The science of nuclear energy

This item contains selected online content. It is for use alongside, not as a replacement for the module website, which is the primary study format and contains activities and resources that cannot be replicated in the printed versions.

Contents

Week 1: Into the atom

Introduction

Welcome to this free course, *The science of nuclear energy*.

In the following video, course authors Sam Smidt and Gemma Warriner introduce themselves and do some experiments with a Geiger counter to show radioactivity.

Video content is not available in this format.

In Week 1 you'll learn about the science behind nuclear energy. This learning will set you up for the rest of the course as you consider nuclear energy in context.

Before you start, The Open University would really appreciate a few minutes of your time to tell us about yourself and your expectations of the course. Your input will help to further improve the online learning experience. If you'd like to help, and if you haven't done so already, please fill in this optional survey.

1.1 The structure of atoms

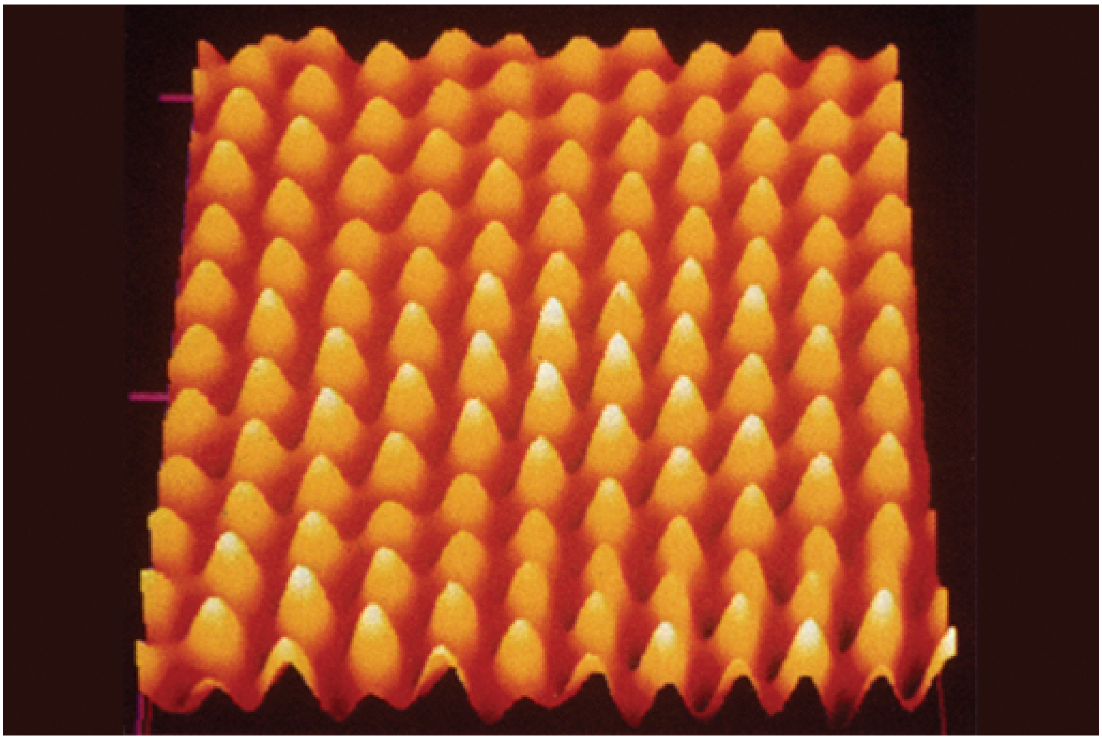


Figure 1 A layer of gold atoms on the surface of a crystal obtained by scanning tunnelling microscopy.

To gain a good understanding of the processes behind nuclear energy and radioactivity, you'll need first to consider the atom.

What are atoms?

If you look around you all the matter in the world is made up of very tiny building blocks called atoms.

Atoms are very small. The diameter of an average atom is a ten-billionth of a metre (or 10^{-10}m if you are familiar with scientific notation). This means that 10 million atoms would fit between a millimetre division on a ruler. It is only recently that technology has progressed enough to enable us to see atoms. Figure 1 was produced with a type of microscope that enables us to distinguish individual gold atoms.

Different types of atoms combine in a number of ways to form the varying substances of matter. You might think there would need to be a huge number of different sorts of atoms to account for all the substances that exist and that can be made, but in fact there are just 118 different types of atom that have been observed. These are known as the chemical elements and of those 118, only about 90 occur naturally. Each element is represented by a chemical symbol, consisting of one or two letters, for example, H is for hydrogen and He is helium. An element important in Week 2 is uranium (U).

What is inside an atom?

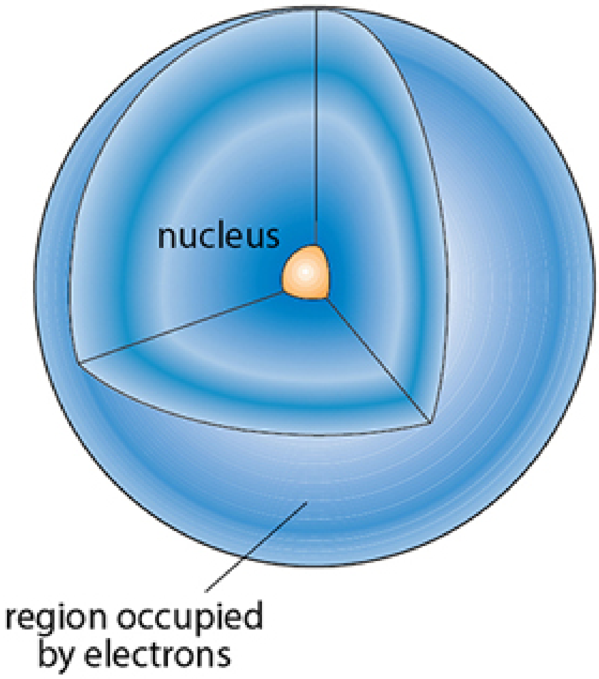


Figure 2 The inside of an atom.

At the centre of an atom is a nucleus. If the atom was the size of a football stadium the nucleus would be the size of an orange at the centre! The diameter of a nucleus is about one ten-thousandth of that of an atom (or 10^{-14}m). Pretty much all the matter in each atom is concentrated in this tiny volume and so nuclei are super dense and packed with energy. In this course we will be concerned with nuclei (NB nuclei is the plural of nucleus) and the release of this energy.

The nucleus itself is made up of smaller particles called protons and neutrons. These have similar (and very tiny) masses. The proton is positively charged and the neutron is neutral giving an overall positive charge to the nucleus. Protons and neutrons can be referred to collectively as nucleons.

The rest of the atom is taken up with the orbital electrons. These are much lighter than the proton or the neutron and are negatively charged, balancing out the positive charge of the nucleus.

What is an element?

Much of the matter around you is made up of compounds. Compounds are made up of molecules where there are two or more different atoms bonded together. Elements are made up of *just one type of atom*. You may be familiar with the periodic table which gives the full list of elements.

The number of protons in the nucleus of an atom is known as its atomic number and given the symbol Z. It is this number that determines the chemical element. Elements are defined by their chemistry, and chemistry is all about the interactions of the electrons of the atom, not the nuclei. The number of electrons in a neutral atom is always the same as the number of protons in its nucleus.

You may be wondering what role neutrons play and you'll find that out in the next section.

1.1.1 Isotopes

So, the properties of a given element are determined by the number of electrons and protons within its atoms.

The number of protons determines what the element is. For example, all atoms of carbon have six protons, and any atom containing six protons must be carbon.

What role do the neutrons play?

An element can have different forms wherein the atoms have the same number of protons but a different number of neutrons. These different forms are called isotopes. The number of neutrons in an atom can be worked out from the mass number given the symbol A. The mass number is equal to the number of protons in a nucleus plus the number of neutrons. So:

Mass number = number of neutrons + number of protons

A = number of neutrons + Z

Number of neutrons = A−Z

The number of neutrons in an isotope can be found from the difference between the mass number and the atomic number.

As a shorthand, isotopes of each element may be represented by using the following notation ${}^{A}_{Z}\mathrm{X}$. X is the symbol for the element itself and two numbers are used to indicate the atomic number (lower number, *Z*) and mass number (upper number, *A*).

So, a normal hydrogen atom is represented as ${}^{1}_{1}\mathrm{H}$ and an atom of a heavier isotope, deuterium, as ${}^{2}_{1}\mathrm{H}$. Isotopes of some other light atoms are shown in Figure 3.

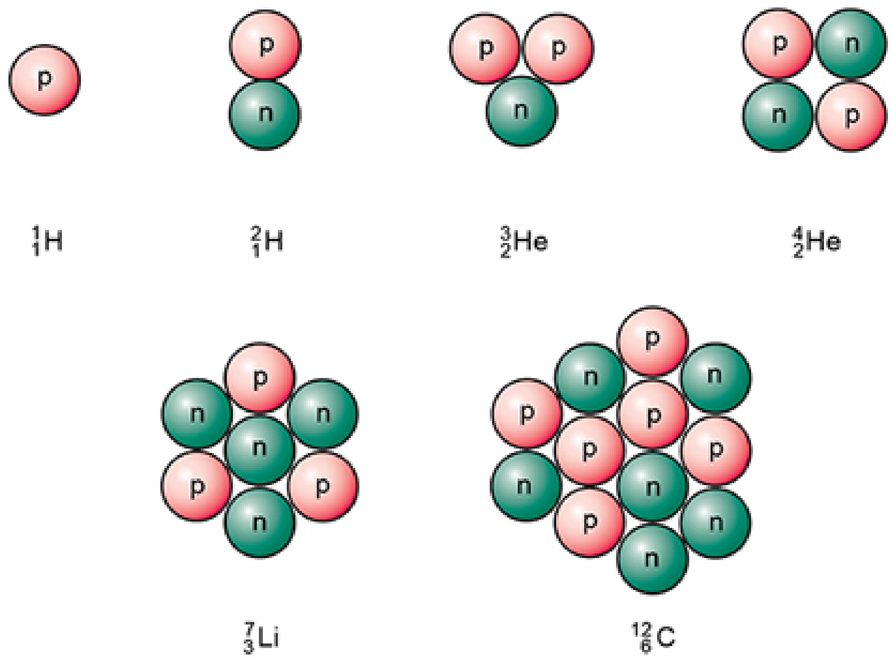


Figure 3 A schematic diagram of the nuclei of some isotopes.

An alternative notation is to use the name of the element followed by a hyphen and then the mass number. For example, helium would usually be denoted by helium-4, but the lighter isotope referred to above would be given as helium-3. These can also be abbreviated to just the chemical symbol and mass number, for example, He-4 and He-3.

In the next section, you will discover more about isotopes.

1.1.2 Common isotopes

Table 1 shows some of the isotopes of the eight lightest elements. Isotopes of the same element have the same atomic number but a different mass number.

Table 1 Common isotopes

Atomic number Z	Mass number A	Isotope name	Isotope symbol
1	1	hydrogen	${}^{1}_{1}\mathrm{H}$
1	2	deuterium	${}^{2}_{1}\mathrm{H}$
2	3	helium-3	${}^{3}_{2}\mathrm{He}$
2	4	helium-4	${}^{4}_{2}\mathrm{He}$
3	7	lithium-7	${}^{7}_{3}\mathrm{Li}$
4	7	beryllium-7 (unstable)	${}^{7}_{4}\mathrm{Be}$
4	8	beryllium-8 (unstable)	${}^{8}_{4}\mathrm{Be}$
4	9	beryllium-9	${}^{9}_{4}\mathrm{Be}$
5	11	boron-11	${}^{11}_{5}\mathrm{B}$
6	12	carbon-12	${}^{12}_{6}\mathrm{C}$
6	13	carbon-13	${}^{13}_{6}\mathrm{C}$
6	14	carbon-14 (unstable)	${}^{14}_{6}\mathrm{C}$
7	14	nitrogen-14	${}^{14}_{7}\mathrm{N}$
8	16	oxygen-16	${}^{16}_{8}\mathrm{O}$

Only the isotopes of hydrogen have their own names. All the H isotopes have one proton but hydrogen has no neutrons, deuterium has one neutron and tritium has two neutrons.

It is worth mentioning that protons and neutrons do themselves have an internal structure and are comprised of even smaller particles, known as quarks.

You will have noticed that some isotopes in the table are labelled unstable. You'll find out the reason for this later this week. Next, take a short quiz about what you've learned so far.

1.1.3 Structure of atoms

Test what you've learned about atoms so far in this short quiz.

Activity 1

Which of the following sentences describes a proton?

○ This particle has no charge and exists in the nucleus

This describes a neutron not a proton. Consider the nature of the other particles in the nucleus.

○ This particle has a positive charge and exists in the nucleus

Yes! The proton is positively charged. The nucleus is made up of positively charged protons and neutral neutrons.

○ This particle is in orbit around the nucleus

Electrons are in orbit around the nucleus, not protons. Consider the nature of the other particles in the nucleus.

○ This particle has a negative charge

Protons are not negatively charged. Consider the nature of the other particles in the nucleus.

Use Table 2 to work out which of the following particles make up an atom of carbon-13.

Table 2

Atomic number Z	Mass number A	Isotope name	Isotope symbol
1	1	hydrogen	${}^{1}_{1}\mathrm{H}$
1	2	deuterium	${}^{2}_{1}\mathrm{H}$
2	3	helium-3	${}^{3}_{2}\mathrm{He}$
2	4	helium-4	${}^{4}_{2}\mathrm{He}$
3	7	lithium-7	${}^{7}_{3}\mathrm{Li}$

4	7	beryllium-7 (unstable)	$^{7}_{4}Be$
4	8	beryllium-8 (unstable)	$^{8}_{4}Be$
4	9	beryllium-9	$^{9}_{4}Be$
5	11	boron-11	$^{11}_{5}B$
6	12	carbon-12	$^{12}_{6}C$
6	13	carbon-13	$^{13}_{6}C$
6	14	carbon-14 (unstable)	$^{14}_{6}C$
7	14	nitrogen-14	$^{14}_{7}N$
8	16	oxygen-16	$^{16}_{8}O$

○ 6 electrons, 6 protons, 6 neutrons
The number of protons and neutrons has to add up to 13 in carbon-13.
Take a look at Isotopes.
○ 6 electrons, 7 protons, 6 neutrons
The number of protons has to equal the number of electrons.
Take a look at Isotopes.
○ 6 electrons, 6 protons, 7 neutrons
Well done! The number of protons and neutrons add up to 13 to make carbon-13.
Take a look at Isotopes.
○ 7 electrons, 7 protons, 6 neutrons
Carbon has atomic number = 6. This is equal to the number of protons.
Take a look at Isotopes.

Using Table 3, what is the difference between an atom of beryllium-8 and beryllium-9?

Table 3

Atomic number Z	Mass number A	Isotope name	Isotope symbol
1	1	hydrogen	$^{1}_{1}H$
1	2	deuterium	$^{2}_{1}H$
2	3	helium-3	$^{3}_{2}He$

2	4	helium-4	${}^{4}_{2}\mathrm{He}$
3	7	lithium-7	${}^{7}_{3}\mathrm{Li}$
4	7	beryllium-7 (unstable)	${}^{7}_{4}\mathrm{Be}$
4	8	beryllium-8 (unstable)	${}^{8}_{4}\mathrm{Be}$
4	9	beryllium-9	${}^{9}_{4}\mathrm{Be}$
5	11	boron-11	${}^{11}_{5}\mathrm{B}$
6	12	carbon-12	${}^{12}_{6}\mathrm{C}$
6	13	carbon-13	${}^{13}_{6}\mathrm{C}$
6	14	carbon-14 (unstable)	${}^{14}_{6}\mathrm{C}$
7	14	nitrogen-14	${}^{14}_{7}\mathrm{N}$
8	16	oxygen-16	${}^{16}_{8}\mathrm{O}$

○ They are different isotopes of beryllium

Yes, the different numbers indicate they are different isotopes of beryllium.

Take a look at Isotopes.

○ They have different numbers of protons

All atoms of beryllium have the same number of protons in their nuclei. Think about what it is that the different numbers tell us.

Take a look at Isotopes.

○ They have the same number of neutrons

The different numbers (8 and 9) indicate differing numbers of neutrons. Think about what it is that the different numbers tell us.

Take a look at Isotopes.

○ They have different atomic numbers

All atoms of beryllium have the same atomic number in their nuclei. Think about what it is that the different numbers represent.

Take a look at Isotopes.

1.1.4 The nature of the nucleus

You have now learned about the particles that make up atoms, protons, neutrons and electrons.

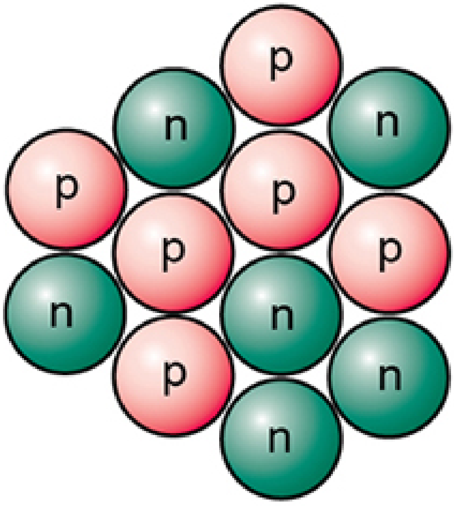
These are collectively termed subatomic particles and are summarised in Table 4.

Table 4 The constituents of atoms: subatomic particles

	Electric charge	Notes
Electron	−1 unit	In a neutral atom, number of electrons = number of protons
Nucleons		*Mass number* = number of nucleons
Proton	+1 unit	*Atomic number* = total number of protons
Neutron	0	Isotopes of the same elements have different numbers of neutrons

In the next sections you will find out how the nature of the nucleus and the nucleons within lead to radioactivity and the fission reactions that power nuclear reactors.

1.2 Radioactive atoms



$^{12}_{6}C$

Figure 4 A schematic diagram of the nucleus of the carbon-12 isotope.

What does it mean for an atom to be radioactive? What forces are at play within the nucleus?

Forces within the nucleus

Consider a nucleus of carbon-12 shown in Figure 4. It contains six positive protons and six neutral neutrons, crammed into an extremely small volume.

You may already know that like charges repel, this is an aspect of the electromagnetic force. Therefore, you would imagine that the positively charged protons would mutually repel each other and the nucleus would fly apart! The fact that nuclei hold together suggests the presence of another force within the nucleus that pulls the nucleons together. The force in question is the strong force. It is beyond the scope of this course to give a full explanation of the strong force, but the key idea for us is that it pulls nucleons together within the nucleus.

So, to summarise:

- There is a repulsive electromagnetic force within the nucleus that acts between protons.
- There is an attractive strong force within the nucleus that acts between both protons and neutrons.

Neutrons are necessary to hold the nucleus together. In Table 5, notice that as nuclei get bigger the ratio of neutrons to protons increases – the uranium nucleus needs significantly more neutrons than protons to hold together.

Table 5 The number of protons and neutrons within isotopes

Element	Isotope	Number of protons	Number of neutrons
carbon	${}^{12}_{6}\mathrm{C}$	6	6
calcium	${}^{40}_{20}\mathrm{Ca}$	20	20
zinc	${}^{65}_{30}\mathrm{Zn}$	30	35
iodine	${}^{127}_{53}\mathrm{I}$	53	74
uranium	${}^{238}_{92}\mathrm{U}$	92	146

Stability and instability

We can now visualise the nucleus as an energetic and dynamic environment; densely packed with two opposing forces acting on the particles within it.

Within many nuclei, the two forces reach an equilibrium. Such nuclei are able to hold together and are said to be stable. In other nuclei the interaction between the forces can make the nuclei unstable. To gain stability, the unstable nucleus will emit particles and energy, and such nuclei are called radioactive. When it emits a particle, the nucleus is said to decay.

Most elements within the periodic table have both stable and radioactive isotopes. For example, carbon-12 is stable while carbon-14 is radioactive. The stable form of each element tends to be the form that is most abundant. It is possible to quantify how radioactive an isotope is by how many particles are emitted in a given time – you will examine this later in the course when you'll consider half-life.

The emitted particles have enough energy to detach electrons from atoms or molecules that they interact with. This turns the neutral atoms or molecules into charged ions and hence the emitted particles are sometimes called ionising radiation.

Radioactivity and nuclear energy are not the same thing but they are linked – if it were possible to somehow get the energy without having to worry about the radioactivity, nuclear energy would be a lot less problematic! But the radioactive particles that are emitted mean that there are all sorts of problems associated with generating nuclear energy.

Radioactivity isn't new – it has been around longer than humans and has always been part of the environment. In fact, it is radioactive decay that provides the majority of the Earth's internal heat that causes volcanoes to erupt and drives plate tectonics. Radioactive materials are all around you!

Watch the video in the next section for some background to the discovery of radioactivity.

1.2.1 Radioactivity

Now watch the following video.

Video content is not available in this format.

Radioactivity was discovered in 1896 by Henri Becquerel who noticed that the radiation from uranium salts had similar characteristics to X-rays that had been discovered the previous year by Wilhelm Röntgen. The uranium salts emitted particles that reacted with photographic plates.

