Chapter 1

General physics

ATOMS AND MOLECULES

Whenever setting out on a project of this type, it is difficult to know what to use as your starting point.

Let us start by looking at what makes up the world as we know it.

We look around and see lakes, mountains, fields, etc., but what if we could look into these things and see what makes them what they are?

We would see atoms and molecules.

There can't be many people who have not heard of these, but what are they?

Atoms and molecules are linked to elements and compounds (here is the problem – almost every time we mention anything, it will lead us straight to something else we need to know).

Elements are single chemical substances such as oxygen, hydrogen, sulphur, etc. We can take a large amount of an element and keep cutting it down to make it smaller and smaller, but there is a limit to how small we can make it.

We come to a point where all that we have is a single atom of the substance; if we then cut it to an even smaller size, we will be breaking down the atom, and it will no longer be that particular substance.

- Atoms are the smallest particle of an element that can exist and still behave as that element.

Breaking down an atom eventually produces just a collection of the bits that make up the atom.

Here we go again! What is smaller than an atom? Or what are atoms made of?

There are many so-called fundamental particles that make up the atoms that provide the basic building blocks for all of the things that we see, touch and know of. Some of these fundamental particles are only now being discovered.

For the purposes of fulfilling the basic guide brief, we will concentrate on only three types of particle: protons, neutrons and electrons.

Basic Guide to Dental Radiography, First Edition. Tim Reynolds.

Protons and neutrons are large (that's relative; remember we would need very powerful microscope to see even these particles), and electrons are small.

To represent the difference in these particles in a way you can visualise, think of placing a single grape pip on the ground and then standing a person 6 ft tall next to it.

The grape pip represents the size of an electron, and the 6-ft-tall person the size of a proton or a neutron. Protons and neutrons are slightly different in size, but for our purposes they can be considered to be the same, but electrons are 1840 times smaller than either of the other two particles.

The protons and electrons each have an electrical charge and these charges are of opposite poles (like the two ends of a battery). The protons have a positive charge (+ve), and the electrons a negative charge (–ve).

Despite the relative size difference of the particles, the two charges, although opposite poles (or signs), are of equal size or strength.

So the positive charge on one large proton is completely cancelled out by the negative charge on one tiny electron.

Neutrons have no charge at all (they are neutral).

How do these particles fit together to make an atom?

Figure 1.1 shows what has become an accepted idea of the appearance of an atom.

There is a large central nucleus, containing protons and neutrons with the electrons circling in a number of orbits at different distances from the nucleus. These orbits have traditionally been called electron shells or energy shells.

This model will be adequate for our understanding, but do remember that the electron orbits are not all in the same plane. The atom is three-dimensional, and the electron orbits taken all together would make a pattern much more like looking at a football.

This makes sense if you think of the electron orbits as actual shells; they completely surround the nucleus much like the layers of an onion. This is difficult to demonstrate on a flat page, and we have become used to the picture as shown (Figure 1.1) with lots of circles having the same centre.

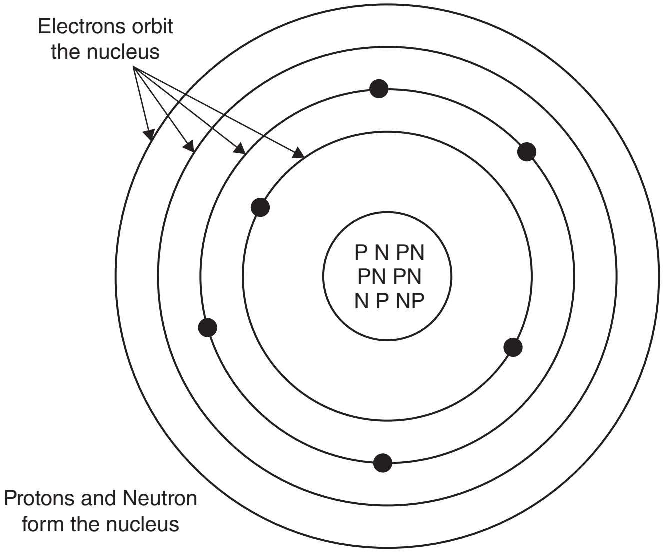

Figure 1.1 Classic basic model for the structure of the atom

The number of protons in the nucleus tells us what sort of atom it is. A nucleus containing 6 protons would be a carbon nucleus, 11 protons sodium, and 82 protons lead. The number of protons present is the atomic number of the element and of course of the atom; the number of protons in fact tells us what chemical substance the atom is.

