4 Current Electricity

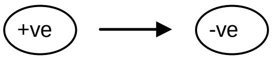
Electric charge is discussed in section 2.8

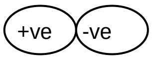
4.1 What is current electricity?

Electricity provides an energy supply: it is a form of energy.

Electrical energy is due to the electrical field between positive and negative electric charges.

Current electricity is the flow of electric charge across an electrical field.





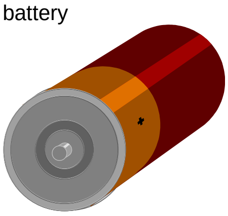
Imagine a negatively-charged particle is pulled away from a positively-charged particle, like separating the North and South poles of two magnets. If you were to let go of the negative particle, it would fly back to the positive particle due to the force of attraction between the two.

As the negative particle is pulled away, it is gaining potential energy (from you doing the work). When you let go, this potential energy is converted into kinetic energy as the negative particle flies back.

When the charges are separated, we say there is a potential energy difference between them, or simply **potential difference.**

This is the basis of current electricity. Negatively-charged electrons are removed from atoms, the atoms being left as positive ions. The potential difference between the two causes the electrons to be attracted back, producing a flow of electric charge: current electricity.

battery



A good example is a battery. Inside a battery, electrons have been chemically removed from atoms. The electrons are stored at the negative terminal of the battery and the positive ions at the positive terminal, so there is a potential difference between the two ends.

If a wire is used to connect the two terminals, electrons from the negative terminal and free electrons in the wire are attracted to the positive terminal and will flow through the wire. Electrons arriving at the positive terminal neutralise some of the positive ions. When all the positive ions are neutralised, the battery is flat: there is no longer a potential difference between its ends, no electrons flow.

When electricity was first discovered, it was thought positive charges flowed. “Conventional current” assumes this although electron flow is actually in the opposite direction. Radiography is concerned with electron flow only.

See section 5: Powers of Ten

4.2 Measuring electric charge

potential difference is also known as "voltage"

Electric charge is measured in coulombs (C) where 1 C is equivalent to the charge on 6.24×10^{18} electrons: this is more than 6 trillion electrons!

4.3 Measuring potential difference (pd)

Potential difference is measured in volts (V).

These 6 trillion negative electrons need 1 joule of energy to be pulled far enough away from 6 trillion positive charges to give a potential difference of 1 volt.

> Q1 THINK ABOUT THIS ... IF 1C OF CHARGE = **6.24×10^{18}** ELECTRONS, HOW MUCH ENERGY WOULD BE REQUIRED IF **ONE** ELECTRON IS MOVED THROUGH A POTENTIAL DIFFERENCE OF 1 V?
>
> DOES YOUR ANSWER LOOK FAMILIAR? LOOK BACK AT SECTION 1.3. See section 4.15 for answer

See section 5.3: SI units

The potential difference across an x-ray tube is typically 70 000 volts.

> Q2 WHAT IS 70 000 VOLTS EXPRESSED IN KILOVOLTS?
>
> See section 4.15 for answer

4.4 Measuring electric current

mA = 10^{-3} A

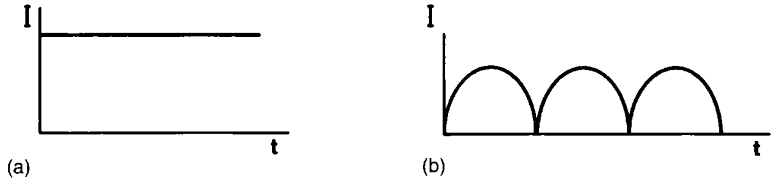
Electric current is the rate of flow of electrons through a potential difference and is measured in amperes (amps), A, where 1 A is 1 coulomb of charge passing a point in one second.

Electron flow in an x-ray tube is measured in milliamps (mA).

4.5 Direct current (DC)

Direct current is electron flow in a single, continuous direction and may be constant over time (a) or pulsed (b).