Over the following 20 years, Marie and Pierre Curie, Ernest Rutherford, and many others worked on identifying the different emissions called initially ‘uranic rays’. Marie Curie was working with a uranium ore called pitchblende, and managed to isolate two new elements within the pitchblende – polonium and radium. This was no mean feat as within a tonne of pitchblende there was less than a gramme of these new, highly radioactive elements.

It was discovered that radioactive materials emit particles of three distinct types and that these had differing masses and charges. These three types of emission were called alpha, beta and gamma particles.

You’ll look at these particles in the next section.

1.2.2 Alpha, beta and gamma radiation

The imbalance of forces within unstable nuclei leads to the emission of particles.

Here you’ll find out about three types of particle that can be emitted; α, β and γ or alpha, beta and gamma particles. Collectively they are often referred to as radiation from a radioactive substance.

Alpha particles

Alpha particles are the largest of the emitted particles and are positively charged. They are composed of two protons and two neutrons that are bonded together, which is the same as a helium-4 nucleus. This makes them the most massive of the types of radioactive emission.

The nucleus therefore loses two protons and becomes a different element!

For example, if ${}^{238}_{92}\mathrm{U}$ emits an **α** particle it will become ${}^{234}_{90}\mathrm{Th}$; uranium has transformed into thorium.

Alpha particles are easier to stop than other forms of radiation because they are bigger than the other forms and because they have a double positive charge (remember that a proton has a single positive charge). They can be stopped by a sheet of paper or by clothing. This is important because they cause a lot of damage if they interact with biological tissue. Even when they are travelling in air, their positive charge means that they attract electrons and quickly become nothing more than harmless helium.

Beta particles

Beta particles are negatively charged and turned out to be an electron ejected from a nucleus. They have a much lower mass than alpha particles. In neutral atoms, electrons exist outside the nucleus, and have a negative charge equal and opposite in magnitude to the positive charge on a proton.

In β-decay, a neutron inside a nucleus changes into a proton and emits an electron, that is the β-particle (another particle called an antineutrino is also emitted but it has no charge and almost no mass, and can be ignored in the present context).

In this case the initial nucleus has gained a proton and so again a new element may be formed. Note that the mass number doesn’t change as the number of nucleons is the same. The number of neutrons has reduced by one, and the number of protons has increased by one.

For example, if ${}^{137}_{55}\mathrm{Cs}$ emits a β particle it will become ${}^{137}_{56}\mathrm{Ba}$; caesium has transformed into barium.

A **β**-particle has more kinetic energy than a normal electron and carries a single negative charge. It’s harder to stop than an α-particle and can get through paper or clothing but is stopped by denser materials such as water or aluminium. Once they are stopped, the β-particles simply become part of the material they are in, like any other electron.

Gamma particles

Gamma rays are high-energy electromagnetic radiation emitted by radioactive elements. They possess energy but no mass. The electromagnetic spectrum, shown in Figure 5, is the range of all possible energies of electromagnetic radiation. A photon can be defined as the basic unit, or elementary particle, of electromagnetic radiation. Like visible light, a γ-ray is just energy but a γ-photon has more energy than a photon of visible light or even of X-rays.

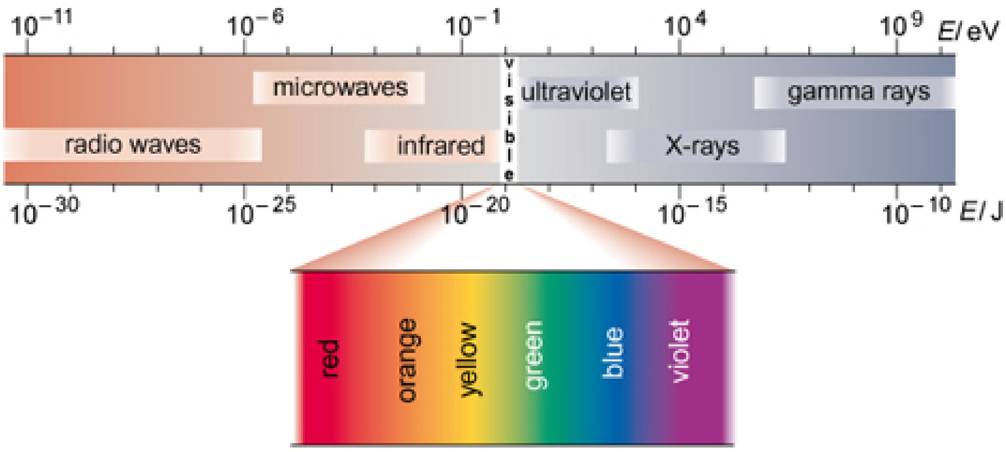


Figure 5 The electromagnetic spectrum (the energy scale is given in two units; both the electronvolt (eV) and the joule (J) are explained later).

Unlike α or β radiation, loss of a γ particle does not change the composition of the nucleus, although it does lose energy. Gamma emission usually occurs together with α- or β-emission and it is rare to get gamma rays emitted on their own.

Because they have no mass or charge and high energy, γ-rays are more difficult to stop than β- or α-particles and it takes dense materials such as lead, or concrete, to absorb their energy and stop them. This is an issue you'll consider in Week 2 when you'll hear about the storage of radioactive waste.

All three types of radiation can damage human cells and this damage can lead to cancers developing in the area affected. All three types of radiation can be detected by a Geiger counter.

Next, you will find out where radiation is found.

1.2.3 Doses of radiation

Radioactive materials are all around you. They are in the air that you breathe and the food that you eat. They are in the materials with which we build our houses and the rocks in the ground.

You are radioactive yourself! Radioactive carbon-14 is decaying within you, as is potassium-40.

This means that we are subject to a constant bombardment of alpha, beta and gamma particles. This is called background radiation. There is no avoiding background radiation and we have evolved within it. The amount of background radiation that we experience is generally so low that it is highly unlikely to do us any harm.

The amount of background radiation at a given place is called the background count. This is due, mainly, to the radioactive elements in the sources. The amount of radiation you experience is called the dose of radiation and is based on both the radiation present and on you and the tissue (bones, organs) involved; the unit is the mSv (milliSievert). The average annual dose from background radiation in the UK is 2.7mSv.

If the radiation locally is raised above the background count then you may receive a bigger dose. For instance, some medical procedures involve the use of radiation and flying increases your exposure to cosmic rays. Cosmic rays are composed of radiation from the Sun and other stars.

In the activity below, you'll find eight activities that would expose you to radiation. Decide which you think would give you the highest annual dose of radiation and sort the items from highest to lowest by dragging the names up and down the list. The computer will tell you when you've got it right, and will offer you help after you've made a certain number of moves.

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1.2.4 Precise doses of radiation

Figure 6

How did you get on with the ordering activity in the previous section? Were you surprised with the results?

The measures were:

- smoking every day (13mSv)
- one chest CT scan (12mSv)
- cooking with natural gas (10mSv)
- living in Cornwall (7.8mSv)
- working for an airline (3 to 9mSv)
- working in nuclear power (0.18mSv)
- eating a banana a day (0.036mSv)
- one dental X-ray (0.014mSv).

In the next section, discover uses for radioactivity.

1.2.5 Some uses of radioactivity

The radioactive nature of some isotopes and the emission of particles can be put to good use.

Four examples are given below but there are many more applications. You will be shown more in the activity at the end of the week – Isotope trumps!

Figure 7

Americium-241

Americium-241 is used in smoke detectors. It is an alpha emitter and the alpha particles ionise the air molecules in a chamber open to the air, so that the air molecules now carry a charge. The charged ions allow a tiny current to flow. If smoke particles enter the chamber this current is disrupted and an alarm sounds.

Carbon-14

Figure 8

Carbon exists in the organic molecules that make up the cells of living organisms and some of this carbon will be radioactive carbon-14, a beta emitter.

Plants can fix carbon from the air so that the amount of carbon-14 in living organisms is roughly constant throughout their lifetime and reflects the amount of C-14 in the atmosphere at the time. Once an organism dies, the C-14 will start to decay – the rate of this decay is known.

If you measure the amount of C-14 in a sample today it is possible to trace back and work out how old the sample is. This has been very useful in archaeology and palaeontology.

Iodine-131

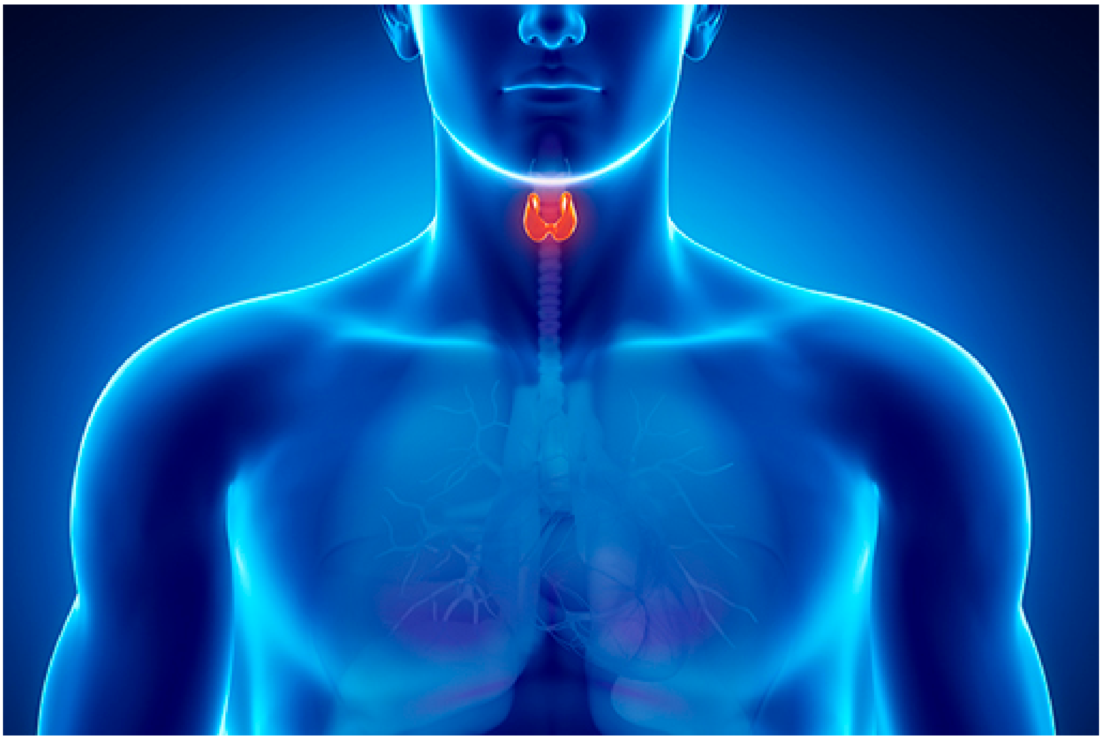

Figure 9

Iodine-131 emits beta and gamma radiation and can be used to treat thyroid problems, such as thyroid cancer or an overactive thyroid, where treatment requires destruction of some of the cells within the thyroid.

When a capsule of I-131 is swallowed, it is absorbed into the bloodstream before concentrating in the thyroid gland. The radiation from the I-131 will destroy the cells locally – which, in this case, is the desired effect.

Technetium-99

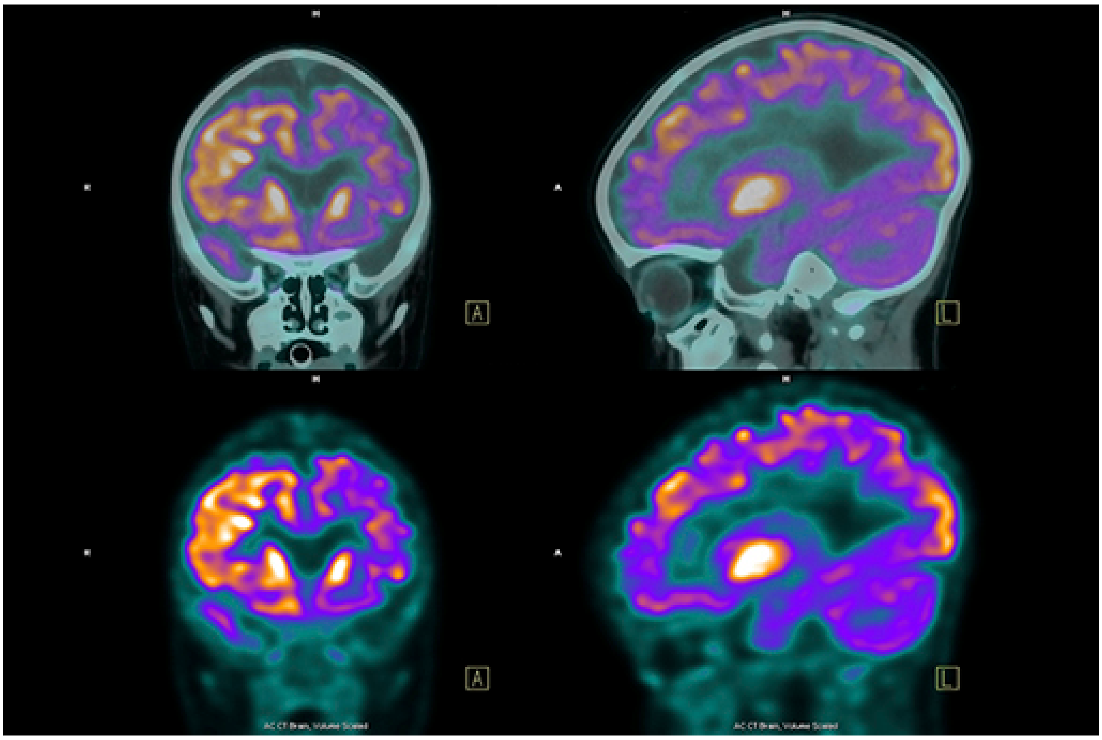

Figure 10

If technetium-99 is introduced into the body it can be used as a tracer. For example, it can show the blood flow through the heart or the brain. The Tc-99 will flow with the blood and emit gamma radiation that can be detected and imaged. This can build up a picture of how the blood is flowing and into what areas. The Tc-99 decays at a good rate for this use and only lasts in the body for a day, with a very low risk of damage.

Tc-99 is produced from the decay of molybdenum-99. In turn, this Mo-99 is usually created commercially by fission of uranium in nuclear reactors. It is a fission product, and these are discussed in the next section.

1.2.6 Myths of radiation

Watch the following video.

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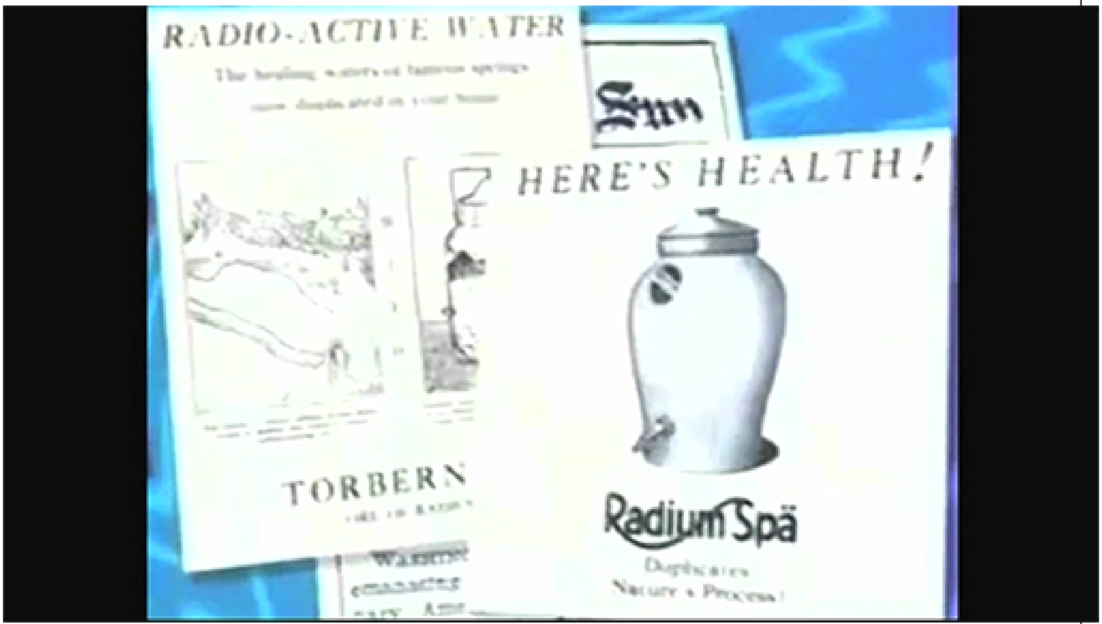

Radium was discovered by Marie and Pierre Curie at the end of the nineteenth century and was one of the first radioactive elements to be identified.

While scientists endeavoured to understand the nature of radioactivity, some were quick to capitalise on its perceived properties. Radium was a brand new element unlike any that had been seen before and seemed to have near magical properties.

Many of these inventions seem bizarre to us today! We have come a long way in our understanding but misconceptions still swirl around radioactivity nowadays.

You’ll have a chance to consider the public perception of radioactivity in the next section.

1.2.7 Ideas about radioactivity

Figure 11

Many bold claims were made in the video about the health benefits of contact with radioactive materials.

In the intervening years the scientific community has learned much about radioactivity, but not all of these ideas are well understood by the wider community.

Activity 2

Consider the following questions:

- Can you contrast the attitude to radioactivity a hundred years ago to our attitude today?
- Do you think that people are better informed today?

Provide your answer...

1.3 Nuclear processes

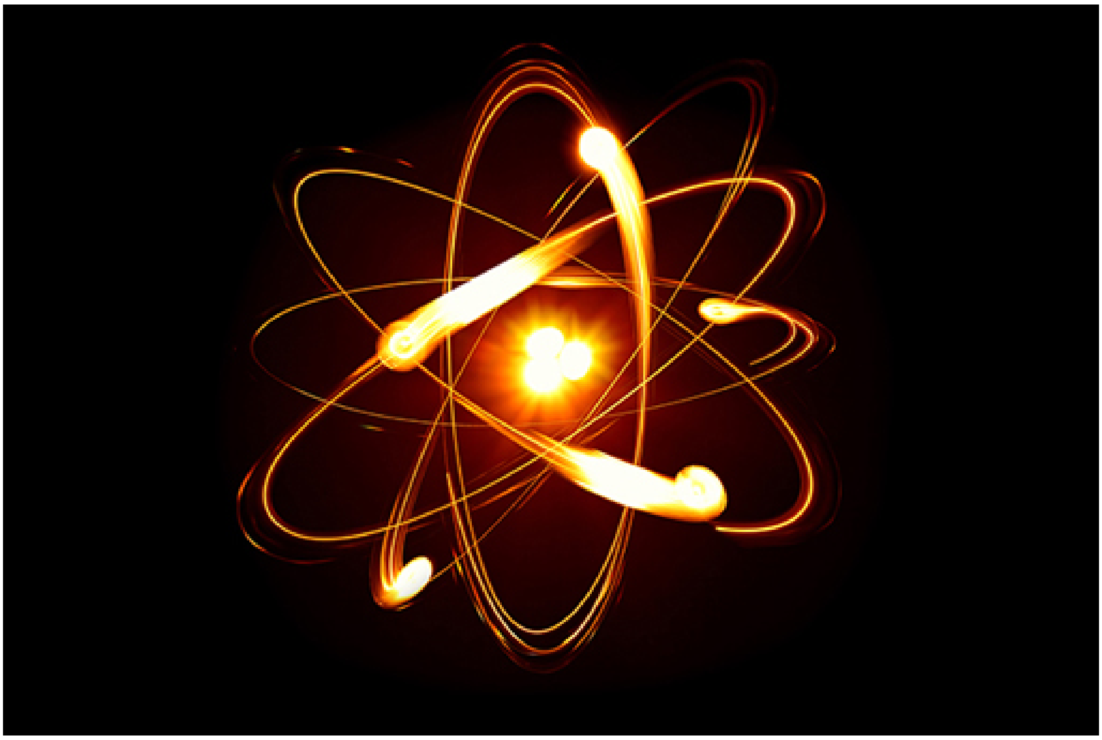

Figure 12

So far, you have looked inside the nucleus and determined its composition. You have learned that the composition of the nucleus and the forces at play can lead to instability and emission of particles.

In fact, something even more dramatic can happen to the largest nuclei such as uranium and plutonium. They can split apart into smaller fragments and release energy as they do so. This process is called **fission** and is the basis of the current nuclear industry.

In the next sections, you will learn about the process of fission and how it may be induced. There is another process where smaller nuclei can bind together called **fusion**. You will come back to fusion during Week 4.

1.3.1 Uranium

Figure 13

Since uranium is an element that you are going to learn more about, it is worth spending a little time now outlining its properties.

Uranium is a naturally occurring element found mainly in small quantities everywhere on Earth. Uranium has played a vital role in the evolution of the Earth. Its natural radioactivity is believed to have provided the heat source powering such processes as plate tectonics and the maintenance of the Earth's molten core. It is likely that without the energy released by radioactive decay, the Earth would have cooled long ago causing it to have a Mars-like environment. Indeed, without uranium it is probable that there would be no life on Earth as the core would have cooled to a point where the Earth's magnetic field would have collapsed, allowing the solar wind to strip away the atmosphere and the oceans.