The protons in the nucleus all have a positive charge, and the tendency for positive charges is to push each other apart just like two magnetic north or two south poles would. They need something to keep them from pushing each other away; this function is performed by the neutrons. The neutrons don't do this job alone, but for the purposes of this particular text, we need look no further into nuclear forces. At very low atomic numbers, there will be equal numbers of protons and neutrons; however as atomic number increases, the higher concentration of positively charged protons needs a higher number of neutrons to overcome the forces of repulsion between them.

The number of electrons in each orbit is specific and is determined by the following formula:

$$E = 2n^2$$

where E is the number of electrons and n is the number of the electron shell.

So, the closest shell to the nucleus is number 1. In that shell, you can have 2×1^2 electrons.

1^2 is 1×1 so that 1 multiplied by 2 tells us we can have two electrons in the first shell.

In the second shell we can have 2×2^2. So $2 \times 2\,(n^2) = 4$ multiplied by 2 gives 8.

In the third shell 2×3^2 gives 2×9. So 18 electrons would be allowed in shell 3.

No electrons can be positioned in shell 2 if shell 1 is not full and none in shell 3 if shell 2 is not full. That is to say that all inner shells must be filled before outer shells can contain any electrons. If an electron were removed from an inner shell, then one would move down from an outer shell to fill the gap. (This becomes important when we consider the effects of exposure to radiation.)

The process works like this because atoms always exist in their lowest energy state (ground state) and inner shell electrons are the low energy ones. So if we take out a low-energy inner shell electron, the atom is at a higher level of energy than it could be, so an electron from a shell further out falls to fill the gap and in the process gives up some of its energy.

The electron filling the gap will give up some energy because it can only be in the lower shell if it has the correct level of energy. This process will continue until the exchange takes place at the outermost shell of the atom. There will then be an electron space free in the outer shell of the atom (the one that is the greatest distance from the nucleus) (Figure 1.2).

From the previous descriptions, it is clear that most of the mass of an atom (it's easier to think of this as weight or just the solid material) is in the nucleus of the atom.

A carbon atom with 6 protons and 6 neutrons (there are forms of carbon with a different number of neutrons, but we are not concerned with isotopes in this text) will have 6 electrons circulating in two discrete orbits (2 in shell 1 and 4 in shell 2). So in terms of the sheer bulk of material in relative terms, the electrons account for six times one, and the nucleus for 12 times 1840.

This means the solid matter that makes up an atom is mostly contained in the nucleus (where the big particles are). However if we look at the overall size of the atom (from one side of the outer electron shell to the other), most of it is not made up of material at all but of empty space. Even taking into account the relatively large particles in the nucleus,

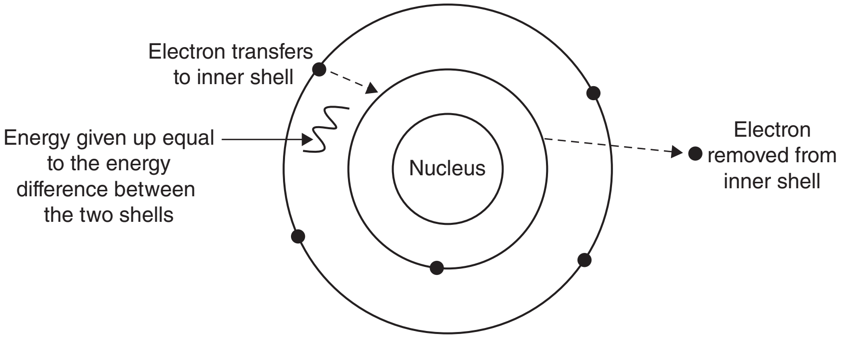

Figure 1.2 Redistribution of electrons to the atoms' lowest energy state

all elements including things like lead have atoms that are almost entirely free space. This is sort of like a large fishing net on a trawler; if the net was 50 yd by 50 yd, the overall size is massive, but if you just put the material making the net together, it would be tiny by comparison; the overall measurements of the net are made up mostly of the gaps between the materials.

To round off our investigation of atoms, the following is presented.

The electron shells are not called 1, 2 and 3 but are denoted by letters, number 1 is K, number 2 L, number 3 M, and so on; this form of atomic structure will be found in any basic science or physics book though not in advanced texts on the topic. The shell numbers simply allow us to calculate the number of electrons allowed to be in the particular orbit or shell.

