148 W at 1.23 A

The University of Jordan / Physics Department

General Physics (102) / Chapter 25 / Sears and Zemansky 14th edition

Sample Solutions / Prof. Mahmoud Jaghoub

(أ.د. محمود الجاغوب)

Q2]

a) $I = \frac{\Delta Q}{\Delta t} = \frac{420}{80 \times 60} = 0.0875$ C/s ≡ Ampere

b) $I = n q v_d A \Rightarrow v_d = \frac{I}{nqA} = \frac{0.875 \times 10^{-1}}{(5.8 \times 10^{28})(1.6 \times 10^{-19})(\pi r^2)}$

$r = \frac{2.6}{2} = 1.3\,mm \Rightarrow v_d \simeq 1.8 \times 10^{-6}\,m/s = 0.0018\,mm/s$.

Q7] $I = 55 - 0.65t^2$ in units of Amperes.

a) $I = \frac{dQ}{dt} \Rightarrow \int dQ = \int I\, dt$

$\therefore Q = \int_0^{8.2} (55 - 0.65t^2)\,dt = \left[55t - 0.65\frac{t^3}{3}\right]_0^{8.2}$

$= 331.5$ C.

b) For a constant current $Q = I_c \Delta t$

$\therefore I_c \Delta t = 331.5 \Rightarrow I_c = 40.4$ A.

(I_c ↑ constant)

Q20] $V = IR = I\frac{\rho l}{A}$

$$\therefore \rho = \frac{AV}{lI} = \frac{[\pi(0.654)^2][4.5]}{[2.5][17.6]}$$

$$\rho \simeq 0.044 \ \Omega.m$$

Q38] $P = \frac{E}{t} \Rightarrow E = Pt$

E ← energy, P ← power, t ← time

$$E = (IV)t = (0.14)(9.5)(1.7 \times 60 \times 60)$$

($1.7 \times 60 \times 60$: time in s)

$$E = 8139.6 \ J$$