Uranium is the main fuel used in nuclear reactors. Natural uranium has three isotopes: uranium-238, uranium-235 and uranium-234. All of the isotopes are radioactive and so are sometimes called **radioisotopes** or **radionuclides**. Uranium-238 forms about 99.3% of all natural uranium, with uranium-235 forming around 0.7% and uranium-234 just 0.0055%, so U-238 is by far the most common uranium isotope.

The properties of the U-235 were crucial to the development of nuclear energy and we are concerned with this particular isotope in this course.

1.3.2 Isotope trumps!

Fancy a hand of cards? Have a go at our Isotope trumps game!

We've placed the same five attributes (proton number, neutron number, half-life, the speed of the emitted particle and the energy of the emitted particle) for a number of isotopes for you to compare.

Half-life will be explained more fully next week but consider it as a measure of how rapidly an atom decays. A short half-life means that it decays very quickly and a long half-life indicates a slower decay.

You win a turn by choosing an attribute that has a higher value than on the card held by your opponent, the computer. You can choose how smart the computer is. Normally, whoever wins a turn plays first in the next turn, but you can give yourself an extra advantage by forcing the computer to always play second.

You will need to take an ‘educated guess’ in many cases. We hope this will improve your feel for the nature and uses of many different isotopes. When you’ve had enough, move on to the next section. You can come back any time you like and try to beat the computer as your knowledge grows.

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1.3.3 What is fission?

Fission is the splitting of large nuclei into smaller nuclei with the release of energy. Spontaneous fission is rare and generally fission is induced by bombarding the heavy nucleus with neutrons.

In the late 1930s it became evident that bombardment of uranium-235 by neutrons could lead to fission. The U-235 nucleus is able to absorb the neutron to become (very briefly) U-236. The U-236 then undergoes fission to form two new nuclei called **fission products**.

Fission also produces neutrons and *energy*. Neutron induced fission is illustrated in Figure 14. Bombarding the uranium-235 nucleus with a neutron leads to the formation of a uranium-236 nucleus, which very quickly undergoes fission. Fission products are formed, and neutrons are emitted. Note that gamma radiation is also emitted.

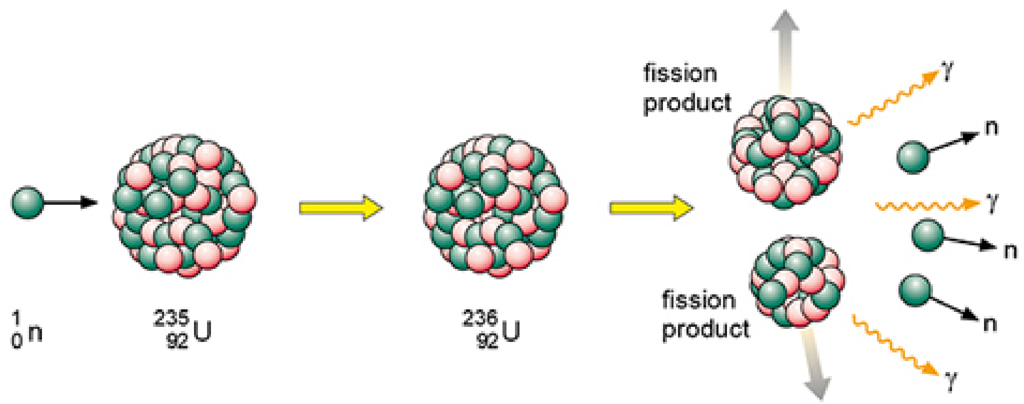

Figure 14 The particles and types of radiation involved in fission

Neutrons are shown as $^{1}_{0}\mathrm{n}$ using the same notation as for isotopes. The fission products themselves can vary but examples would be xenon-140 and strontium-93. An equation representing this particular fission would be:

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{93}_{38}\mathrm{Sr} + 3{}^{1}_{0}\mathrm{n}$$

In words this would be: ‘A uranium-235 atom absorbs a neutron to become uranium-236 which then undergoes fission to form the products xenon-140 and strontium-93 with three neutrons.’

Some important points to note:

- Fission products tend to be radioactive. These by-products of nuclear power form the majority of the radioactive waste that we will consider next week.
- The fact that neutrons are also produced means that these neutrons can go on to induce further fissions. Once started, fission can become self-sustaining – this is called a chain reaction.
- For fission to occur the neutrons must be going at the right speed – too fast and they will bounce off rather than be absorbed. The neutrons may need to be slowed down and are then referred to as thermal neutrons. Both the number and speed of the neutrons is crucial within a working reactor.
- The energy released per fission is relatively large. It is 50 million times more energy than burning the equivalent amount of carbon. We will consider where the energy comes from in the next section.

While uranium-235 is the isotope that undergoes fission it is worth noting that uranium-238 atoms can absorb neutrons to become plutonium-239 which is another atom that can undergo fission.

1.3.4 The chain reaction

A fission chain reaction can proceed without intervention, as the free neutrons created by one fission event go on to trigger the next fission event.

As two or three neutrons are produced by each fission event, it is easy to see that a chain reaction could get out of hand and ‘runaway’, producing too much energy too quickly.

Terminology

- **Criticality:** the number of fission events is steady and the chain reaction releases a steady amount of energy.
- **Sub-critical:** the number of fission events decreases and the chain reaction releases progressively less energy.
- **Super-critical:** the number of fission events increases and the chain reaction releases progressively more energy.

In Figure 15, the left image shows a mass that is too small to sustain a chain reaction, as too high a proportion of neutrons escape by passing out of the mass. The right image shows that increasing the mass to the ‘critical mass’ causes a higher proportion of neutrons to stay within the volume long enough to induce further fissions.

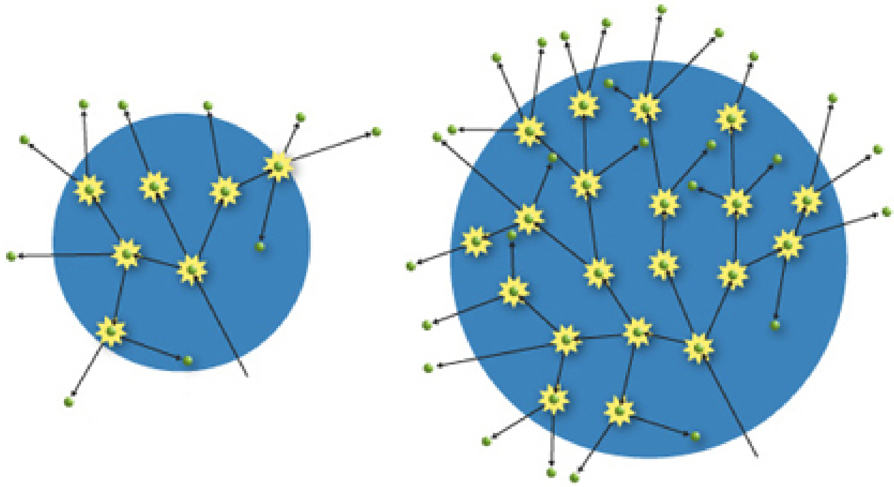

Figure 15 On the left, a mass too small to sustain a chain reaction; on the right, increasing the mass to 'critical mass' has enabled further fissions

As you will discover, the requirement in a nuclear power station is to maintain the reaction at, or close to, criticality. If it is sub-critical, the fission reaction will gradually reduce; if super-critical the reaction could run out of control.

In order for a fission reaction to go 'critical' it needs a critical mass of uranium. Effectively, the important property is size rather than mass and the fact that small objects have a greater surface area to volume ratio. If the amount of uranium-235 is too small the neutrons will escape from the surface and the chain reaction will peter out.

1.3.5 Energy from fission

Nuclear power is based on the energy that is released each time a uranium nucleus undergoes fission.

Energy and mass

In nuclear reactions, the energy released can be understood from Einstein's most famous equation:

$E = mc^2$

Here E is energy; m is mass and c the speed of light.

This shows that there is a clear equivalent relationship between mass (m) and energy (E). The speed of light is shown as c and it is has a large value. Light travels at 300 million ms $^{-1}$. In fact, the speed of light is squared in the equation giving an even bigger number, 90 million billion! (The units of this would be $(\text{ms}^{-1})^2$ but we don't need to worry about this.) Suffice to say, to work out the amount of energy bound up in a mass we multiply the mass by a huge number – a small mass converts into a very large energy.

This equation holds true if you can convert mass into pure energy – although this is easier said than done! One place that this conversion takes place is within the nucleus, so if we can master nuclear reactions we can tap into this energy.

Binding energy

Imagine you had a marble and knew its mass was 5g. If you then received a bag of 20 identical marbles and were asked the total mass of these marbles you may reason that it is 20 × 5g = 100g. And you would be correct!

Mass of 20 marbles = 20 × mass of one marble

Now imagine you had a nucleon and knew it was a certain mass m (protons and neutrons have pretty much the same mass) and you were then asked the mass of a nucleus containing 20 nucleons. You may reason, as before, that its mass would be $20m$. But in fact the mass of the nucleus would be less than this – the mass of the nucleus is less than the mass of the constituent parts! This is represented in Figure 16.

Mass of a nucleus containing 20 nucleons < 20 × mass of one nucleon

The *difference* in mass is called the mass defect.

Mass defect = Mass of separate nucleons − Mass of nucleus

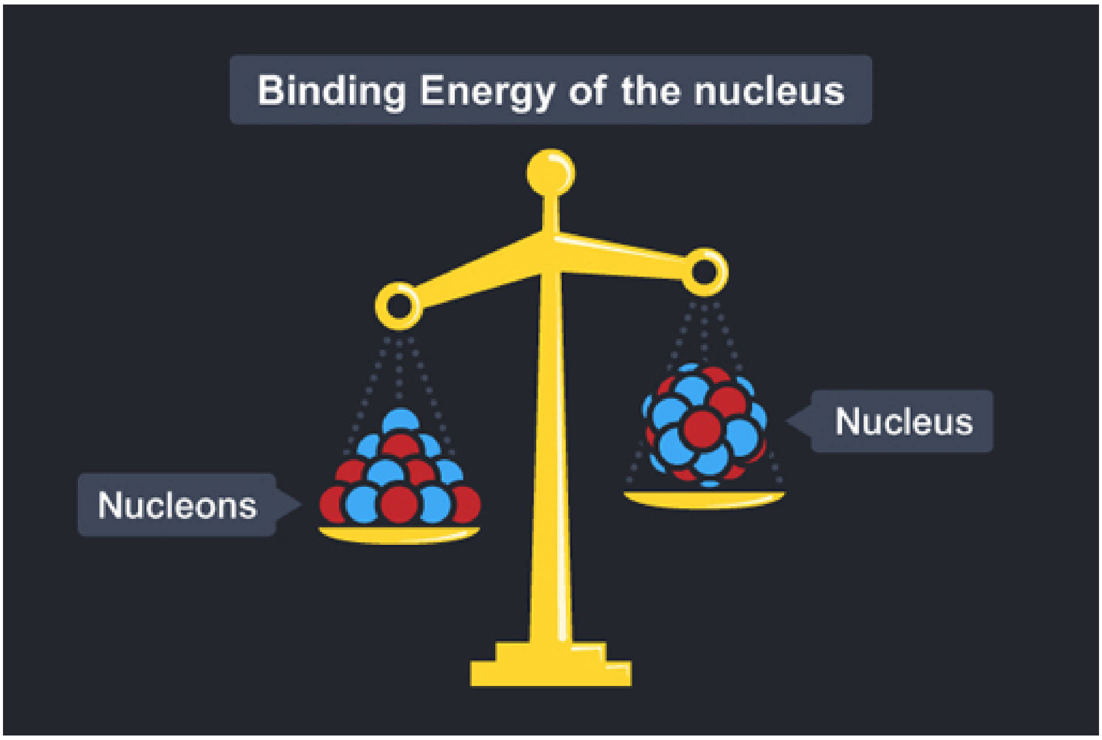

Figure 16

Where has the missing mass gone? It has been converted into energy – this is called the binding energy of the nucleus. The binding energy is associated with the forces that bind the nucleus together.

From $E = mc^2$

Binding energy = mass defect × c^2

Different nuclei have differing amounts of binding energy. In fission, a large nuclei is split into smaller parts. The total mass of these parts may be lower than the initial large nucleus. This difference in mass is due to the difference in binding energy between the nuclei and is released as energy.

Energy from fission

$${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{93}_{38}\mathrm{Sr} + 3{}^{1}_{0}\mathrm{n}$$

The mass of the fission products and the three neutrons is less than of the U-236, although the number of nucleons is the same. This missing mass is released as energy – generally taken away by the fission products, the neutron and the gamma radiation.

The energy released from one fission is small but with many nuclei, the energy adds up to far exceed the amount from the equivalent chemical reactions. The fission of 1kg uranium provides a million times more energy than the burning of 1kg of coal. Fission can provide a great deal of heat energy.

It was this knowledge, before the ability to harness this energy had been developed, that led nuclear physicist Leo Szilard, in 1934, to speculate about planned experiments that, if successful, would lead to:

Power production … on such a large scale and probably with so little cost that a sort of industrial revolution could be expected; it appears doubtful for instance whether coal mining or oil production could survive after a couple of years.

(Quoted in Weart and Szilard, 1978, p. 39)

Next week, you will be learning more about the use of fission as an energy source to generate electricity.

In the next section is a video outlining the development of working nuclear reactors.

1.3.6 The early days of fission

The following video outlines the early days of induced fission and the development of nuclear reactors based on induced fission.

The timeline of development is:

- In 1948 and 1951, electricity was first generated by a nuclear reactor in the US in two experiments.
- In June 1954, the Soviet of City of Obninsk opened the world's first nuclear power plant to generate electricity for a power grid.
- In October 1956, the first full scale nuclear power station opened at Calder Hall in Cumbria, England.

Video content is not available in this format.

Next week, you will be examining nuclear power stations, how they function and some of the problems associated with them.

1.4 Quiz for Week 1

Now take the quiz for this week, which allows you to test and apply your knowledge of the material in Week 1.

Week 1 quiz

Open the quiz in a new window or tab and return here when you have finished.

1.5 Summary of Week 1

In this week, you have examined the science behind nuclear energy. You’ve learned that atoms are made up of a much smaller nucleus with electrons in orbit around it. The nucleus contains positively charged protons and neutral neutrons, collectively known as nucleons.

The same elements contain atoms that always have the same number of protons within them but can have differing numbers of neutrons. These different forms are called isotopes.

The interplay of forces within a nucleus leads to some isotopes being stable while others are unstable. Unstable nuclei emit particles to gain stability and are called radioactive. Alpha, beta and gamma radiation can be emitted from radioactive substances.

Radiation is all around us and is measured by the background count. The radioactive nature of some elements is put to good use.

Some heavy isotopes (such as uranium-235) can undergo fission. Fission involves the nucleus splitting into smaller nuclei and releasing energy. The products from fission are very radioactive and must therefore be disposed of with care.

In Week 2, you will examine how the energy from fission can be harnessed into a workable energy resource that can be used to generate electricity. You will look at the National Grid and the components of a nuclear power station.

One of the most contentious issues surrounding nuclear power is that of nuclear waste. You will look at the different types of nuclear waste and current ideas on how to deal with it.

You can now go to Week 2.

Week 2: Using nuclear energy

Introduction

In the following video, Sam and Gemma discuss our energy needs, where our power comes from and how it is delivered.

Video content is not available in this format.

In the next section, you will find out about the principle of the conservation of energy.

2.1 Energy and power

Figure 1

One of the most fundamental principles in physics is that of the conservation of energy.

This means that in any process energy cannot be created or destroyed; it can only be transformed from one form into another. The total amount of energy is therefore said to be conserved.

This might or might not be a familiar concept to you, but here are a couple of examples to help explain it.

- Chemical energy stored in food is transformed when you digest what you eat into a form of energy that your body can use as 'fuel'.
- Solar energy, from the Sun, is used in photosynthesis by plants to create chemical energy that enables the plants to grow and to perhaps produce food for the previous process!

The standard unit that energy is measured in is the joule (J). To get an idea of the size of the joule, look at these examples:

- energy content of a cereal bar: 800,000J
- energy stored in an AA battery: 9000J
- energy required to climb a flight of stairs: 3000J.

These are rough values and may vary a bit in reality, but they can give a general idea. In this course, you'll be concerned with the transfer of nuclear energy into heat energy and then to electrical energy.

Power is the *rate* at which energy is transferred. For example, an electric fire transfers energy in the form of heat to its surroundings.

Energy can be related to power and time by the equation:

energy = power × time

power = energy/time

A watt (W) is the unit of power and it corresponds to an energy transfer of 1 joule per second. Many domestic appliances have their power given in thousands of watts, or kilowatts (kW), and electricity power stations normally have their outputs rated in millions of watts, that is, in megawatts (MW). The energy requirement for the UK as a whole is often given in gigawatt (GW). Each gigawatt is 1 billion (1 000 000 000) watts.

Appliances around your home will have power ratings on them which indicate how many joules of energy they transform every second.

For example, an average kettle is rated at 3kW. That means that it uses 3000J every second it takes to heat up and boil water. To make one cup of tea, the amount of water needed takes one minute to boil.

So using:

$$\text{energy} = \text{power} \times \text{time}$$
$$\text{energy} = 3000\text{W} \times 60\text{s}$$
$$= 180,000\text{J}$$

It takes 180,000J of energy to make a cup of tea. This is equivalent to the energy required to climb 60 flights of stairs!

When you plug in a kettle, this 180,000J is provided by the electrical energy supplied from the National Grid. Modern life requires a great deal of electrical energy to be produced and it is sometimes difficult to get a tangible idea of how much energy this is.

In the next section, you will be asked to estimate the energy requirements of appliances found around the home.

2.1.1 What uses most energy in the home?

Most of us are aware of the need to be careful of how much energy we use in our homes.

Do you know which electric appliance would use the most energy if it was switched on for an hour?

Have a look at the power rating on some of your own appliances then see if you can put the list of domestic appliances in order. Put those using the most energy at the top by dragging the names up and down the list. The computer will tell you when you’ve got it right, and will offer you help after you’ve made a certain number of moves.

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In the next section, you will watch an experiment where human cyclists were used to provide the electrical energy to run a house.

2.1.2 Human power station

In the following clip, *Bang goes the Theory* demonstrates how much electricity we use without even thinking about it.

Video content is not available in this format.

In the experiment, cyclists were used to provide the electrical energy to run a house. When Bradley Wiggins broke the hour record recently, his average power over the hour was 400W.

In the next section, you'll think about where the energy in the video came from.

2.1.3 Generating electricity

Figure 2 Pylons taking electricity away from the Sizewell A and B nuclear power stations

From the human power station video, it is apparent how much energy is required for one short power shower!

The shower is 8kW which means that 8000J of energy is required every second.

Chemical energy within the cyclists themselves is being converted into the kinetic (or moving) energy of the pedals. It is then converted to electrical energy via dynamos in the bicycles. In a dynamo, a magnet is rotated within some coils of wire and the changing magnetic field induces a current within the wire and electricity is produced.

Electricity production within power stations is on a much larger scale, but is based on the same essential principle as the dynamo. Rather than pedals, a turbine is spun and this in turn spins a magnet. Again, the changing magnetic field induces a current within the wire – this is the origin of the electricity you use within your home.

All the electrical appliances in your home need an input of electrical energy to work. For the most part we get this electrical energy from the National Grid and its network of pylons and generators maintaining the flow of electricity around the country.

Figure 3 A steam turbine with the case opened revealing the turbine blades

The electricity is produced in power stations. Most power stations (but not all) employ similar processes. They use fuel to heat water to produce steam under pressure. The steam is then used to turn the blades of a turbine (in Figure 3), causing the central shaft to rotate. This in turn rotates a generator, which produces electrical power.

Next, find out about the different fuels used.

2.1.4 Energy sources

Power stations use different resources to produce energy. Each method has environmental and technical issues associated with its use.

Some sources of energy, such as nuclear and fossil fuels, are finite and will run out at some point in the future. The finite nature of fossil fuels in particular will be examined further in Week 4. Other sources are renewable and are naturally replenished on a small enough timescale to be useful to us. These sources include solar, wind, hydroelectric and geothermal. You'll consider both types of energy source below.

Fossil fuels

The majority of the power stations in the UK use fossil fuels. They create steam from the heat produced from burning coal or gas.

The remains of living organisms, plants and animals, buried and compressed over millions of years, have formed the fossil fuels, coal, oil and natural gas. Plants absorb solar radiation and use it in a process called photosynthesis to produce new plant material.

The issues associated with the burning of fossil fuels will be discussed further in Week 4.