On page 1 when we started talking about atoms, we also mentioned molecules, so we now need to bring those back into our thinking.

When we introduced molecules we said the atoms and molecules were linked to elements and compounds.

We have discussed elements, so what are compounds?

A compound is a combination of two or more elements; a combination that everyone knows is H_2O (water).

The formula indicates that there are two hydrogen atoms and one of oxygen. The collection of three atoms shown is a molecule of water. If we try to cut this down to make an even smaller amount, we end up with something that is no longer water. Take the oxygen out and we simply have two atoms of hydrogen; if we take away an hydrogen atom, we have an hydroxide or an hydroxyl radical.

- A molecule is the smallest particle of a compound that can exist and still behave chemically as that compound.

NB: Molecules are not always made up of atoms from different elements; a molecule is a collection of two or more atoms; they could be two atoms of oxygen or any other element.

Why do the atoms of different elements join together to make molecules of compounds? We could get into a big discussion on chemistry here, but we don't actually need to.

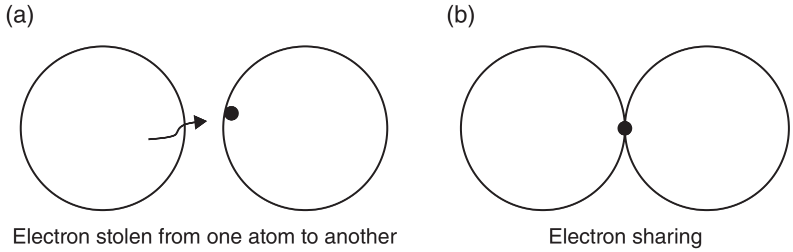

Figure 1.3 (a) Atomic bonding (ionic bond). (b) Atomic bonding (covalent bond)

The simplest way of thinking about the reason for these combinations is that all atoms would like their outer electron shell to be full.

If it isn't then they may combine with another material by taking an electron from it; the materials are then held together by a tug of war over the electron because both atoms want it in their outer shell. This type of joining is called an ionic bond (Figure 1.3a).

Another way in which atoms join is that they may share electrons, so that electrons in their outer shells effectively take part in the outer orbit of both atoms; this is a bit more like walking hand in hand down the road with your partner. This is a covalent (sharing) bond (Figure 1.3b).

We have just learned that the outer shell electrons of an atom give the atom its chemical properties; they are what make the atoms of one element bond with atoms of other elements to make the molecules of a compound. We can consider outer shell electrons to be 'chemical glue'.

Remember previously we said the electrons could not be put into outer shells if inner ones were not filled and that if an electron were taken out of an inner shell, its place would be taken by an electron from a shell further out; this process continues until all inner shell vacancies are filled. The result is that following the final movement, there will be a vacancy on the electron shell most remote from the nucleus (the outside shell). This shell gives the atom its chemical properties, so removing electrons from atoms changes their chemical properties. This is an important concept for understanding the biological effects of X-rays.

ENERGY

The previous section looked at the material (stuff) that makes up the world that we live in. Next thing to consider is what makes things work.

As always we should look for clues in what we do or say every day. If you have had a tough couple of days, worked hard and not slept, you come to a point where you say I have had it, I can't go on, and I've got no energy.

When we want to measure either amount of energy stored or used in a system, we might use a different word to describe it in different situations. There is however a general measure of energy that can be used in any circumstances; it is the Joule.

If you have ever been on a diet and watching food labels, you will have seen a statement telling you the number of joules (usually kilojoules (kJ)), so you can work out how many chocolate bars you need to just get you through the day.

So there it is, energy is what enables us to do work (or to play); some physics books actually define energy as the ability to do work.

There are lists indicating many sorts of energy, but if you look carefully at each, you can pretty well fit them all into one of the following two categories: kinetic energy (KE) and potential energy (PE).

Kinetic energy is the energy of movement, and potential energy is stored energy.

In classical physics we have the conservation of energy that says energy can be neither created nor destroyed but merely changed from one form to another.

In a very simple example of energy conversion, we could consider lifting a weight from the floor to a shelf six feet high. The work that you have done in lifting that weight is now stored as potential energy. If the weight is then pushed off the shelf, it falls; during the fall it has kinetic energy (energy of movement). On hitting the floor there will be a loud bang (sound energy), and a little heat will be produced.

The potential energy has been through two changes: potential energy to kinetic and kinetic energy to sound and heat.