These graphs are called waveforms: see section 1.5 Waves

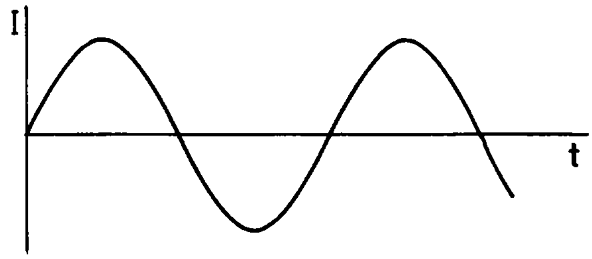


Constant direct current is produced from a battery, since the electrons always flow from the negative terminal to the positive terminal.

Pulsed direct current is both a necessity and a problem in x-ray generator circuits, but there are ways to make the pulses more continuous.

4.6 Alternating current (AC)

Alternating current changes direction: electrons flow first in one direction and then in the opposite direction: this constitutes one cycle of AC.



This sinusoidal waveform describes electron flow gradually increasing in the positive direction up to a maximum and then decreasing to zero. Electron flow then reverses direction up to a peak and decreases back to zero

This is how the mains electricity is supplied. Alternating current is much easier than direct current to produce, by rotating a turbine (using steam, water or wind) which then turns an alternator, similar to the small version found in cars.

See any GCSE textbook eg Pople (1987) Explaining Physics Section 7.9 Generators

In the UK, AC is generated at a frequency of 50 cycles per second (50 Hz).

frequency is measured in units called hertz (Hz)

DOES THE ELECTRON FLOW CHANGE DIRECTION?

See section 4.15 for answer

Some x-ray generator circuits are operated at a much higher frequency of 5000 Hz.

4.7 Effective Current

Since electrons are flowing first in one direction and then in the opposite direction, the net electron flow is zero.

The effective current, also known as the root-mean-square (RMS) current, is the amount of direct current which would produce the same heating effect.

Effective current is calculated by dividing the peak current by the square root of two:

$$\text{effective current} = \frac{\text{peak current}}{\sqrt{2}}$$

The alternating potential difference produces alternating current

The same method is used to calculate effective voltage, since the potential difference of alternating current varies in the same way.

Q4 THE MAINS SUPPLY IN THE UK IS 240 V. THIS IS THE EFFECTIVE VOLTAGE. CAN YOU CALCULATE THE PEAK VOLTAGE?

See section 4.15 for answer

4.8 Power

see section 1.1 What is energy?

An electrical circuit converts its input energy, from the mains supply or a battery for example, into another form of energy eg light, sound, heat, kinetic energy, depending on what it has been designed to do.

Power is the rate at which the input energy is converted and is equal to the pd x current in the circuit.

40 kW = 40 000 W
see section 5.3: SI units and prefixes

Q3 AT 50 CYCLES PER SECOND, HOW FREQUENTLY

Resistance is measured in units called ohms.

4.9 Resistance

Resistance in an electrical circuit impedes the flow of electrons and decreases current flow.

In a conducting wire, resistance should be as low as possible. In some devices resistance is deliberately high to create heat, as in the element of an electric fire which is similar to the filament of an x-ray tube. Resistance can be increased by using a long, thin wire made of a metal with high resistivity eg tungsten. Copper has a low resistivity

V is directly proportional to I

Potential difference (or voltage, V), current (I) and resistance (R) are related by Ohm's Law where $V = IR$ in a simple electrical circuit.

4.10 Capacitors

A capacitor is an electrical component able to store electric charge temporarily, giving it a potential difference. It can then be considered as a battery, since if it is put into a circuit it will discharge by allowing electrons to flow from its negative terminal to its positive.

Capacitor discharge unit

Capacitance is measured in units called farads (F).

capacitor smoothing

Capacitors are used in some mobile x-ray units which are charged from the mains supply and then allowed to discharge across the x-ray tube.

Capacitors are also used in x-ray generator circuits to reduce voltage variation (ripple).

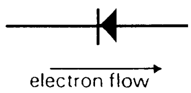
The charging/discharging of a capacitor is an example of exponential growth/decay.

Power is measured in watts (W). Xray generators typically have a power rating of around 40 kW.

4.11 Diodes

A diode is an electrical component which allows electrons to flow through it in one direction only.