Nuclear

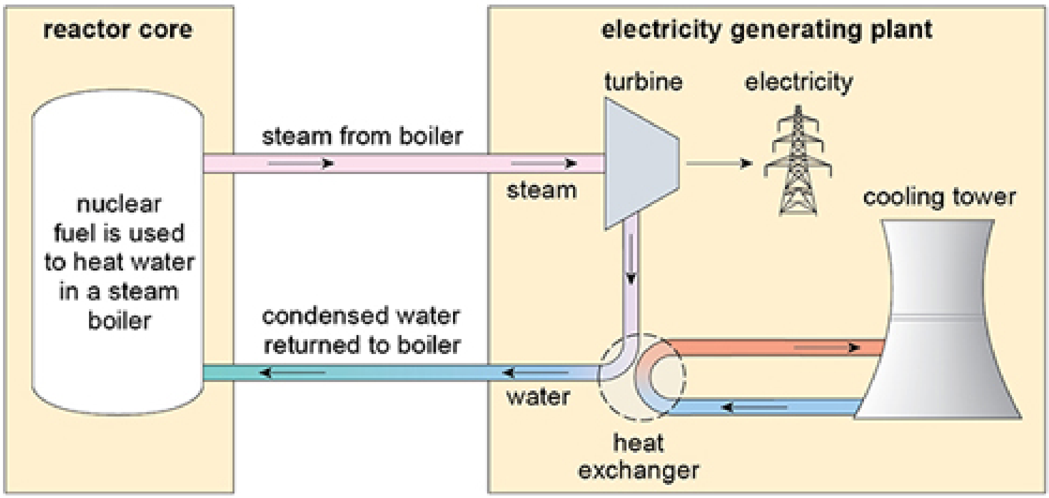

Figure 4 The basic design of a nuclear power station

The fission of uranium or other heavy elements produces a great deal more energy than fossil fuels but needs additional safeguards. However, the basic structure of the power stations is very similar. The use of fission will be discussed more fully later this week. A schematic diagram of a nuclear power station is shown in Figure 4.

Biofuel

Organic materials, collectively called biofuel, can be used to generate electricity. Biofuel can be obtained directly from plant material, such as peat and wood, or indirectly from agricultural, commercial, domestic and industrial waste.

It can be burned directly, in the same way as fossil fuels in a power station, or used to produce gas (biogas) that can then be burned. It is generally used in vehicles and not in power stations.

There are problems surrounding the technology, economics and the environmental impact of biofuel. Nonetheless, the constructive use made of waste material makes this a worthwhile field to develop.

Wind power

Figure 5 Wind turbines

The rotation of the blades in windmills harness kinetic energy from the wind and so wind farms are able to produce electrical energy. Clearly, the position of the windmills is an important consideration. They can be installed both onshore and offshore.

Single wind turbines generate in the order of 2.5 MW of electricity – enough to power the needs of over a thousand households. In 2015, it was the most productive of the UK's renewable energy resources.

Hydroelectric and wave power

Figure 6 The Hoover Dam in Nevada

Most hydroelectric power comes from dammed water being allowed to fall and then turn a turbine. The falling water loses gravitational energy and this is converted to kinetic energy of the turbine. It is the most widely used form of renewable energy but the damming of rivers can have huge impact to those communities situated downstream.

There are plans to harness ocean wave power to generate electricity, but this is proving difficult to do on a commercial basis. Waves, of course, are also produced largely by wind. Tidal power can be obtained from barrages built across estuaries.

Solar energy

Solar energy is the ultimate source of nearly all the energy sources! Solar energy can be harnessed directly via the use of photovoltaic cells which produce electricity. There have been great advances in the efficiency of photovoltaic cells in recent years.

Solar energy can also be used to heat water directly, replacing the need for heating by gas or electricity derived from other sources.

Geothermal power

Another source of electricity is hydrothermal power, which usually depends on water being pumped down into the ground, heated by hot rocks deep below the surface and the steam produced is then used to run turbines.

In Iceland, the Svartsengi geothermal power station uses naturally occurring hot water (at about 90 °C), which gushes to the surface of the volcanically active island at a rate of over 400 litres per second. The steam from this hot water is used to run turbines. Access to geothermal energy is only possible in a tectonically favourable setting so not all countries can use this source of energy.

The job of those running the National Grid in the UK is to utilise these different energy sources to provide electrical power to all our homes and businesses.

In the next section you will find out about how the National Grid runs.

2.1.5 Running the National Grid

Maggie Philbin spends the morning in one of Britain's most secret locations, the control room of the National Grid where she monitors our demand for electricity with supply.

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In the next section, you will look in more detail at where the UK's power stations are sited.

2.1.6 The National Grid

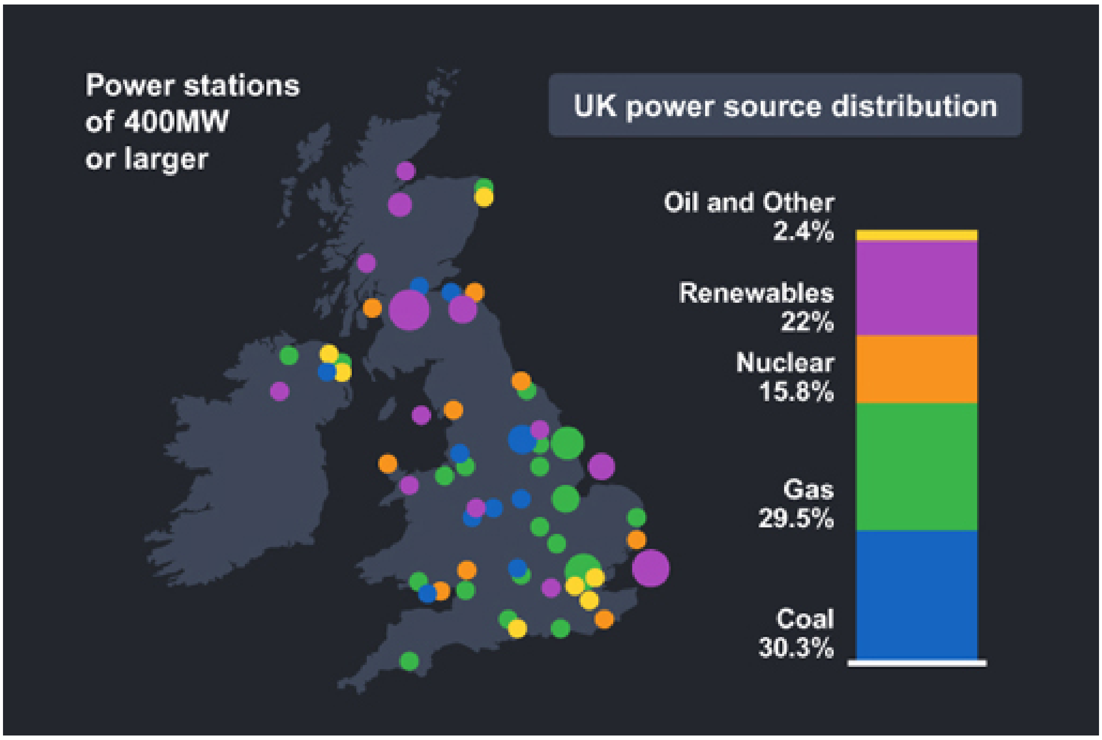

Figure 7 The UK's power stations

As you saw in the video in the previous section, the majority of power stations in the UK use fossil fuels – oil and gas – as their energy source. In Week 4 you will consider the implications of these fossil fuels running out.

The video mentioned Ironbridge and West Burton power stations, which are coal fired and gas fired respectively. Figure 7 shows the distribution of the different power sources across the UK.

After fossil fuels, nuclear and renewable sources contribute roughly equal amounts to the National Grid.

In the next section, check out what the National Grid is doing right now.

2.1.7 Peak output

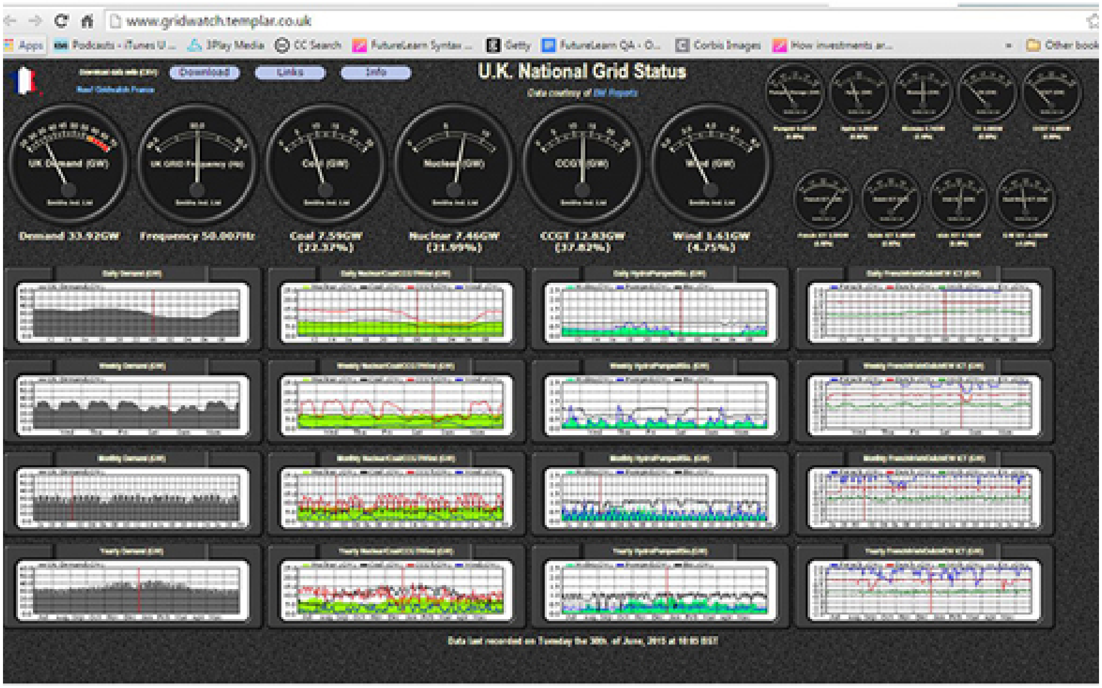

Figure 8 The National Grid

The UK’s National Grid provides information about its status right now on their website. There is a great deal of information on this page and it is updated every ten minutes!

In Activity 1, you are asked to visit the page and gather information.

Activity 1

You will see the total demand in GW or gigawatt. One gigawatt is 1 billion watts. The dials along the top show the proportion from the different energy sources. You should see four:

- coal
- nuclear
- CCGT – the energy source here is natural gas
- wind.

For each, the number of GW used can be seen on the dial and also underneath. On the left you can see graphs of the demand in GW. The daily, weekly, monthly and yearly demands are shown. The other graphs show more detailed information on how the different sources meet demand over these timescales.

Visit Gridwatch.

At the time that you looked:

- What was the total UK demand? How much was supplied by nuclear power stations?
- When was peak demand that day? Why do you think that was the case?

- When was peak demand in the previous year? Why do you think that was the case?

Look at the French National Grid. What differences do you notice?

In the next section, you'll move on to learn more about nuclear power stations.

2.2 Components of a nuclear power station

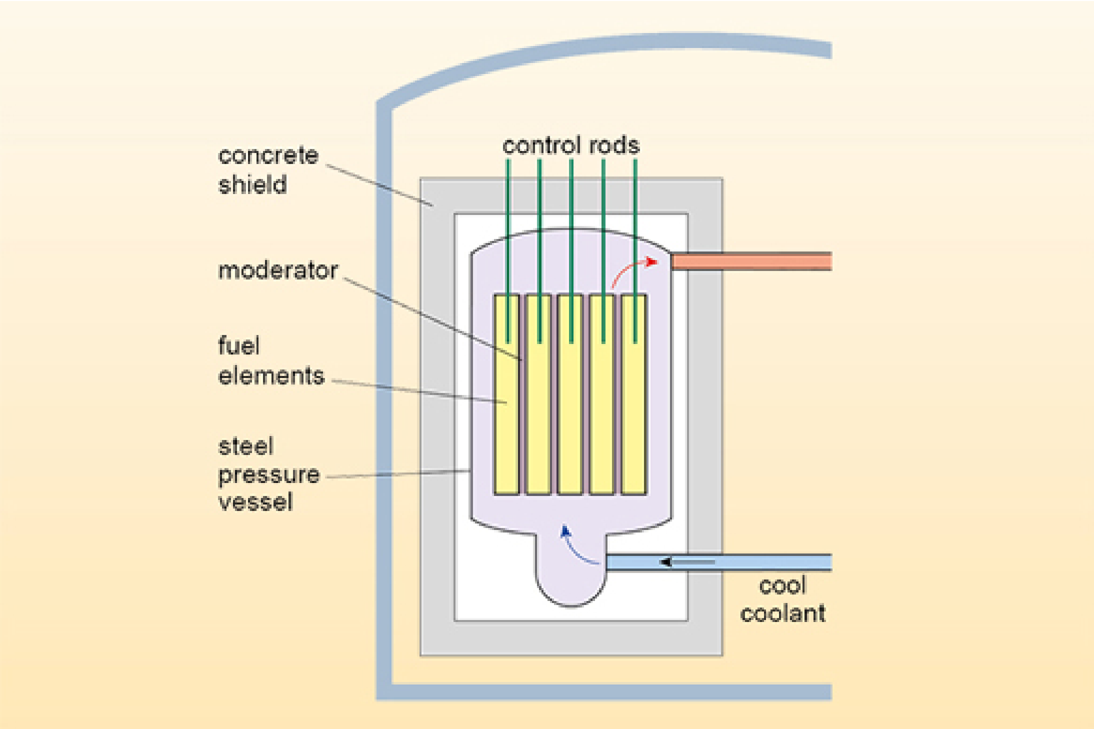

Figure 9

In essence, a nuclear power station is a system for maintaining a fission chain reaction and extracting the resulting heat.

The key to creating so many fission events is the two or three free neutrons that are typically released by each fission event. The chain reaction takes place in the core of the reactor, and the resulting heat passes into a fluid, or coolant, which is pumped through the core. The different components of a nuclear reactor are described below.

The fuel

The elements that undergo the fission are generally uranium (U) or plutonium (Pu). The fuel itself is normally in the form of uranium or plutonium dioxide (UO_2 or PuO_2). In UO_2 the uranium is bonded to two oxygen atoms via its electrons but the nucleus of the uranium is still free to undergo fission, and the same is true of the plutonium in PuO_2. The fuel is referred to as the fissile material as it undergoes fission.

The fuel is arranged in the form of a cylindrical rod (or a stack of cylindrical pellets) in a thin-walled metal container; often the metal is zirconium. The containing material is known as cladding and works as a physical barrier, preventing the fission products and fuel from entering or reacting chemically with the coolant. In practice, a nuclear fuel element will produce energy for three to six years before it needs to be replaced.

You will recall from last week that the majority of the products of fission are radioactive, and it is obviously important to prevent them from escaping from the reactor. The simplest way to do this is to keep them *in the fuel* and this is the purpose of the cladding.

The control rods

A nuclear fission reaction at criticality can be maintained by controlling the critical mass (as you heard about in Week 1). However, the critical mass will change as fuel is used up or even as the temperature fluctuates so a dynamic method is needed that can adapt to changing circumstances and control the neutron population.

The standard method for controlling a chain reaction in a nuclear power station is by control rods. Control rods are made from a material that absorbs neutrons. As the rods are inserted further into the fissile material, more neutrons are absorbed and so fewer fission events are triggered.

Other control methods may be used in addition to inserting rods. For example, some reactors have the option of introducing neutron absorbing material into the coolant in order to reduce the rate of fission.

The moderator

As you learned last week, induced fission is often more likely with neutrons of lower energy (slower) rather than higher energy (faster). If this seems counter-intuitive, imagine a golfer trying to putt a ball. The ball is more likely to be 'captured' by the hole if it is not going too fast.

If the free neutrons created by fission are not slowed down, they are described as fast neutrons. If they are slowed down to lower energies (the process of moderation), they are called thermal neutrons.

In the moderation process, fast neutrons are slowed down by interaction with a moderator. The moderator is a volume of a material such as hydrogen. The neutrons collide with the nuclei of the moderator and, in the process, are slowed down to the same average speed as those of the moderator. If the moderator is at room temperature, the neutrons emerge with a range of velocities typical of a material at this temperature.

The three most important isotopes used as moderators are:

- hydrogen in the form of light water H2O
- deuterium in the form heavy water D2O
- carbon in the form of graphite.

The coolant

The coolant is a gas or liquid that passes through the hot reactor core and carries away the heat produced. It flows around the fuel rods and is in contact with the cladding, rather than with the fuel itself. Apart from being able to remove heat from the fuel rods efficiently, coolants should not react chemically with the cladding, or with any other part of the cooling circuit, and they should not absorb too many neutrons. The coolant should also not be too expensive because a lot of it is used.

Taking all these factors into consideration, the coolants used in the majority of reactors are the gases carbon dioxide and helium, and liquid water.

If water is used as the coolant, it may be allowed to boil, and hence to produce steam directly for use in the turbine: this is called a direct steam cycle. Alternatively, the light water may be prevented from boiling by keeping it under very high pressure, and the hot water pumped to a steam generator, where steam is produced by heating a separate water supply: this is called an indirect steam cycle.

If a gas coolant is used, the gas that has been heated by the core is pumped to the steam generator, where steam is produced – this is also anindirect steam cycle.

Note that water can be used as both a coolant and a moderator – some nuclear reactors use water for both purposes.

In the next section you will see a diagram of a nuclear power station.

2.2.1 Looking inside a nuclear reactor

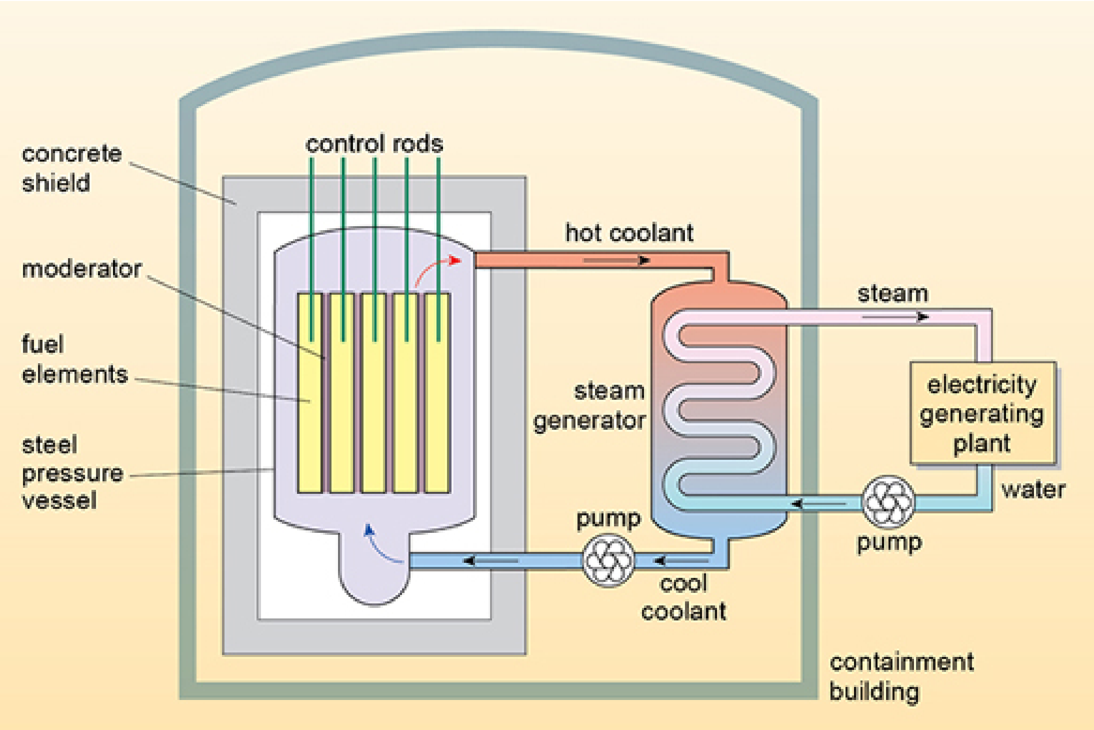

Figure 10 A nuclear reactor

Figure 10 shows the basic components of a nuclear power station.

The control rods that determine the number of neutrons are shown within the fuel elements. Note the moderator that controls the speed of the neutrons is close to the fuel rods too. This reactor works on an indirect steam cycle and so heat energy from the coolant is used to heat water to produce steam that turns the turbine.

In the next section, you will watch a video which shows inside a real nuclear reactor.

2.2.2 Inside a nuclear reactor

The video shows Jem Stansfield looking around the Zwentendorf nuclear power plant in Austria.

This reactor was designed as a boiling water reactor (BWR). In this type of reactor, the reactor heats the water which produces steam that then turns the turbine. The steam is then cooled back to water and returned back to cool the core. The water is also used as a moderator.

The Zwentendorf reactor was built but never used; it was prevented by a vote within a referendum on the issue. Since 1978 Austria has banned using fission as an energy source in power stations.

Video content is not available in this format.

In the next section you'll consider the distribution of nuclear power stations around the world.

2.2.3 Types of nuclear reactor

Figure 11

There are many different types of nuclear reactor and the list below is not exhaustive! By far the most common type of nuclear reactor is the pressurised water reactor or PWR.