Other types of energy that you might see are electrical and chemical; there are others but we do not need to produce a full list to examine the basic principles.

What type of energy is electrical energy? The answer is, 'it depends what it's doing'.

Electrical Energy in a battery is potential energy; it's there but it is doing nothing, but it does have the potential to make a small light bulb or a small electric motor work. When we turn on the switch to make the battery work, the electrical energy travels along wires or another form of connection to the item we want to work. As the electrical energy travels to the object, it is kinetic in nature (energy of movement). When the electrical energy arrives at its destination, it may be converted again. In a light bulb, it will produce light and heat energy. In a small electric motor, it will produce mechanical kinetic energy (it makes the motor parts move).

Heat energy is kinetic energy. We think of things as hot or cold, and we can feel the difference what we can't see is happening to the molecules in a hot or cold object.

When objects are cool the molecules do not move very much; as we increase the temperature, they move around more and much more quickly. We can see some evidence of this because we all know that as things warm up, they get bigger (expand). They do this because the molecules are moving about more. You can do an experiment to show this with a group of friends. Get them together and stand as still as you can and as close together. You will be able to fit into quite a small space. Now start moving around as if you might be dancing, and see how much more space is required by the group as a whole. This is exactly what happens when an object is heated (Figure 1.4).

When the bar is cold, the individual molecules (represented by the circles) are packed close together. After heating each molecule will move about; let's say they move backwards and forwards between the lines I have set at each side of them. Look at how much longer the bar would have to be to allow this movement.

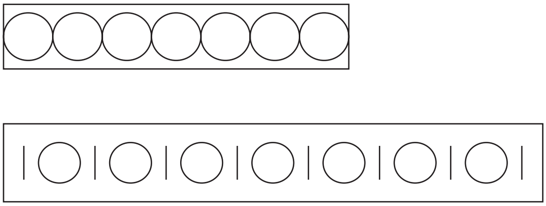

Figure 1.4 Explanation of expansion due to heating

When we give objects heat energy, we change their temperature. Heat energy can be transferred (moved) in three ways: conduction, convection and radiation.

Conduction of heat energy is through simple physical contact. The heat energy is passed from one molecule or one body to another. If you were standing in that closely packed group of friends and you were the only one that wanted to dance, the person next to you would soon be forced to move and then the one next to them and so on. If you were standing next to another group, they would also soon be forced to start moving.

Convection is how heat is generally transferred in liquids and gases; the warm molecules actually move from one area to another. If you have a bath with the tap set at one end and you fill it with cold water and then put hot water in the tap end, you can make the other end warm by swishing the water round with your hand. Eventually all of the water will have the same temperature because hot mixes with cold and the hot water molecules pass some of their heat to the cooler ones through conduction. So there will always be some conduction along with convection simply because the molecules are in contact with each other.

Radiation is the most difficult to understand as it does not pass through particles by movement or contact; in fact it does not pass through particles at all as it can move through a perfect vacuum (i.e. an area containing not even a single fundamental particle). Radiation is how we can feel the heat of the sun as it passes through millions of miles of space and gives kinetic energy to the molecules of our skin.

Large amounts of heat energy are produced when an X-ray machine is working, and we have to be able to move it away to stop it from damaging the machine, so these heat transfer methods are important during the production of X-rays.

ELECTRICAL ENERGY

The basis of electrical energy comes from the existence of the two types of electric charge that we have mentioned already, the positive charge on a proton and the negative charge on an electron. Electric charge is measured by a unit called the coulomb (C). This is a relatively large unit of charge, and for there to be 1 C of negative charge, we would need to collect 6×10^{18} electrons (that's 6 followed by 18 noughts), or the same number of protons will produce 1 C of positive charge.

These charges have an influence on each other; forces will exist between them. If the charges are alike (two positives or two negatives), they will push each other away (Figure 1.5a and 1.5b). If they are unlike charges, they will attract each other (Figure 1.5c). This force is always present, it's strength will depend the size of the charges and a number of other factors.

The force of attraction can also be seen in objects that have no charge if a large enough external charge is brought close to it. This happens because the electron orbits around an atom can be distorted (have their shape changed) (Figure 1.6).