Diodes are constructed from silicon semiconductor material, usually a PN junction



this is the electrical symbol for a diode

If AC is applied to a diode, electrons in the reverse half-cycle will be suppressed.

Hence, diodes have an important role in *rectification,* where alternating current is converted into pulsed direct current.

In the x-ray generator circuit, the AC supply must be rectified.

4.12 AC Transformer

The AC transformer converts (transforms) alternating voltage/current from one value to another:

- to a higher voltage (and lower current): step-up transformer
- to a lower voltage (and higher current): step-down transformer
- to the same voltage and current: to isolate part of an electrical circuit since there is no direct electrical contact through a transformer.

Transformers are used in x-ray generator circuits to supply a high voltage across the x-ray tube and a low voltage across the x-ray tube filament.

Transformers work on the principle of *electromagnetic induction*. Electricity and magnetism are closely related: a current flowing through an electrical conductor will produce a magnetic field around it. If this current is alternating,

This principle also applies to a spinning electron: it produces a magnetic field. This is used in magnetic resonance imaging.

changes in direction and size. Similarly, a changing magnetic field will induce a potential difference and current in an electrical conductor.

A transformer consists of two coils of wire. An alternating voltage is applied to one coil. The changing magnetic field around this coil induces an alternating voltage in the second coil.

Step-up transformer

Step-down transformer

If the second coil is bigger (has more turns) than the primary coil, the voltage induced will be greater than the primary voltage. If the secondary coil has fewer turns, the induced voltage will be less than the primary.

The *turns ratio* indicates how much the voltage will be stepped up or down. For example, a 1:500 turns ratio indicates for every one turn on the primary there are 500 turns on the secondary coil. Hence the input voltage will be stepped-up 500 times, for example from 100 V to 50 000 V.

Q5 A STEP-DOWN TRANSFORMER HAS A TURNS RATIO OF 20:1. IF THE **INPUT PEAK VOLTAGE** IS 200V, WHAT WILL BE THE **OUTPUT PEAK VOLTAGE**?

WHAT WILL BE THE **OUTPUT EFFECTIVE VOLTAGE**?

see section 4.15 for answers

The delay in magnetising and demagnetising is called hysteresis

Transformers are very efficient with little energy loss. To maximise efficiency, the coils are wound on a metal core that is easily magnetisable and demagnetisable, to concentrate the magnetic field; the secondary coil may be wound on an arm of this core, or on top of the primary coil. The core is laminated to reduce eddy currents from electromagnetic induction in the core, leading to heating.

Modern x-ray generators use high frequency technology

At high frequencies, the number of turns on each coil is less to change the voltage in the same way, reducing the physical size of the transformer.

the associated magnetic field will change direction and size as the current potential difference

- distinguish between conventional current and electron flow
- give the units of electric charge, potential difference, current, frequency, resistance, capacitance
- differentiate between direct current and alternating current
- recognise DC and AC waveforms
- calculate peak voltage/current given the effective voltage/current and vice versa
- outline factors affecting resistance
- outline the uses of capacitors and diodes in electrical circuits
- explain the term rectification
- give the uses of the AC transformer
- use the AC transformer turns ratio to calculate its output voltage

4.14 Further Reading

BALL JL & MOORE AD (1986) 2nd Ed. Essential Physics for Radiographers chapters 3,5,6,7,9,10,13

BUSHONG SC (1997) Radiologic Science for Technologists (6th ed) chapter 6

GRAHAM DT (1996) Principles of Radiological Physics (3rd ed) chapter 10,13,14,16,17,19,20

4.13 Check that you can:

- explain what is meant by

electrons requires 1J

$\therefore$ 1J/6.24 x 10^{18} gives energy for 1 electron
= 1.6 x 10^{-19} J
(equivalent to one electronvolt)

Q2 70 000 V = 70 kV (kilovolts)

Q3 50 cycles per second = 1/50 s
= 0.02s per cycle

0.02/2 = 0.01 s per change of direction.

Q4 peak voltage = 240 x $\sqrt{2}$ = 339 V

Q5 output peak voltage = 200/20 = 10 V

output effective voltage = 10/$\sqrt{2}$ = 7.1 V

4.15 Answers

Q1 charge on 6.24 x 10^{18}