The main types of reactor currently in use (or used in the past) to generate electricity are:

- **Pressurised water reactor (PWR)**: pressurised water reactors are the most common – about two-thirds of all reactors in the world are of this type. These work on an indirect steam cycle.
- **Boiling water reactor (BWR)**: boiling water reactors are a popular alternative to pressurised water reactors – both are used in the USA and in Japan. These work on a direct steam cycle.
- **Advanced boiling water reactor (ABWR)**: advanced boiling water reactors incorporate improvements on earlier boiling water reactors and are used in Japan, with new reactors planned in Japan and Taiwan.
- **Pressurised heavy water reactor (PHWR)**: pressurised heavy water reactors use heavy water as the coolant and the moderator, and natural uranium as the fuel. They were developed in Canada and are sometimes called CANDU reactors.
- **Gas-cooled reactor (GCR)**: a gas-cooled reactor has a graphite moderator and a carbon dioxide gas coolant. It is only found in the UK. Early models were known as Magnox reactors and later versions as the advanced gas-cooled reactor (AGCR or more commonly AGR).
- **Light water-cooled graphite-moderated reactor (LGR)**: these water-cooled, graphite moderated reactors were used mainly in the former Soviet Union. They are sometimes known as RBMK (*reaktor bolshoy moshchnosty kanalny*) reactors and there were four such units at the Chernobyl plant at the time of the accident there (in 1986), about which you will read more later.

The various reactor types are mainly defined by the materials used as moderator and coolant and, although these factors affect the design of the reactor, the basic principles are common to all nuclear power stations.

Another type of reactor worth noting is the EPR – the European pressurised reactor. The EPR is a pressurised water reactor designed to improve on safety and security, and enhance economic competitiveness. It is not fundamentally different from the pressurised water reactors described earlier but it is the most widely discussed reactor under consideration for new nuclear power stations. The design was developed by a consortium of French and German companies. An EPR is under construction in the UK at Hinkley Point C in Somerset.

Next, find out more about where new power stations are planned.

2.2.4 The world's nuclear power stations

Figure 12

In January 2015, 30 countries worldwide were operating 437 nuclear reactors for electricity generation and 71 new nuclear plants are under construction in 15 countries. Nuclear power plants provided 12.3% of the world's electricity production in 2012 according to the Nuclear Energy Institute.

Activity 2

Find out for yourself the distribution of nuclear power stations across the world and what type of reactors they are using via the *Guardian* nuclear power station interactive map (Clark, 2012).

Note the colour coding at the top which distinguishes between active and non-active power stations and those that are being built. As with street view you can drag the orange figure to the vicinity of the power stations and have a look around!

- Find a power station that is planned or under construction. What type of reactor will be used?
- At a glance, estimate which countries have the most nuclear reactors under construction.
- Contrast the situation between France and Italy. Why do you think that the situation differs between these two countries?

Next, you'll move on to think about nuclear waste.

2.3 Waste produced by nuclear power

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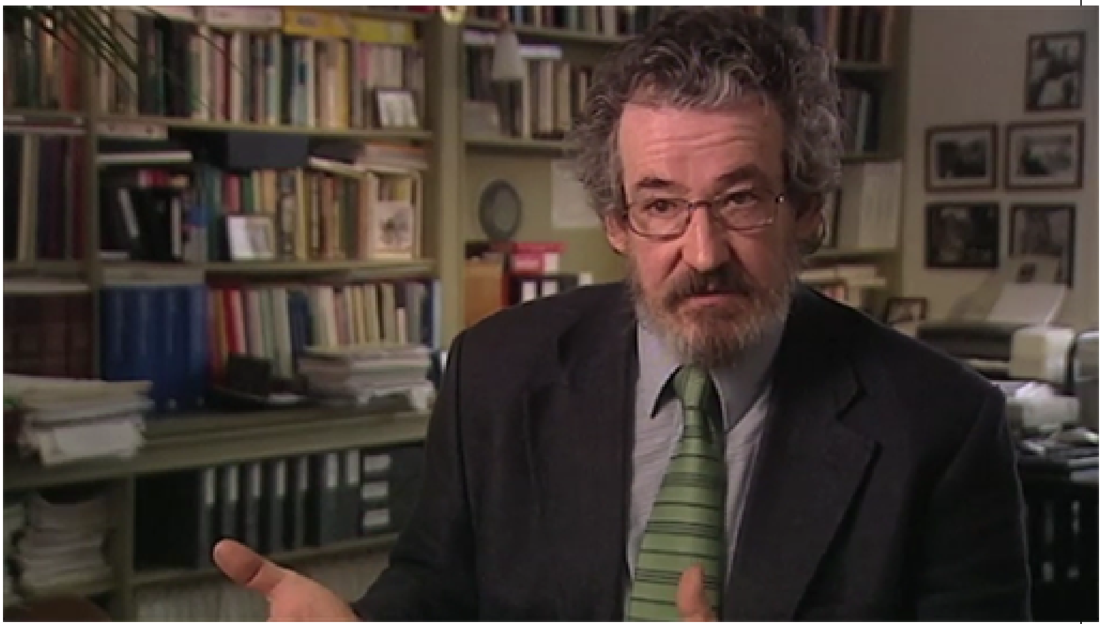

The reactor at Calder Hall, which was on what is now the Sellafield site in Cumbria, was the first operating nuclear power station in the world.

It connected to the grid in 1956 and was a Magnox type reactor. Initially its main purpose was the production of plutonium from uranium-238, but the secondary process of electricity production soon took over and became the primary function of the site. Calder Hall was closed in March 2003 and decommissioning began.

Older reactors produced a great deal of radioactive waste, 20 000 tonnes were produced from Calder Hall.

The video states that ‘Some of that radioactive waste has to be stored for tens of years, some for hundreds of years and some for thousands of years.’ These timescales are obviously problematic! To understand why such forward thinking is involved we need to look again at the nature of radioactivity and the concept of half-life. You’ll do this in the next section.

2.3.1 Half-life

Figure 13

When quantifying the risk posed by a particular isotope, it's important to consider the amount of time that it will remain radioactive and its activity during this time. Both of these quantities relate to the half-life of the isotope.

Last week, we defined activity as a measure of the number of particles (alpha, beta or gamma) that are emitted in a given time. As the particles are emitted, the isotope is said to decay and changes into an isotope of another element.

Let's consider the alpha emission that you looked at last week:

$^{238}_{92}\mathrm{U}$ emits an α particle and decays to $^{234}_{90}\mathrm{Th}$.

If there are a certain number of uranium-238 atoms in a particular sample, the half-life is the time taken for half of these radioactive atoms to decay. After another half-life, half of the remaining atoms will decay and so on.

Imagine you were given 1200 atoms of uranium (in reality it would be a much larger number). After one half-life, half the uranium atoms will have decayed into thorium, so you will only have 600 uranium atoms left. After another half-life, another half will have decayed so you will have 300 uranium atoms, after another half-life you will have 150 uranium atoms. After four half-lives you would be left with 75 atoms of uranium and 1125 atoms of thorium.

Now, in fact, the half-life of uranium is 4.5 billion years so you would have to watch your atoms for a long time to see them decay! Half-lives can vary from billions of years to nanoseconds. Some half-lives are shown in Figure 14.

Radionuclide	Half-life
uranium-238	4.5×10^9 years
$\alpha\downarrow$	
thorium-234	24.1 days
$\beta\downarrow$	
protactinium-234	1.17 days
$\beta\downarrow$	
uranium-234	2.45×10^5 years
$\alpha\downarrow$	
thorium-230	7.5×10^4 years
$\alpha\downarrow$	
radium-226	1600 years
$\alpha\downarrow$	
radon-222	3.82 days
$\alpha\downarrow$	
polonium-218	3.05 minutes
$\alpha\downarrow$	
lead-214	26.8 minutes
$\beta\downarrow$	
bismuth-214	19.7 minutes
$\beta\downarrow$	
polonium-214	1.6×10^{-4} seconds
$\alpha\downarrow$	
lead-210	22 years
$\beta\downarrow$	
bismuth-210	5 days
$\beta\downarrow$	
polonium-210	138 days
$\alpha\downarrow$	
lead-206	stable

Figure 14 The main decay chain for uranium-238; other radioisotopes similarly have their own characteristic decay chains

If an isotope has a short half-life, it will decay quickly, and emit more particles in a given time than an isotope with a longer half-life. So isotopes with shorter half-lives have higher activity than those with longer half-lives. The activity of all isotopes will diminish over time as the number of atoms that are present decay away. It is worth noting that, unlike chemical reactions, the rate at which radioactive isotopes decay at any particular moment cannot be changed; heating them, subjecting them to high or low pressures, or to any other physical process, does not alter the half-life.

Both the high rates of decay, or activities, of radioisotopes with short half-lives and the longer life span of those with long half-lives have an impact on the disposal of radioactive waste. Some products of fission have half-lives of the order of hours or days, while others have half-lives of thousands of years or more. This requires both short- and very long-term planning when considering what to do with the waste.

Next, you’ll look in more detail at the different sorts of radioactive waste produced.

2.3.2 Types of radioactive waste

Figure 15

One of the major issues with nuclear power is what to do with the radioactive waste intrinsic to the process of fission.

Classifying the waste

Radioactive waste comes in a wide variety of forms, from the clothing worn by workers at a power plant to the fuel rods themselves. The range of activity levels of the materials in the waste is also wide ranging, for example, from minute traces of radioactivity on a pair of worker's gloves to the contents of spent fuel rods which have levels of activity more than 100 million times that of natural uranium.

Classifying the items is helpful to ensure that each item is dealt with in an appropriate manner, for safety and economic reasons. Different schemes have been proposed and used in different countries at different times. These schemes can become quite complex but all classify waste into three broad categories: low-, intermediate- and high-level waste.

Low-level waste

Laboratory clothing that has become contaminated, used paper towels, as well as liquid, gaseous and solid wastes from different parts of the fuel cycle can be classed as low-level waste. These items share low activity and low heat production: in fact, the heat produced in them is negligible.

Although low-level wastes require isolation and containment for a few hundred years, they can be stored at facilities near the surface with limited regulation. Most of the material is barely radioactive but is nonetheless sealed in steel drums and checked before storage.

Intermediate-level waste

Intermediate-level waste has higher activity (per unit mass or volume) than low-level waste, and so poses a greater radiation hazard. It includes fuel cladding and wastes from different stages of fuel reprocessing. The storage needs to be more elaborate than that for low-level waste, but no cooling is necessary, or only very limited cooling, during storage and disposal.

Waste in this category requires disposal at greater depths than low-level waste, of the order of tens of metres to a few hundred metres.

High-level waste

The fission products found within the used fuel or waste materials remaining after spent fuel is reprocessed are high-level waste. These items produce so much heat from the decay of radioisotopes that continuous cooling is required, and safe storage requires elaborate precautions to be taken. Such waste requires specially constructed disposal facilities.

Disposal

Whatever the form of the waste, some initial processing usually takes place to reduce the volume of the waste, or to make it safer and more convenient to handle. For example, low-level waste may be incinerated or compressed and possibly encapsulated in concrete; intermediate-level waste may be evaporated if it is in liquid form or cut up or crushed if it is in solid form, prior to encapsulation in concrete-filled drums as shown in Figure 16.

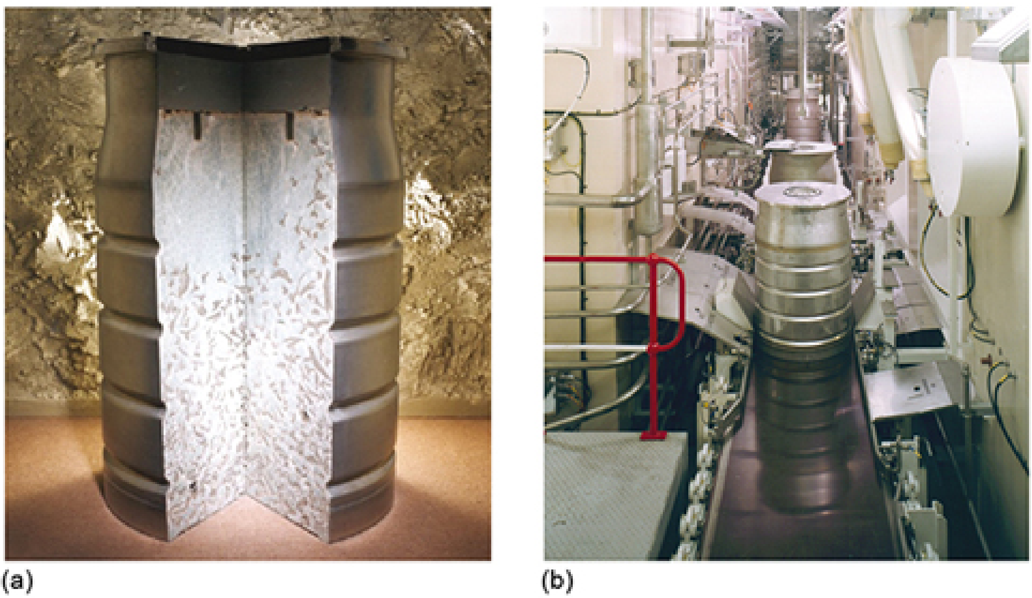

Figure 16 (a) A drum used to store intermediate-level waste encased in concrete, cut away to show its contents, (b) waste packaging and encapsulation plant (Sellafield, UK)

High-level waste is generally placed in containers and stored, often under water, for some years in order for its activity level to reduce. A proportion of spent fuel is also reprocessed.

Only the low-level waste currently has established and accepted mechanisms for final storage or disposal. It is typically either sent to regulated landfill sites or buried in special low-level waste repositories. Currently, intermediate- and high-level wastes are held in storage on the surface, often at the nuclear power stations from which they originated, while a longer-term solution is sought.

Initially this high-level waste is so active that it will be extremely hot. The emission of the radioactive particles transfers energy and raises the temperature in the vicinity. The fuel rods, therefore, need to be actively cooled for years before they can be dealt with.

In the next section, you will look at the decommissioning of Dounreay power station.

2.3.3 Decommissioning at Dounreay

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The video shows the progress made, by 2011, of the decommissioning of the Dounreay power station in the north of Scotland, UK.

The task of dealing with the waste continues. The end date for the entire process is given as 2022–25, that is about 30 years after the last reactor closed in 1994.

You can learn more at the Dounreay decommissioning website (Dounreay Site Restoration Ltd, n.d.).

Next week you'll consider the decommissioning of reactors that have malfunctioned.

2.3.4 What can be done with nuclear waste?

Figure 17

The Dounreay video mentioned that the radioactive waste would need to be stored 'forever'. Forever is a long time!

Let's recap what is known about nuclear waste:

- The production of radioactive materials is intrinsic to the process of fission so all nuclear reactors produce radioactive waste. The reactors you've heard about so far produced thousands of tonnes of waste.
- The waste can be classified into different levels.
- Some of the waste is very active now. Some of the waste has a long half-life indicating it will be active for many thousands of years.

Activity 3

You may have your own thoughts on the issue of nuclear waste and about what happens in your own country.

Think about these questions:

- What would you do with nuclear waste?
- Do you know the nuclear waste disposal policy in your country? For example, read about the UK Government's policy on radioactive waste.
- What do you think of your country's policies?

In the next section, you'll find out about some possible solutions.

2.3.5 Solution: reuse

Figure 18

Three ways that nuclear waste can be dealt with are reuse, transmutation and burial. The most common method is burial – you will look at this later. Some radioactive waste can be reduced by reprocessing, or reusing, some of the spent fuel.

Fuel reprocessing is a complex technological process which is only performed at a relatively small number of sites worldwide, for example, the COGEMA plant at La Hague in France and the Sellafield plant in Cumbria in the UK. If the fuel is to be reprocessed, it first needs to be transported to one of these sites.

On arrival at the site, the fuel is stored under water until it can be handled for reprocessing. The main reprocessing stages are summarised in Figure 19.

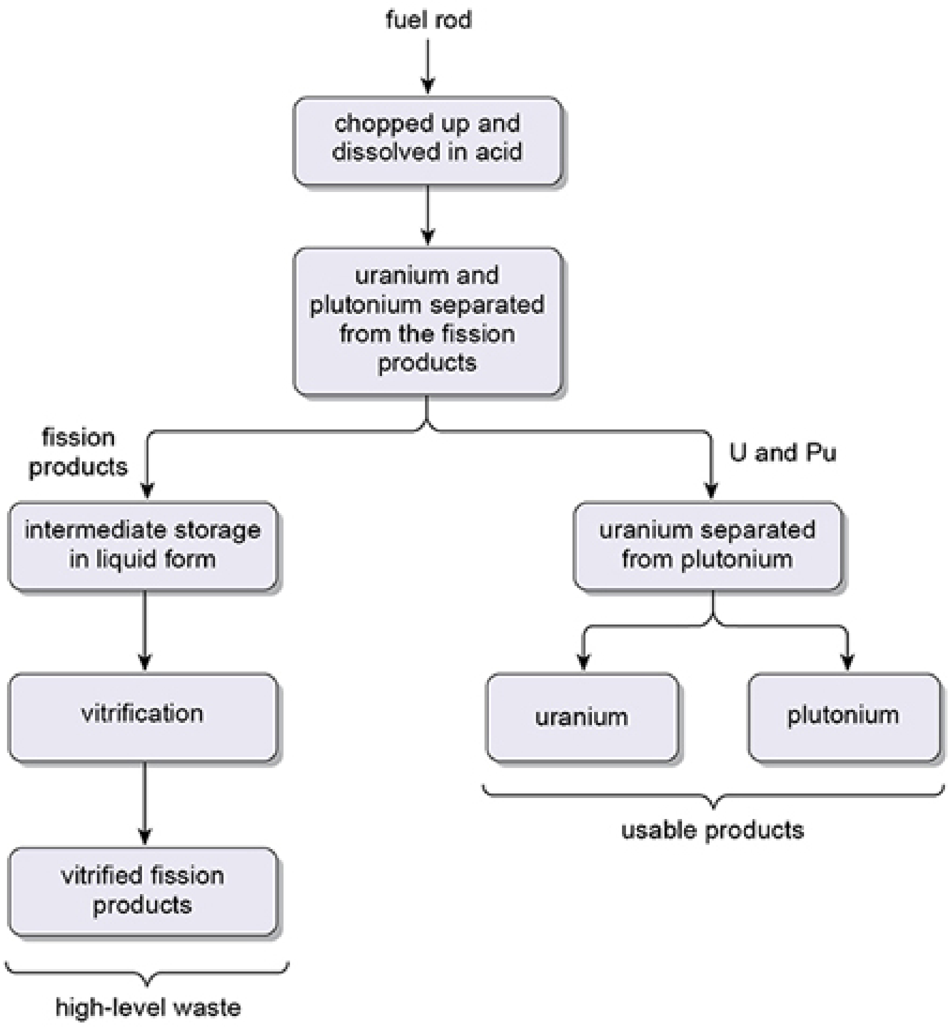

Figure 19 The main stages in reprocessing nuclear waste

After being separated from the fission products, the uranium and plutonium are separated from each other. The plutonium may be combined with depleted uranium from an enrichment plant to form what is known as MOX (mixed oxide) fuel. MOX has similar characteristics to normal uranium dioxide fuel and it may be used in place of a proportion of this fuel in the same reactors. There are issues with the relative proportion of isotopes within MOX and such issues affect the economic viability of reprocessing fuel. The various stages of reprocessing spent fuel create a considerable quantity of high-, intermediate- and low-level waste themselves.

Aside from reprocessing, increased thought is given to other uses of waste. For example, the fission product molybdenum-99 decays to technetium which is used in medical tracers. Caesium 137 and strontium-90 can both be used in radiotherapy. Extraction of these useful isotopes is not always straightforward but will reduce the quantity of waste that needs storage.

In the next section, you will look at another solution – transmutation.

2.3.6 Solution: transmutation

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The video shows the process of transmutation. Heavy fission products with long half-lives are bombarded with neutrons and split into smaller fragments with shorter half-lives.

Opinion on transmutation is mixed. It does provide a solution to the problem of storing the long-lived isotopes in radioactive waste. It is also possible that the process of transmutation could itself be used to generate electricity and future power stations could incorporate transmutation into their running. This would reduce the volume of long-lived isotopes that are produced by fission of uranium.

However, the technology is not able yet to deal with large amounts of waste in an economically viable way and the research in this field would be expensive. Also transmutation would itself generate low-level radioactive waste!

In any event, while transmutation may significantly reduce the long-term risk of the radioactive waste, it wouldn't replace the need for storage. The next section considers the siting of this storage.

2.3.7 Solution: deep geological repository

The favoured option for nuclear waste management around the world at the time of writing, 2015, is to bury the waste in purpose-built underground repositories.

The siting of such a repository requires much thought as many of the fission products will remain active for thousands of years. Thus, a repository needs to be secure, both now and into the far flung future!

There are two main issues that need to be considered:

1. The possibility of seismic activity. Earthquakes could bring the material to the surface.

2. The problem of water. It is vital that water is not able to come in contact with the radioactive material now or in the future.

In order to reduce the possibility of either of these problems arising, the design of repositories includes containers with multiple layers enclosing the waste and other engineered barriers or seals around the containers. Great attention is also paid to the suitability of the surrounding environment, particularly the geology in terms of stability and rock composition, and the way water can move through it. Several processes combine to cycle water globally, and these in Figure 20.