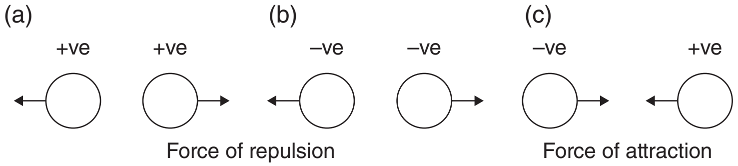

Figure 1.5 (a, b and c) Electric forces

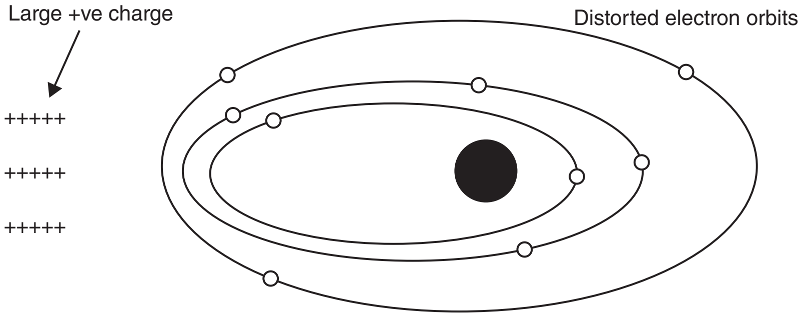

Figure 1.6 Charge induction through electron orbit distortion

The electron orbits have been distorted by the close positive charge; the electrons have been attracted to it, and the orbits have become elliptical. The positive charges of the nucleus are effectively further from the large external positive charge than the electrons are, and the two objects are attracted towards each other because the atom behaves as if it is negatively charged. If the external electric charge had been a negative one, the electrons would have been pushed away, and there would effectively be a force of repulsion between the external charge and the atom.

This effect has been induced by the external charge.

In some materials some of the electrons are free to move so that when a large positive charge is applied, the electrons will move through the material.

Electrical charge then can be the driving force to make other charges move – we call this driving force, voltage. When electrical charges do move, they are called current.

Voltage (it will not surprise you to learn) is measured in volts and current is measured in amps (Amperes).

1 Amp of current flows when 1 Coulomb of charge passes a point in 1 second (that's a lot of electrons, 6×10^{18} moving past a particular point past in 1 second).

When electrical charges move it is almost always electrons that move, simply because they are small enough to be influenced by other charges. In addition to being very large (atomically speaking), protons are usually firmly fixed together with other protons and the other large particle neutrons, right in the middle of the atom in the nucleus.

We have previously looked at the structure of the atom and described a number of electron shells, but rather than shells they become energy bands (it's like comparing a country lane to a six-lane motorway). The shells become bands because of the influence of all the other atoms around them.

We also talked about the outer shell (band) being responsible for the chemical (bonding) properties of the atom – this band is called the valence band. There is however another band outside of this one – it's called the conduction band. As the name implies, this is where electrical conduction (the movement of electrons) takes place.

Of course not all materials conduct electricity; if they did we would not be able to walk around our own homes without getting a shock as we have electrical wires behind all of our walls.

So what makes the difference?

The conduction band of electrons is an area where, effectively, the electrons belong to the atom but are not firmly fixed to the nucleus; they are free to move around as long as

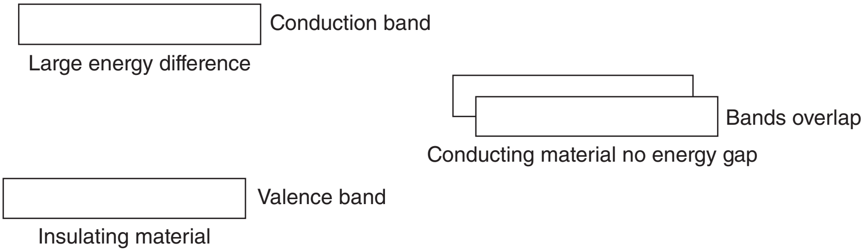

Figure 1.7 Valence and conduction bands in conductors and insulators

there is some influence (e.g. voltage) to cause that movement. The atom doesn't change because for every electron that moves out, one will move in.

The difference between an electrical conductor and an insulator is the energy difference (how big a step) between the valence band and the conduction band. In the valence band the electrons are fixed firmly in place; in the conduction band they are free to move under the influence of an applied voltage.

In an insulating material there is a large energy difference, and electrons are highly unlikely to ever have an energy increase sufficient to take them into the conduction band. In a conducting material the bands actually overlap so that there are always unattached electrons free to move through the material (Figure 1.7).

Even when electrons move there will still be the correct number of electrons associated with each atom because as electrons move out of one atom into the next, they are immediately replaced by electrons from the atom on the other side.