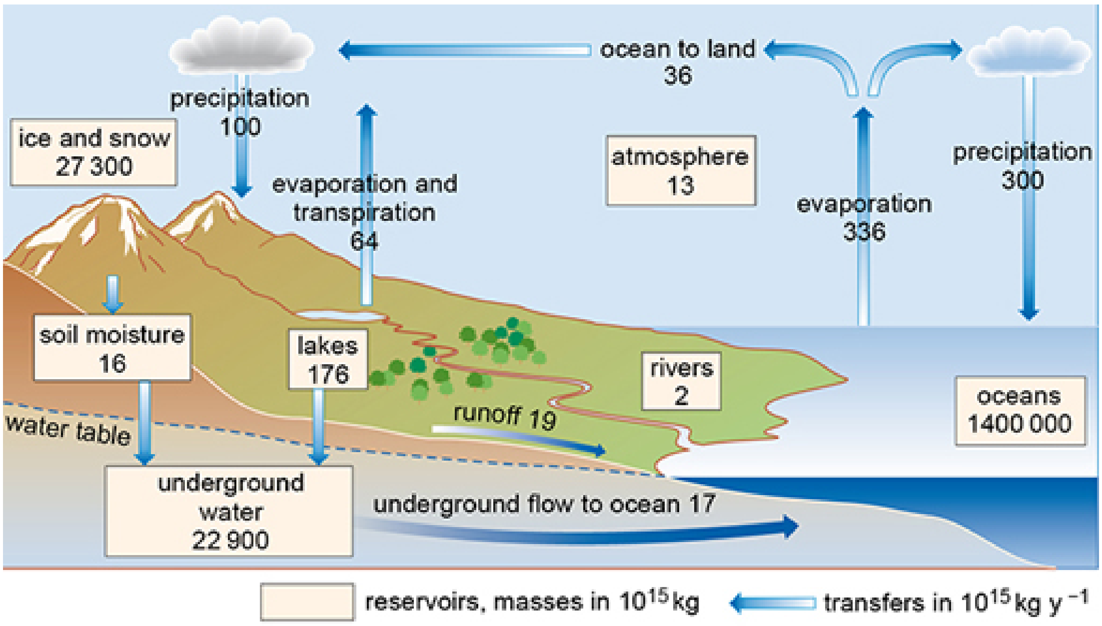

Figure 20 The global water cycle: showing the distribution of the world's water. 'Lakes' includes freshwater and saline lakes. The values shown as transfers represent the amounts of water cycled annually (in units of 10^{15}kg y^{-1}), as opposed to that stored in reservoirs (in units of 10^{15} kg)

At any stage in the water cycle where evaporation occurs, anything dissolved in the water is left behind. In particular, radioisotopes transported into the oceans would accumulate there; they would not evaporate and re-enter the water cycle.

How water flows through the ground is largely determined by the geology. Many of the rocks that make up the Earth's crust contain voids, which can hold water. These voids can take various forms. In sandstones, for example, they consist of small interconnected pores between the grains of sand. In granites, which are made up of interlocking crystals, there may be fissures or fractures, which can be interconnected so allowing water to travel through the rock. Below a certain level, the rock voids are all filled with water. This level is called the water table, and the rocks below it are said to be saturated. By using the voids as a pathway, water can flow through the saturated rocks.

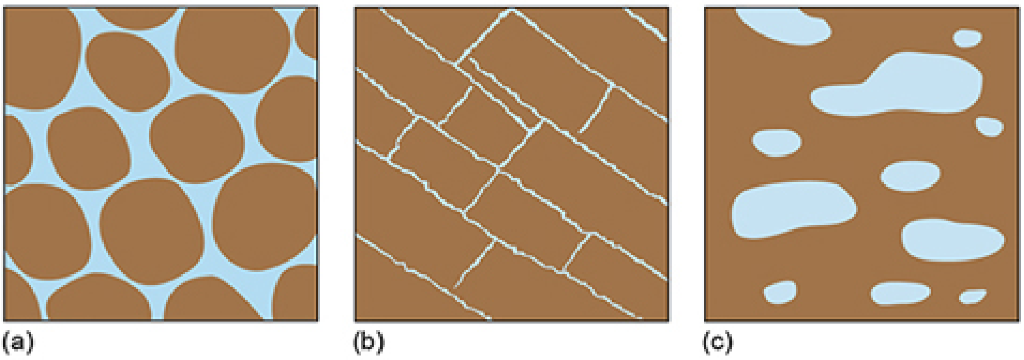

Figure 21 Void structures in different rock types.

The ease with which water flows through rocks varies with the rock types. For example, if the rock contains large well-connected pores or voids, like the sandstone in (a), or extensive linked fractures, like the granite in (b), the water will flow easily through the rock. In (c) there are large pores in the rock, but the pores are not interconnected, so the water cannot flow easily through the rock. Any repository would ideally need to sit above the water table and within a rock that resisted the flow of water.

In the next section you'll see a video of the planning for a depositary in Yucca Mountain, a mountain in Nevada, US. This site was deemed to be near perfect as regards its geology.

2.3.8 Case study: Yucca mountain

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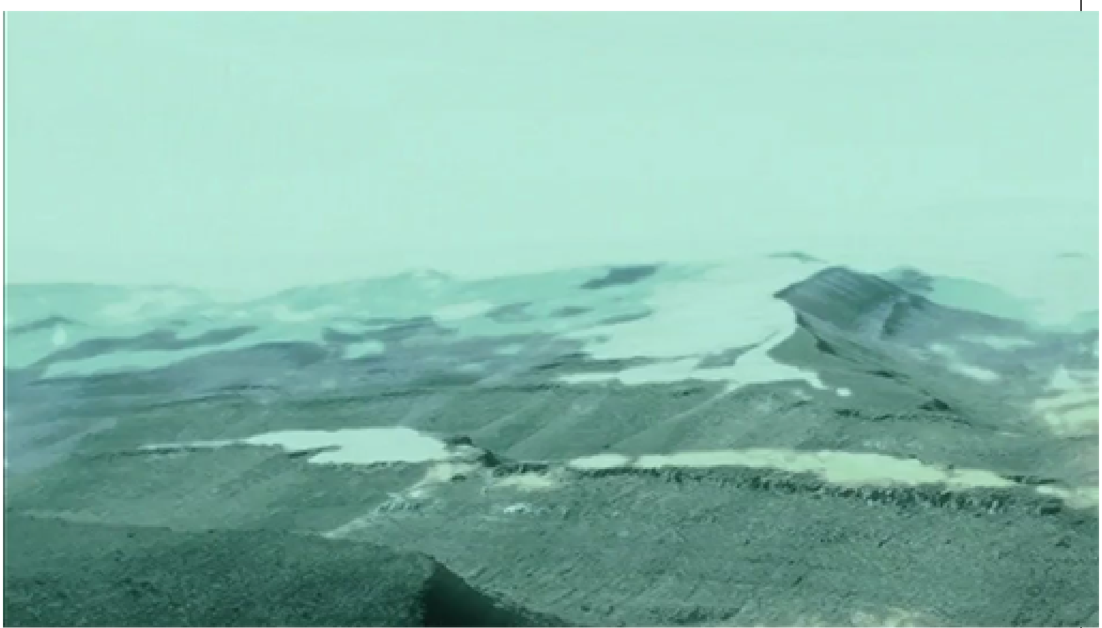

Funding to the Yucca Mountain repository project was removed in 2009 due to protests from the people of Nevada.

Strong views exist on both sides. The situation is complicated as the closure is in conflict with a federal law designating Yucca Mountain as the nation's nuclear waste repository for the US.

For more on renewable energy in the UK, look at information from the Renewable Energy Trade Association RenewableUK (2016).

There is lots of information on nuclear power in the UK on the World Nuclear Association website (2016).

Next week, you will look at another contentious issue – the possibility of meltdown in nuclear power stations.

2.4 Quiz for Week 2

Take the quiz to test and apply your knowledge of the material in Week 2.

Week 2 quiz

Then come back here.

2.5 Summary of Week 2

Figure 22

This week you looked initially at how to quantify the energy we use and how this links to nuclear power.

The electrical energy we use within the home is provided by the National Grid, which utilises various energy sources including coal, gas, nuclear, wind and solar. Nuclear power stations exploit the energy produced from induced fission released in the form of heat energy. The elements within the power station are there to safely sustain the chain reaction and to extract the heat produced. A major issue surrounding nuclear power is the production of nuclear waste which may remain active for many years. A proportion of radioactive waste can be reused or transformed via transmutation but the favoured option for nuclear waste management at the moment is to bury the waste in purpose-built underground repositories.

Next week, you'll examine another controversial aspect of nuclear power – the fear of a nuclear accident. Historically, there have been very few accidents at power stations but you'll examine the causes in each case and look at the recent events at Fukushima in some depth. You will look at the long range effects on the surrounding environment and the local population.

You can now go to Week 3.

Week 3: Is nuclear power safe?

Introduction

In the following video, Sam and Gemma discuss the safety of nuclear power.

Video content is not available in this format.

Next, you will find out about the excitement at the start of the nuclear industry.

3.1 Atomic men!

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In the early 1950s, the nuclear industry was very young – the video shows the initial excitement surrounding it; ‘we were in the vanguard of something really new’. People began to talk of an ‘atomic age’.

Windscale was perceived as an exciting and dynamic place. It was located on the Sellafield site in Cumbria (right next to Calder Hall that you looked at last week) and was home to the Windscale Piles which were part of the weapons industry, producing plutonium for nuclear bombs.

In 1957, Windscale experienced a reactor accident that profoundly affected public confidence in the nuclear industry. Other accidents you might have heard of, that involved nuclear power plants (i.e. those designed to generate electricity), include the accident at Three Mile Island, in Pennsylvania USA, in 1979 and the accident at Chernobyl in the former Soviet Union in 1986. The most recent accident occurred in Fukushima, Japan in 2011.

In the next sections, you will examine these accidents and what can go wrong in a nuclear power station.

3.1.1 What can go wrong in a nuclear power station?

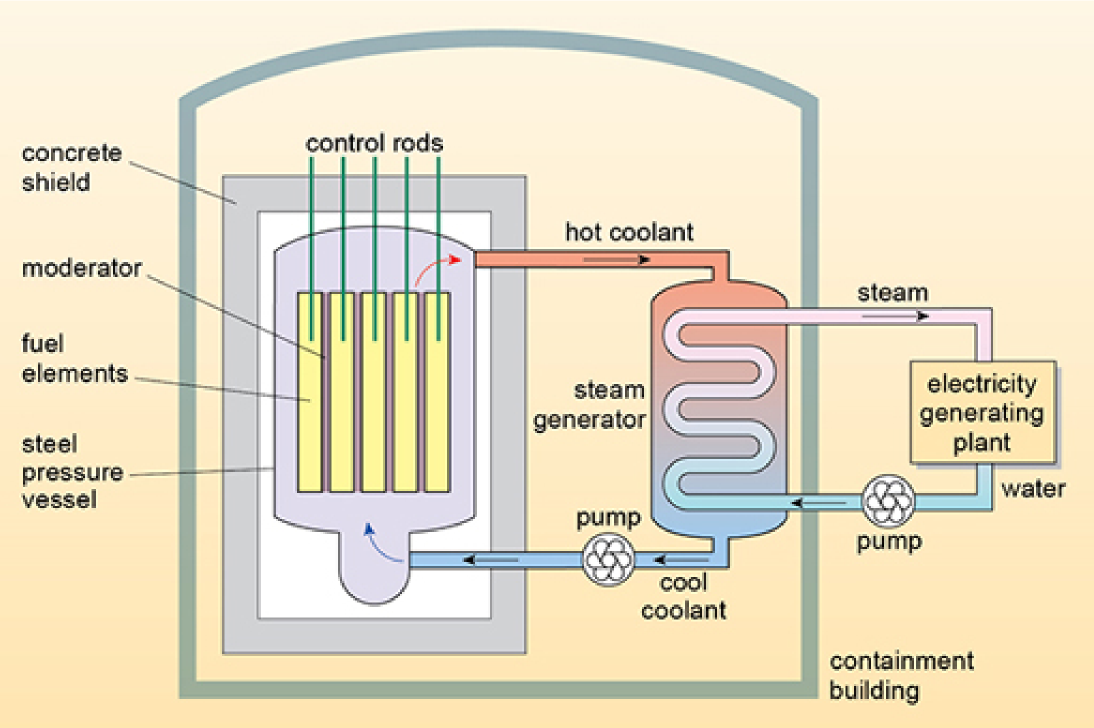

Figure 1

The design of every nuclear power station includes many safeguards that are put in place to ensure that the core is protected from the environment.

Every serious nuclear accident has arisen because a sequence of events has led to the core going into meltdown. You have probably heard of the term meltdown before. It is an informal term for the more technical descriptions core melt accident and partial core melt.

A meltdown occurs when the heat in the core of the reactor rises high enough that the fuel rods begin to melt. This can have disastrous consequences as, under these circumstances, the fuel cladding can be breached and highly radioactive materials leak into the environment beyond.

Have a look at Figure 1 to remind yourself of the layout of a nuclear reactor.

There are three different situations that can lead to a meltdown:

Control of the fission reaction is lost and the reactor goes supercritical

You will recall that for a critical reaction the population of neutrons is such that the number of fission events is steady and that the chain reaction continues in a controlled manner and releases a manageable amount of energy. The reactor will be designed to have some tolerance, but there will be a limit to the amount of heat energy that the coolant can safely transport away.

If the number of neutrons is allowed to increase, the number of fission events increases and the chain reaction releases progressively more and more energy. This uncontrolled chain reaction is what is allowed to happen in a nuclear bomb but needs to be avoided in a power station!

The control rods control the number of neutrons. A supercritical reaction can occur if the control rods are not adequately inserted within the fuel.

In April 1986, the Chernobyl nuclear power plant was running tests on one of the four reactors based there. The nature of the test led to the control rods being fully pulled out from the fuel before the test began, as the fission product xenon (Xe) had begun to build up which is itself a neutron absorber.

Once the test started the fission began to go supercritical and the control rods could not be inserted again quickly enough. The reactor was no longer under control and rapidly jumped to ten times its usual energy output (some reports have the final measured output as 100 times higher). This led to two explosions in the core.

The fuel elements became exposed and extremely radioactive materials were released into the environment. Chernobyl is considered the worst nuclear power disaster in history.

Coolant failure

All may be well with the fuel rods and the criticality of the fission reaction but if the coolant fails and the heat is allowed to build up then the temperature can become dangerous in the reactor core. Heat will build up even if the fission reaction itself has been stopped. This is due to the radioactivity of the fission products within the fuel rods. These will be highly active and able to heat the surroundings sufficiently to melt the fuel rods.

At Three Mile Island a partial meltdown occurred in one of the two reactors on the site. A small valve was accidentally stuck open and allowed coolant to escape. It took a while for operators to understand the situation and in the interim some steps were taken that made matters worse, in particular the decision to release more of the coolant.

The temperature rise was slower than at Chernobyl but the delays allowed the diminishing coolant to expose fuel elements within about two hours of the initial malfunction. The cladding around the fuel elements was damaged and radioactive isotopes leaked into the remaining coolant and into the surrounding environment.

A coolant failure also occurred at Fukushima which you will look at in more depth later in the week.

Fire within a reactor

The reactor that was built in Windscale used carbon graphite as the moderator. The graphite was therefore bombarded with neutrons which led it to a change of structure, allowing energy to build up with each new neutron interaction.

This process was known about (it is called Wigner energy) and efforts were made to release it. However, in October 1957, the release of the Wigner energy was not successful and the moderator caught fire, which soon spread to the fuel elements.

Windscale was an air-cooled power station and this air was vented up and out of a chimney. The fire in the core caused radioactive materials to escape out through the chimney with the air and into the surrounding environment. Lessons were learned from the events at Windscale and the Magnox design of reactor was phased out.

Next, you will find out more about the accidents at Three Mile Island and Chernobyl.

3.1.2 Accidents at Three Mile Island and Chernobyl

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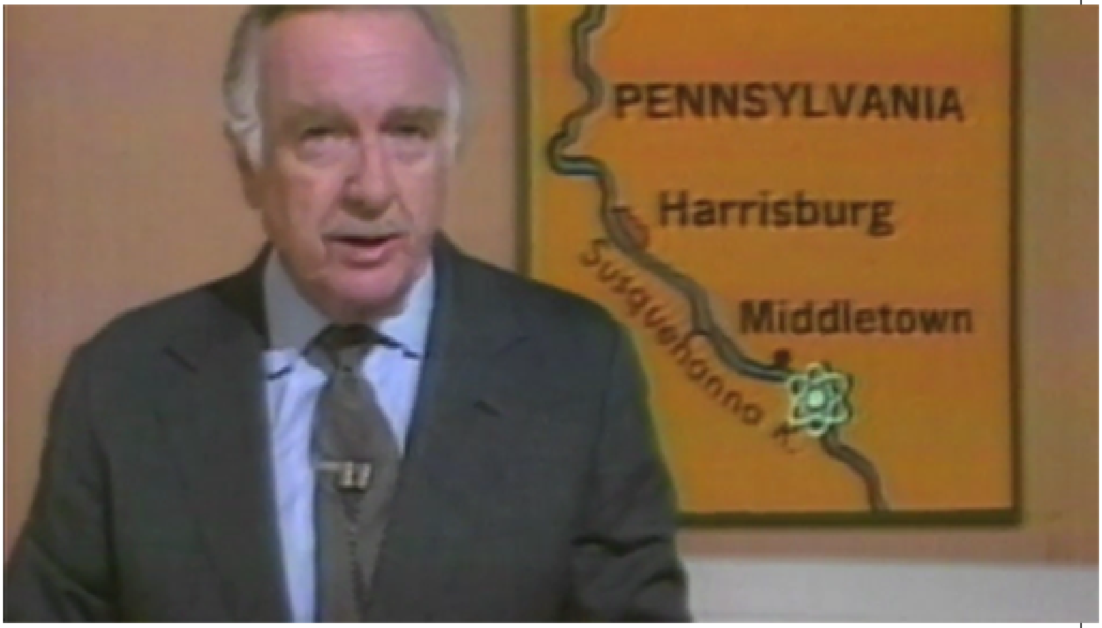

Accidents occurred at the Three Mile Island nuclear facility in Pennsylvania and the Chernobyl nuclear power station.

(Remember that PWR stands for pressurised water reactors.)

In the next section, you will consider what could be learned from these incidents.

3.1.3 Errors

Figure 2

The video in the previous section identified errors that contributed to the severity of both the accidents at Three Mile Island and Chernobyl.

Activity 1

Think about these questions and write a paragraph explaining your thoughts.

- Is there any link between the disasters at Three Mile Island and Chernobyl?
- How could they have been avoided?

Next, find out the fate of the Three Mile Island nuclear facility and the Chernobyl nuclear power station.

3.1.4 Clean-up at Three Mile Island and Chernobyl

Figure 3

It is 36 years since the events at Three Mile Island. The reactor that underwent meltdown was permanently shut down.

Over the years much of the radioactive waste has been removed although the site remains monitored. The other reactor was also closed temporarily but began to operate again in 1985. It has a licence to operate until 2034 when it is planned that the entire site will be decommissioned.

After the disaster at Chernobyl the remains of the reactor will remain radioactive for hundreds of years. Shortly after the meltdown, it was entombed in a concrete and steel structure called a sarcophagus. This was an attempt to shield the surrounding environment from the worst of the radiation.

The other reactors at Chernobyl functioned for some years after but are now all shut down. At the end of the week, you'll come back to Chernobyl and examine what conditions are like there today.

In the next sections, you will find out the sequence of events that led to the crisis in the Fukushima nuclear power plant.

3.2 The Fukushima Daiichi reactor

Figure 4

The Fukushima Daiichi nuclear power plant lies on the east coast of Japan in the Futaba District.

It is one of two nuclear power stations in the vicinity – the other is Fukushima Daini, sited a little further south. Both are owned and run by the Tokyo Electricity Production Company (TEPCO).

Figure 5

Fukushima Daiichi is a large plant containing six boiling water reactors (BWRs) with water used as both the moderator and coolant. The reactors are referred to by numbers 1–6. You can see the reactor buildings in Figure 5.

The BWR reactors were old and of a design popular in the 1960s. The first reactor connected to the Japanese grid in 1971.

Japan is situated near the boundary of several tectonic plates so it is a region where earthquakes are relatively frequent and can occur at all magnitudes.

In the next section, find out what happened when the reactor was affected by an earthquake.

3.2.1 What caused the meltdown at Fukushima?

Figure 6

At 14:46 Japanese time on Friday 11 March 2011, a magnitude nine earthquake struck Japan with its epicentre 30km east of the Oshika peninsula and 150 km north-east of the Fukushima Daiichi site.

The earthquake

On the day, only reactors 1, 2 and 3 were running with the other three reactors shutdown for routine inspection. The earthquake produced significant tremors within the site and although some tolerance was built into the design of these reactors, the shocks were large enough to exceed this tolerance in reactors 2, 3 and 5.