There are also semiconducting materials where the gap is small, and small amounts of energy can make electrons move into the conduction band.

ELECTRIC CURRENT

For current to flow there must be a closed circuit, a complete uninterrupted path for the voltage to be applied across and for the electrons to flow in. When using a light switch or pressing the exposure button on an X-ray machine, we are simply completing the circuit (Figure 1.8).

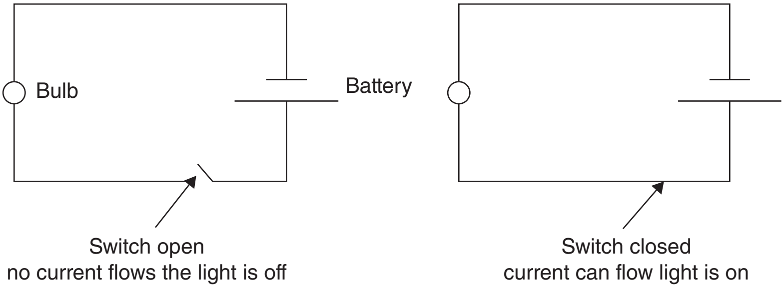

Figure 1.8 Open and closed circuits

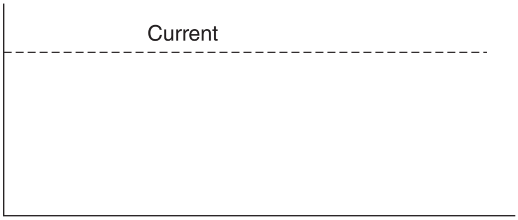

Figure 1.9 Direct current flow

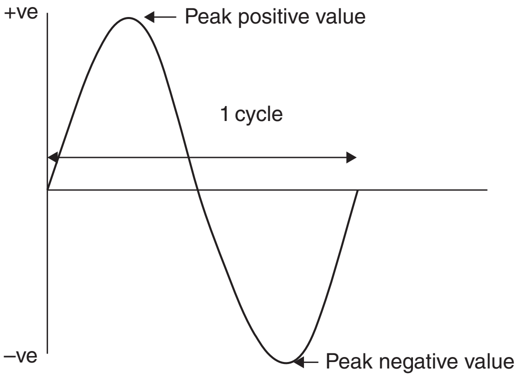

Figure 1.10 Alternating current flow

There are two ways in which electric current can flow in a circuit – there is direct current (DC) and alternating current (AC).

DC does not vary as it is the sort of current flow we get from a battery.

Seen in the form of a graph, DC looks like that shown in Figure 1.9.

With AC the movement effectively shuffles backwards and forwards as the voltage at each end of the connection changes constantly from positive to negative and back again (alternates between positive and negative).

Seen on a graph AC looks like that shown in Figure 1.10.

Both current and voltage follow this positive/negative pattern, but are not exactly the same shape.

The full progress of current and voltage from zero to positive peak down to negative peak and back to zero is called a cycle. Frequency is the number of times a supply goes through a full cycle in a second. The frequency of mains electricity in the United Kingdom is 50 Hz (that's 50 cycles per second).

This shunting backwards and forwards of electrons may seem like a waste of time, but sometimes it is not important for electrons to arrive at a particular point simply that they are moving because the movement of electrons in a conductor has a number of important effects.

Looking at the graph it is clear that as we look at the average value of voltage or current, it will be zero because they both spend exactly the same amount of time being positive and then negative.

The average value of voltage and current being zero makes it seem that no energy is used when passing an AC.

This however is not the case as to move the electrons; work still has to be done against the electrical resistance.

Electrical resistance tells us how easy or difficult it is to move current through a particular material or through a different sample of the same material. Many factors have an effect on the resistance, but discussion of these factors falls outside the scope of this text.

Rather than use average current or voltage to describe the effects within an electrical circuit, we use effective current and effective voltage.

The effective current or voltage in an alternating supply is that Direct Current or voltage which acting for the same period of time would result in the use of the same amount of energy as the alternating supply.

Effective current or voltage is also referred to as the root mean square (RMS) value.

The RMS value of both current and voltage is a little more than 70% (seven tenths) of the maximum peak value. We need to know this when calculating things like power (energy used) in a circuit. You will be pleased to know that this study will not include such calculations.

The knowledge we have so far of atoms, molecules, energy and electricity gives us most of what we need to know about how X-rays are produced for diagnostic purposes.