The reactors had built-in safety systems that responded to the earthquake by implementing an immediate and automatic shutdown. This was achieved by lowering control rods into the fuel to absorb enough neutrons for fission to cease.

The connections to external power failed but the emergency diesel generators on site successfully kicked in, these were crucial to power the pumps that kept the coolant circulating through the core. Remember that, although the fission had been successfully stopped, the fission products within the fuel elements would be extremely active, creating a great deal of heat from radioactivity.

In addition to the fuel rods situated within, there were spent fuel rods within the building of reactor 4. These also needed cooling due to the concentration of fission products within them.

After the earthquake the safety mechanisms performed well and the power station was in a stable condition, with cores shutdown and able to cool.

The tsunami

The stability within the power station was not to last. The earthquake triggered a huge tsunami and 50 minutes after the earthquake it hit the Daiichi site. A tsunami had been anticipated within the power plant's design, with a 10m wall built for protection from the sea. Unfortunately, this tsunami was 14m and able to surge over the barrier. Seawater flooded into the plant and its buildings.

Disastrously, the buildings housing the back-up generators were also flooded despite being situated on higher ground. The generators were now unable to power the coolant pumps. Power was now being supplied from batteries that had a lifespan of eight hours maximum.

This left the site both flooded with seawater and with an extremely worrisome situation regarding power for the cooling system. An emergency was declared surrounding the status of generators 1, 2 and 3.

The earthquake and tsunami had also left the local infrastructure badly damaged and it took many hours for additional batteries to arrive on the scene. Portable generators were also acquired but there was little success in connecting these up.

The next few days

In the days after the incident, the workers at the Daiichi site desperately battled to manage the hot cores while the rest of the world looked on from a distance. There were explosions at the plant itself and the issue of containment became a serious concern.

The reactors suffered a series of explosions. These were not nuclear explosions due to fission but chemical explosions caused by the action of heat at the centre of the core on the coolant. The next section describes how the hydrogen explosions occurred and later sections discuss the issue of containment.

3.2.2 Hydrogen explosions demonstration

Video content is not available in this format.

The three explosions at Fukushima caused a great deal of damage. The video illustrates how dramatic a hydrogen explosion can be!

In 2011, TEPCO who owned the Daiichi plant would declare that cooling systems for reactors 1–4 were beyond repair and would have to be replaced.

The video in the next section shows the damage within the Daiichi plant.

3.2.3 Inside the Daiichi power plant

Video content is not available in this format.

This video shows the inspection of the Daiichi plant in May 2011, two months after the initial crisis.

The damage done to the plant by the explosions is apparent as is the continuing presence of seawater.

The inspectors are an international group of scientists. They are there to work out what happened and why; to fully understand the physics so that appropriate precautions can be taken within the nuclear industry.

During the first few weeks, many were frustrated at the piecemeal nature of the information coming out of Daiichi so this visit was also an opportunity to increase transparency of information.

Initially, the main battle was with the reactors themselves. As time went on the overriding issue became the continuing effort to limit the radioactive contamination of the area and to try to contain the Daiichi site.

In the next section, find out about the exclusion zone set up around Fukushima.

3.2.4 Exclusion zone

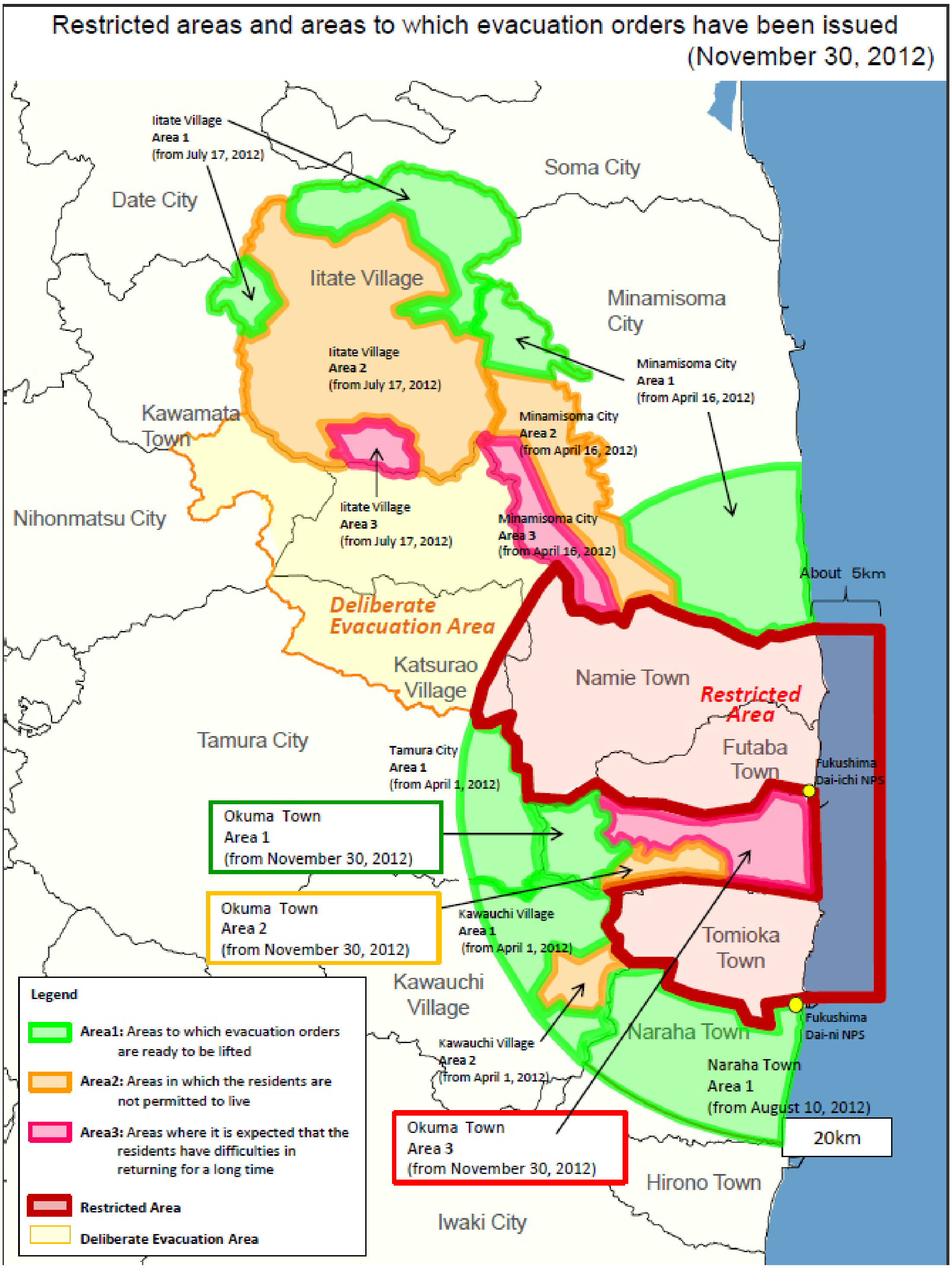

Figure 7

The meltdowns within the reactors led to some of the radioactive fission products leaking into the environment.

This was exacerbated by release of gases and material by the explosions and the venting of gases that occurred to try to reduce pressure within the reactors and limit further explosions. In addition, the entire plant was flooded with seawater that provided a medium to transport the radioactive isotopes into the surrounding area and into the sea!

From 17 March, the decision was made to drop seawater from helicopters on the reactors targeting reactors 3 and 4 in particular. This would create radioactive steam that also contaminated the environment, but it was getting desperately necessary to cool the reactors down.

In response to the radiation leaks the Japanese government ordered an evacuation around the Daiichi plant initially of 2km but as the crisis developed it extended up to 20km by the evening of 12 March. The exclusion zone around the site is shown in Figure 7. In total about 160,000 people were evacuated as a result of the meltdowns.

Clean-up of the exclusion zone could not begin in earnest until December 2011 when the nuclear plant was cool enough to be deemed in ‘cold shutdown’.

Two particular isotopes were of concern, both fission products spread extensively within the exclusion zone:

- **Iodine-131.** This is commonly ingested by humans as an element within many foodstuffs. Iodine-131 is a beta emitter with a half-life of eight days and can pose a serious health risk. This means that is active initially, but will decay rapidly enough to cease to be a threat in the long term. Iodine tablets were distributed to workers and those near the plant. The tablets are taken so that this non-radioactive iodine will be taken by the body to the thyroid gland. The aim is to ‘fill up’ the thyroid gland so that any radioactive iodine ingested will pass through the body and not linger in the thyroid gland to cause damage.
- **Caesium-137.** This is also readily incorporated into the human body and its salts are water soluble. It is also a beta emitter and has a much longer half-life of 30 years. This means that caesium-137 continues to be a threat for many years.

The clean-up involved removal of the contaminated topsoil within the exclusion zone. This is fraught with many difficulties including that there is a variable radiation within the zone, that each worker is only allowed a limited time within the zone and the issue of where to store the radioactive soil once collected. Another problem is the huge area that needs to be covered. It is estimated that the clean-up will cost tens of billions of pounds.

In the next section, you will look at the measurement of radioactivity within the soil four months after the crisis.

3.2.5 Clean-up of Iitate

Video content is not available in this format.

Iitate is a village outside the exclusion zone, 39km northwest of the Daiichi Nuclear plant. It is outside the exclusion zone but the prevailing winds were able to bring radioactive material with them and in April 2011 the village was evacuated.

The scientists are particularly interested in iodine-131 and caesium-137. The iodine is found to be decayed but the presence of caesium is still a worry. The top two and a half cm of soil are found to have high activity. This would need to be removed to make Iitate safe.

The evacuation order was listed on 1 April 2017. Residents were keen to go back to their homes and were proactive in measuring radiation levels themselves, so that they could make an informed decision about their return.

In the next section, you'll find out how the accident was graded.

3.2.6 Fukushima level 7

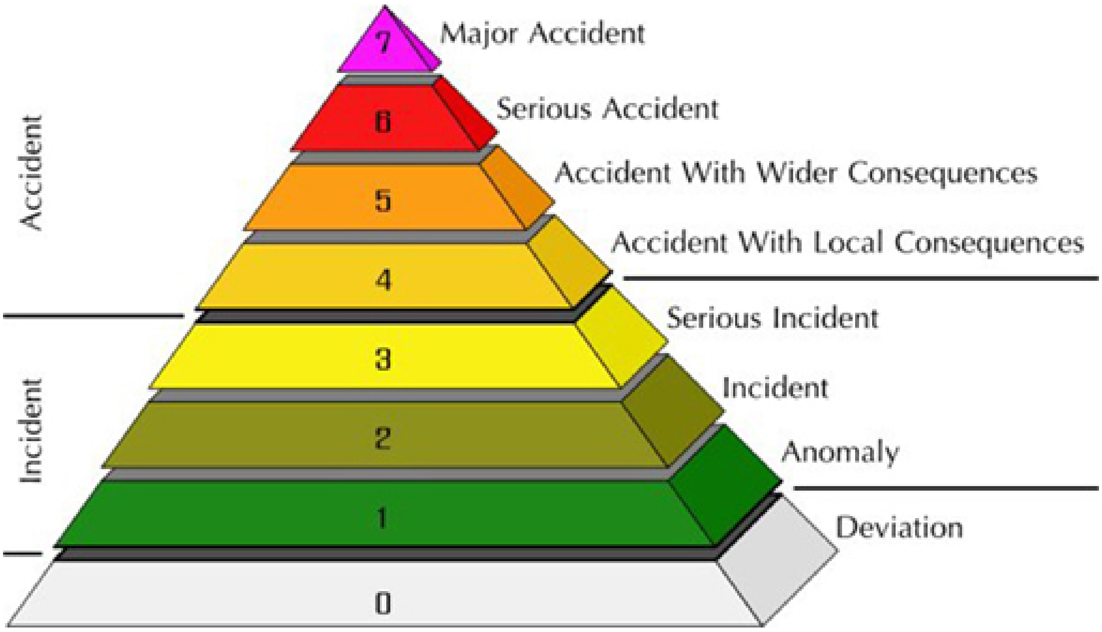

Figure 8

One month after the tsunami the Fukushima nuclear crisis was upgraded from a level 5 nuclear incident – an accident with wider consequences – to a level 7 incident – a major accident.

This is the maximum level and puts it in the same category as Chernobyl. At the time, many found the classification to be misleading as the severity of the disaster was determined by measuring the total amount of radiation emitted over the month. Ten times the amount of radiation had been emitted at Chernobyl over a much shorter time span.

In addition, the authorities in Japan evacuated the area far more quickly and, to date, no one has suffered ill effects from the radiation from Fukushima.

The next section looks at the levels of radiation in the population six months after the meltdown.

3.2.7 Fukushima – six months later

Figure 9

The text below is from the *New Scientist* and describes the situation in Fukushima six months after the incident.

The fallout from the radiation leak at the Fukushima Daiichi nuclear reactor in Japan may be less severe than predicted.

Radiology researcher Ikuo Kashiwakura of Hirosaki University, Japan, and colleagues responded immediately to the disaster, travelling south to Fukushima prefecture to measure radiation levels in more than 5000 people there between 15 March and 20 June.

They found just 10 people with unusually high levels of radiation, but those levels were still below the threshold at which acute radiation syndrome sets in and destroys the gastrointestinal tract. Geiger-counter readings categorised all others in the area at a ‘no contamination level’.

How did the population of Fukushima prefecture dodge the radioactivity? Gerry Thomas at Imperial College London, director of the Chernobyl Tissue Bank, says the answer is simple. ‘Not an awful lot [of radioactive material] got out of the plant – it was not Chernobyl.’ The Chernobyl nuclear disaster released 10 times as much radiation as Fukushima Daiichi.

Rapid response

Thomas says the quick and thorough response by the Japanese government limited radioactive exposure among the population. On 12 March, the same day as the first explosion at Fukushima Daiichi, the government ordered the evacuation of residents within 20 kilometres, and asked various institutions to begin monitoring contamination levels.

'They had no faxes, no emails, nothing was working,' says Thomas, adding that other countries might not have coped as well with a combined earthquake, tsunami and nuclear plant malfunction. 'Given the circumstances, they did phenomenally.'

The Japanese authorities also removed contaminated food and gave iodine to those who were very young, she says. Radioactive iodine can contaminate the thyroid gland in the body, leading to radiation-induced cancer, but can be counteracted by introducing non-radioactive iodine into the body.

Health researchers will have to keep an eye on radiation levels, however. 'There are many "hotspot" areas where radioactivity has accumulated locally,' says Kashiwakura. This is because rainfall deposited radioactivity unevenly. 'The Japanese people have a responsibility to continue research on the effect of radioactivity in humans.'

(Whyte, 2011)

Next, you'll move on to finding out how the situation developed in Fukushima and how it compares to Chernobyl.

3.3 Fukushima – water issues

Listen to the news report from the BBC’s Tokyo correspondent, Rupert Wingfield-Hayes talking to Adam Rutherford, dated August 2013, about two and a half years after the incident at Fukushima.

It discusses plans for an ice wall that was being designed to help stem the flow of water at the Fukushima. Rupert Wingfield-Hayes explains why the geographical position of the site and the flow of groundwater are making the task extremely difficult.

Audio content is not available in this format.

The two main issues identified are:

1. Containment of the contaminated water. There is an increasing amount of this in storage!
2. Isolating the groundwater from the contaminated water.

In fact the ice wall method of containment failed and was abandoned in 2014. Various attempts were made to cool the water sufficiently for it to freeze but were unsuccessful, leaving the issue of water flow ongoing.

In the next section, find out about the other ongoing challenges at Fukushima.

3.3.1 Fukushima – ongoing challenges

Figure 10

Like any nuclear incident site, the problems at Fukushima will take many many years to solve.

Some of the challenges the Japanese government face are:

Daiichi site

The ice wall failed and radioactive material at the site is still being released through contaminated water, four years after the crisis.

From 2014 onward, efforts were made to treat the water and remove some of the radioactive isotopes within it using the filtering system mentioned in the news report you heard in the previous section. This has had some success. The long-term aim is to be able to safely release the water to the sea with a legal discharge concentration of activity. The presence of radioactive isotope of hydrogen-3 (tritium) is limiting how much water can be returned.

The problem is likely to continue as long as the source of the radioactivity is still present. There are however severe problems connected with the removal and containment of melted fuel and debris. The radiation is still so high that workers cannot safely be within reactors 1 to 3 for even short amounts of time so technological advances would be required to begin dismantling in the near future.

In all likelihood, it will take 30–40 years for all the cores to be dismantled and removed off-site and the flow of water may well remain a difficult issue until then.

Exclusion zone

In April 2014, the first group of the people that had been evacuated in 2011 were allowed to return home. This first group were 350 residents of the Miyakoji district in Tamura city, which lies inside the 20km-radius exclusion zone. In October 2014, residents of Kawachi village were also allowed home.

While this appears positive, many of those evacuated are too fearful to return and wary of the information they have been given by the government and by TEPCO.

Also those allowed to return are very much in the minority. In the Fukushima prefecture overall, 130,000 people are still displaced. It is very unclear when the remaining evacuees will be able to return home. The large scale decontamination continues but some areas are likely to have very high levels of radiation for many years to come.

In the next section, you will consider the health effects on the misplaced population of Fukushima.

3.3.2 Fukushima – health effects three years later

Video content is not available in this format.

Three years after the tsunami in Fukushima, the majority of those evacuated are still living in temporary accommodation and unable to return home.

The video states that the ongoing fear of the radiation is leading to more health effects than the radiation. To date, no one has died from the radiation from the nuclear fallout. Only a few of the workers at the Daiichi plant have the possibility of suffering any health effects. In contrast, the earthquake and tsunami took thousands of lives.

Nonetheless, those unable to return home lost everything, their homes, woodlands, fields and farmlands. Many have suffered with their health and are traumatised.

Things will not be able to go back to how they were in Fukushima for many decades. If we want to imagine what Fukushima's exclusion zone will be like in future it is helpful to look at Chernobyl today, which you'll do in the next section.

3.3.3 Chernobyl today – the reactor

Figure 11

It is nearly 30 years since the nuclear disaster at Chernobyl's power plant. The Chernobyl nuclear plant remains entombed in its concrete and steel sarcophagus which is due to end its 30 year lifespan in 2016.

The sarcophagus will be replaced by a 'New Safe Confinement' which is under construction. This is designed to contain the radioactive material within the plant and act as a shield from the weather for the next 100 years. It is a huge engineering challenge.

In the future, it is hoped that one day all this radioactive material will be disposed of safely – that will be an even more challenging task! The New Safe Confinement will provide a protected space where the dismantling can begin, but this is likely to be performed by machines as the radiation levels are still too much of a risk for humans. Figure 11 shows the stages of assembly – the building is being built in two domed halves.

The radiation in the exclusion zone is variable and dependent on the weather, still needs constant monitoring for those that are working on the abandoned plant. Levels of radiation are still high but have dropped sufficiently for workers to be able to spend a week or two working on the plant. Care stills needs to be taken not to ingest radioactive material in the air and to wear suitable protective clothing.

In the next section, see images from the exclusion zone around Chernobyl.

3.3.4 Chernobyl today – exclusion zone

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The 30 km exclusion zone around Chernobyl remains predominantly abandoned and much is a wilderness. The nearby Red Forest has encroached on the plant and the nearby town of Pripyat.

The exclusion zone may look lush but the vegetation itself contains high levels of radioactive material. The forest is monitored for wildfires as a large fire in forest would lead to dangerous levels of smoke particles entering the atmosphere.

Further out than Pripyat, there have been some attempts at resettlement into areas evacuated in 1986 due to the fallout from Chernobyl. In 2010, the Belarus government adjusted their policy on Chernobyl, with some regions reclassified with a view to begin the process of returning the region to normal use. They state that for many areas and with minimal restrictions, the annual dose will be between 0.1 and 1 mSv – significantly less than the annual dose from granite to those living in Cornwall.

The task is large as the infrastructure, utilities and new buildings (to replace those that will be demolished) all need to be provided. Much caution is required in the use of local resources such as wood due to lingering high-level of caesium in some places, although in others the level is low and agriculture may be attempted. Cultivated food will be safe to eat although wild fruit will still be restricted.

The images in the video were taken on a tour around the Chernobyl reactor and the town of Pripyat.

3.3.5 Chernobyl today – health effects

Video content is not available in this format.

In the video, Jim al-Khalili talks to Professor Mykola Tronko at the Institute of Endocrinology and Metabolism in Ukraine.

Initially, there were great fears about the health risks of the radiation on the nearby community. Pripyat was not evacuated until two days after the explosions, so the residents would certainly have been exposed.

From 1990, there were higher incidences of thyroid cancer in children and this was a cause of great concern. This particular cancer was screened for as it was known that any ingested iodine-131 would collect in the thyroid. As we learned in Week 1, the emitted particles from radioactive substances can damage human tissue and lead to cancers forming.

However, there was no rise in other cancers. From the vantage point of today we can see that the effects from the fallout were substantially less than were feared at the time.

In the next section, you will think about the lessons that can be learned from these disasters.

3.3.6 What have we learned?

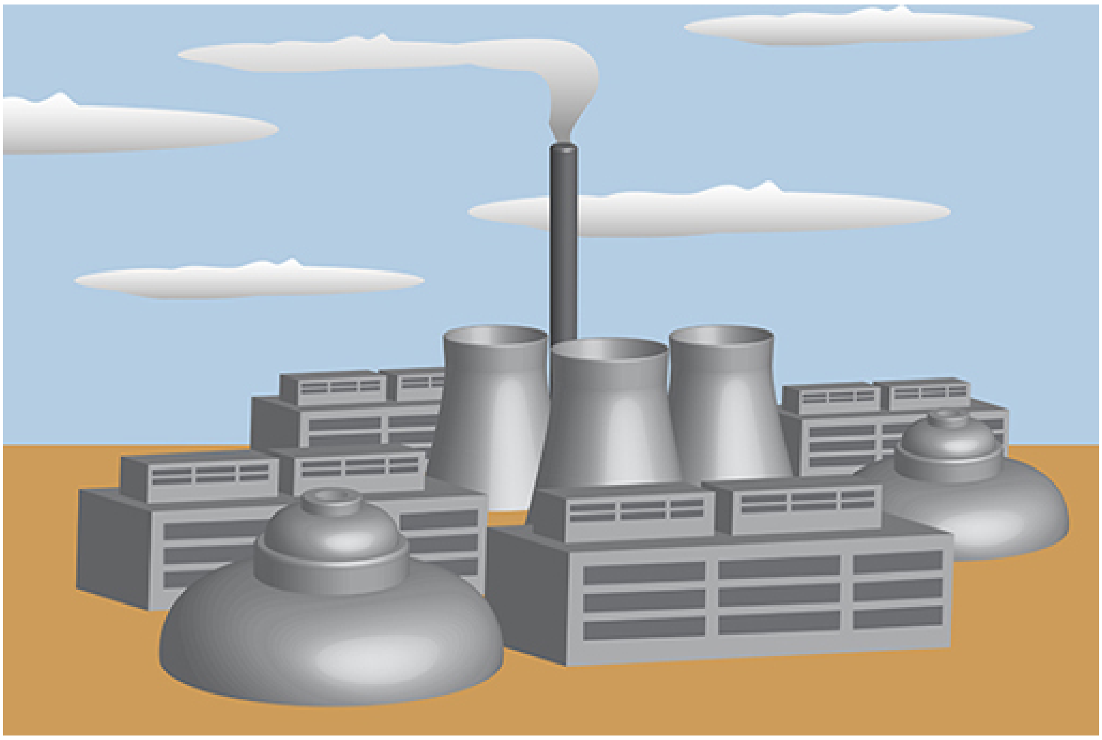

Figure 12

In this final section of this week, you will use what you have learned so far to think about what you would do if you were involved with a nuclear power station.

Activity 2

Imagine that there is a nuclear power station being built ten miles from where you live. You have an advisory role in its construction!

Based on what you have learned this week about previous nuclear incidents, think about the advice you would give and write a paragraph explaining your answers to these questions:

- What would you require from the reactor to minimise the risk of meltdown?
- If there was an incident, what guidelines would you recommend for action afterwards?
- If these measures were put in place, would you be happy to live in the vicinity?

3.4 Quiz for Week 3

Take the quiz which will test and apply your knowledge of the material in Week 3.

Week 3 quiz

Come back here when you are done.

3.5 Summary of Week 3

Figure 13

The nuclear incidents that you examined this week were the result of reactors going into meltdown.

In the case of Chernobyl, an error with the control rods led to the fuel rods going supercritical. The accidents at Three Mile Island and Fukushima were both due to failures in the coolant circulating.

At Fukushima, the reactors were shut down satisfactorily after an earthquake but a tsunami then flooded the building and this was the primary reason for the coolant failure. Meltdown and hydrogen explosions followed which led to radioactive fission products contaminating the surrounding area.

The containment of the reactors at both the Fukushima plant and Chernobyl is an ongoing problem and the decommissioning of the reactors themselves cannot happen for decades.

Next week, you will consider the environmental issues that surround the need to limit our use of fossil fuels. You will look at the design of the new nuclear reactor, being built at Hinkley Point, which has taken the events at Fukushima into account. You will also look at new developments including the use of thorium as a fuel and the pursuit of nuclear fusion.

You can now go to Week 4.

Week 4: A future for nuclear power?

Introduction

In the following video, Sam and Gemma discuss developments in energy sources in a replica of the JET facility at Cullham.

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4.1 Energy for the future or relic of the past?

Figure 1

The Flamanville plant is the first new nuclear plant to be built in France for 15 years.

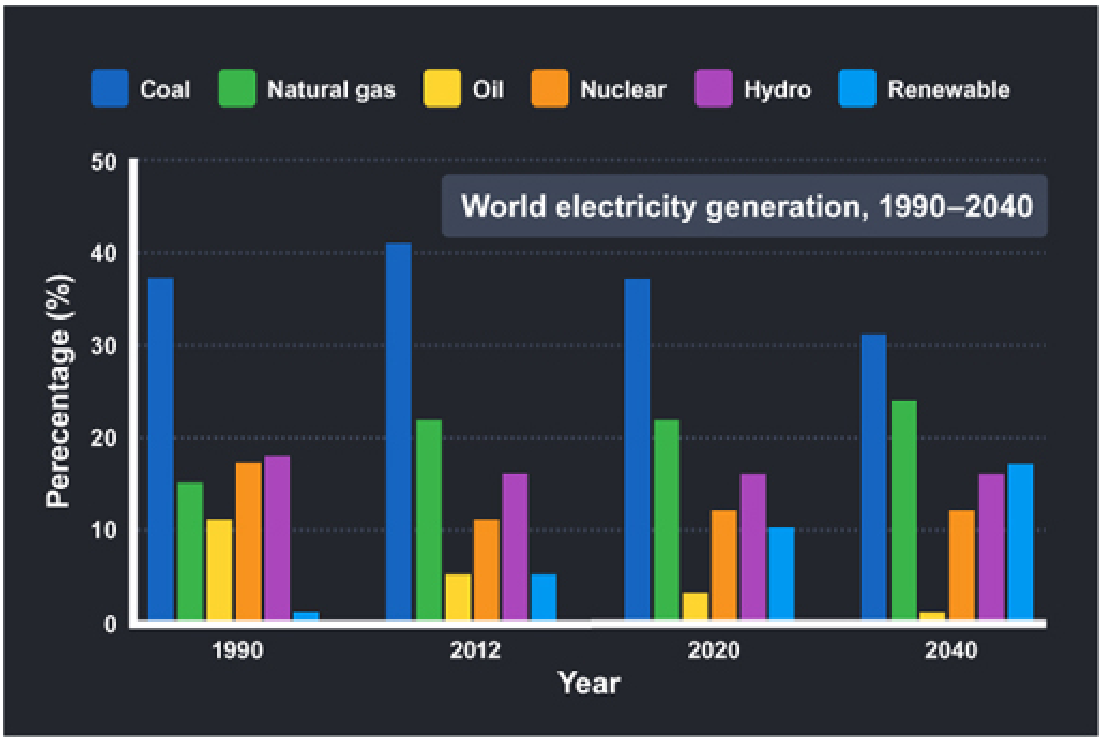

Figure 2

Nuclear power – an energy source for the future?

The events at Fukushima had repercussions around the world. It led many to question whether nuclear power is an energy for the future or a relic of the past.

It was well publicised that in the wake of the accident at Fukushima, Italy and Germany announced plans to phase out their nuclear industry, with the latter intending to phaseout all reactors by 2022. Both Spain and France aim to reduce their dependency on nuclear power.

Less publicised is, what you learned in Week 2, that there are many nuclear reactors under construction and a further 500 proposed plants! Table 1 shows in which countries these are to be situated.

Table 1 Nuclear reactors around the world

Country	Reactors operable	Reactors under construction	Reactors planned	Reactors proposed
US	99	5	5	17
France	58	1	1	1
Japan*	48	3	9	3
Russia	34	9	31	18
South Korea	23	5	8	0
China	22	27	64	123
India	21	6	22	35
Canada	19	0	2	3
UK	16	0	4	7
Ukraine	15	0	2	11
World Total	**437**	**70**	**183**	**311**

This table shows the top ten countries with the most nuclear reactors and the world total. *Japan shut down all of its nuclear reactors following the Fukushima disaster in 2011.

(Source: World Nuclear Association)

Many countries intend to increase the amount of nuclear energy that they use; these include Hungary, Romania and Ukraine. Poland and Turkey plan to build their first nuclear reactors and as you can see from the table, China has many reactors planned.

Why are so many countries forging ahead with nuclear power?

You will examine the answers to this question in the following sections along with some of the issues that surround the use of fossil fuels. In particular, you will look at the need to find cleaner energy sources that reduce the emission of carbon dioxide.

4.1.1 Carbon emissions and global warming

There is much research going into energy resources that have low carbon emissions because it's recognised that carbon dioxide damages the Earth's atmosphere.

Most of the Earth's atmosphere is composed of nitrogen and oxygen but there are other gases in the atmosphere that concern us here: water and carbon dioxide.

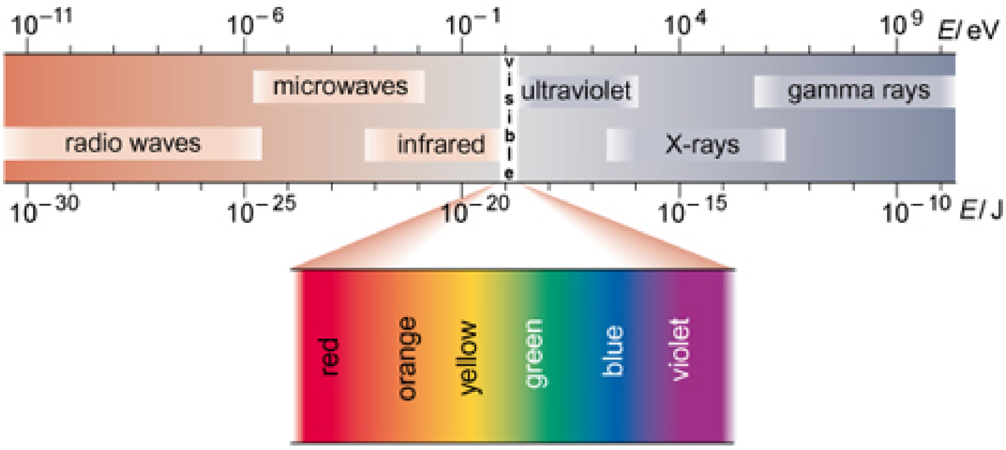

Figure 3 The electromagnetic spectrum (the energy scale is given in two units; both the electronvolt (eV) and the joule (J) are explained later)

These gases consist of molecules which are made up of more than one type of atom and as a consequence of this the bonds between the atoms vibrate. These vibrations enable the gases to absorb infrared (IR) radiation which comes from the Earth's surface. If you look at Figure 3 you can see that IR is next to visible light, and this part of the electromagnetic spectrum has slightly lower energy.

It means that IR cannot pass through the gases, it is absorbed and re-emitted by the gases in the atmosphere, warming up the Earth's surface. This warming is called the greenhouse effect and gases such as water and carbon dioxide that are able to absorb IR are called greenhouse gases. If the amount of greenhouse gas in the atmosphere increases, then more energy is absorbed by the atmosphere and re-emitted towards Earth.

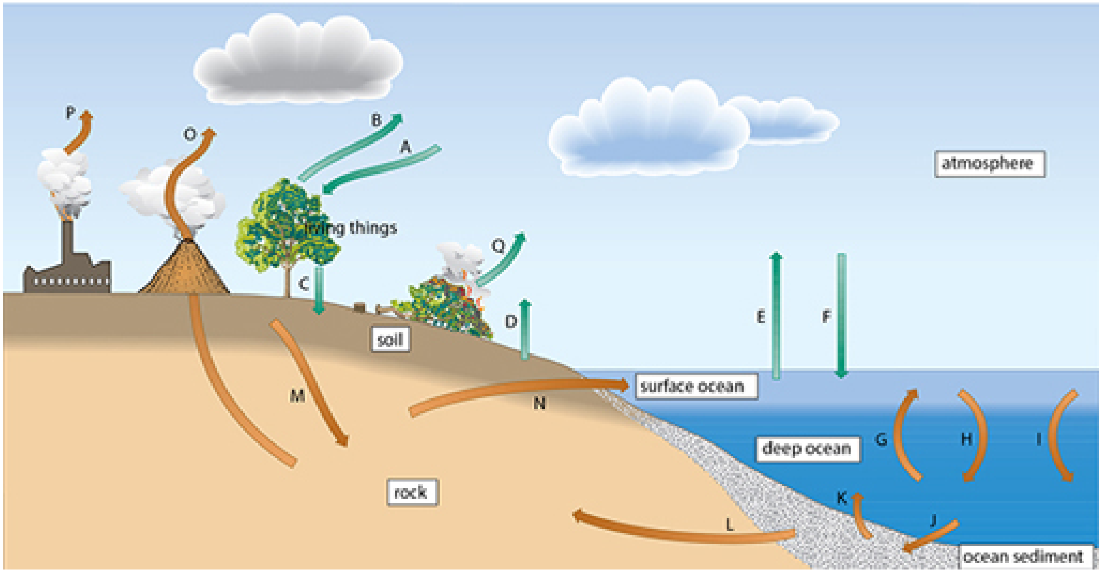

Figure 4 Today's carbon cycle; the transfers P and Q represent human-accelerated release of carbon from the rock reservoir to the atmosphere (P) and from living things reservoir to the atmosphere (Q)

Carbon exists in many different forms on the Earth and the carbon cycle consists of the flow of carbon between different reservoirs – these are shown schematically in Figure 4. There are many natural processes that exchange carbon between the different reservoirs.

One of these reservoirs is the atmosphere. If more carbon dioxide enters the atmosphere, it is possible that more will be retained within it and there will be an increased greenhouse effect and temperature rise leading to global warming.

There are processes that remove carbon from the atmosphere – for example, photosynthesis into the reservoir of 'living things' – and throughout Earth's history the flow between reservoirs has been able to adjust in times of increased temperature or cooling. However, burning fossil fuels over the past 100 years has led to a new and additional process by which carbon can be transferred to the atmosphere.

When fossil fuels burn in air, oxygen reacts with organic carbon to form carbon dioxide and water vapour, usually released into the atmosphere. These are both greenhouse gases. The fear is that our prolonged burning of fossil fuels in power stations and vehicles may lead to a situation where the carbon cycle is unable to adjust and carbon (as carbon dioxide) will build up in the atmosphere and lead to irreversible climate change.

Consequently, there have been moves recently to reduce the release of carbon dioxide to a sustainable level – one that would allow the carbon cycle to cope with its absorption from the atmosphere.

In both the UN Kyoto protocol and at a G8 summit, steps have been taken to legally require nations to limit their carbon dioxide emissions. The UK is committed to reducing its carbon emissions to 80% of its 1990 value by 2050. You can have a look at the UK regulations on the Committee on Climate Change website (n.d.). You may want to find the requirements of your own country.

As a result of these issues everyone is encouraged to reduce their carbon footprint as individuals. You can calculate your carbon footprint in the next section.

4.1.2 Find your carbon footprint

Figure 5

You may have heard the term 'carbon footprint'; this is a measure of how much carbon dioxide is released into the atmosphere as a result of activities carried out.

Activity 1

Calculate your own carbon footprint by answering questions about your home, car, travel and eating habits. The calculator will give you a figure for your approximate carbon footprint – this is the number of tonnes of greenhouse gas that is released due to your actions.

The first section is about your house. If you have your utility bills to hand you can add in figures for your consumption. At the end you'll see your footprint in comparison with the average in the UK and the target for the world.

Calculate your carbon footprint using Carbon Footprint's carbon calculator (2016).

- What was your carbon footprint?
- What made the largest contribution to it?
- In what ways could you reduce it?

In the next section, you can find out how the government plans to meet the carbon reduction targets.

4.1.3 The energy gap

Video content is not available in this format.

The UK National Grid faces supply problems due to the closure of gas and coal powered power stations.

These are being closed, primarily, to reduce carbon emissions and meet targets. But even if there weren't environmental reasons, the amount of fossil fuel of any type is finite and the reserves within the Earth will run out in the future.

The video mentions the use of nuclear energy as an energy source that will fill part of the gap in energy resources that is left from the diminishing use of fossil fuels.

In the next section, you will look at nuclear energy in the context of carbon emission and cost.

4.1.4 The role of nuclear energy

In the current era, there are three main factors driving energy policy.

They are:

1. climate change and the need to look for energy sources that reduce emissions of carbon dioxide into the atmosphere
2. the finite supply of fossil fuels
3. energy security and the need for countries to be able to supply their own energy with reduced dependency on other nations.

Given all of these factors, nuclear energy is given serious consideration.

How does nuclear energy fit the bill?

The graph in Figure 6 shows the cost of nuclear energy in comparison to other emissions and also an indication of the carbon emission status. Note that the costs are in US dollars per megawatt.

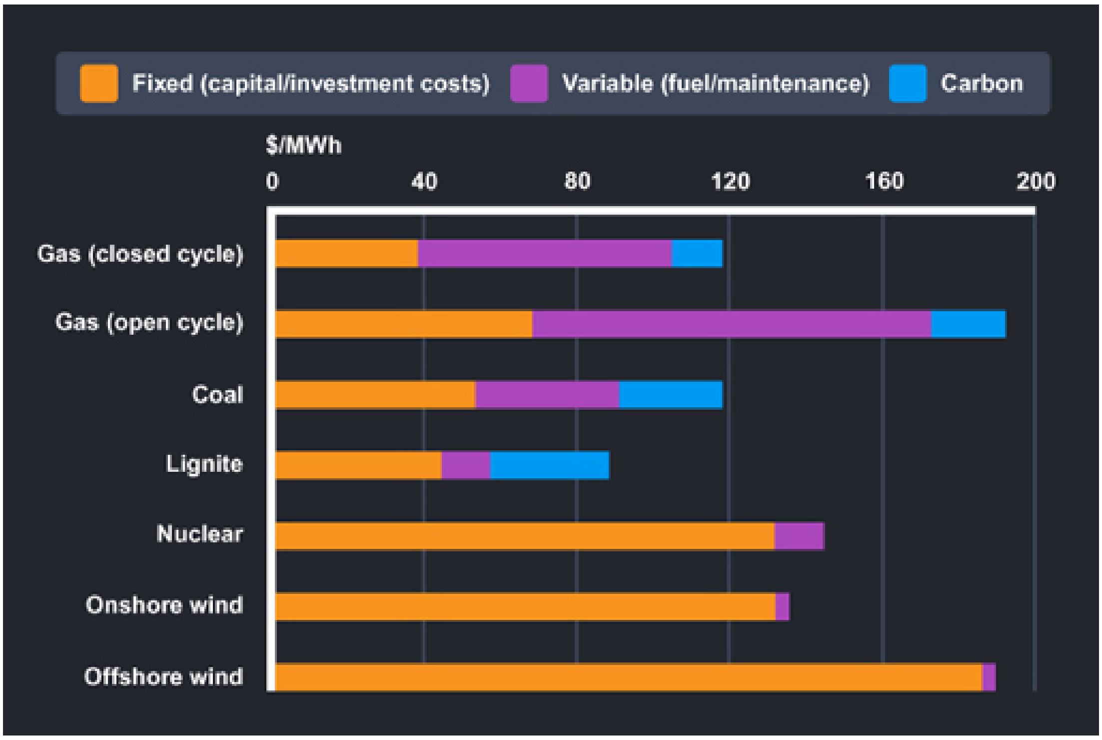

Figure 6

You can see that the running costs of nuclear power (shown in purple) compare favourably to those of other alternatives and once up and running nuclear power is very efficient. However, the cost of building nuclear power stations (in orange) is large. This means that if a government wishes to use nuclear power as a resource they need to commit to a large initial investment.

The initial outlay is comparable to renewable energy resources such as wind but still much more expensive than solar energy, for example. Some people feel that the money spent on nuclear energy is better spent elsewhere.

Carbon emissions are shown on the graph and while there may be some carbon emission involved in the construction of nuclear power stations, the process of fission itself has no carbon emissions.

Next, you will find out how plans have started to be implemented in the UK.

4.1.5 New reactor at Hinkley C

Figure 7

In Week 2, you heard that, at the moment, nuclear power provides up to 20% of the electricity requirements of the UK. This is a large proportion, but many of the UK's power stations are old and will need replacing soon.

To address the energy shortfall that will occur from limitations on the use of fossil fuels, a new nuclear power station in the UK was given the go ahead in 2013. The power station, called Hinkley C, is being built at Hinkley Point, Somerset. On the same site is Hinkley A, a decommissioned Magnox reactor and Hinkley B an AGR reactor that has been running since the early 1970s. Once built, it is hoped that the two new reactors will provide about 7% of the UK's electricity. They are being built by a consortium led by EDF Energy and will be half owned by Chinese investors.

Hinkley C will be a modern power station with significant differences to the older reactors on the site, in both the design of the power station and the issue of radioactive waste. Hinkley C's reactors are the first to be built post-Fukushima and their design takes into account lessons learned there and in other nuclear incidents.

Some of the improvements are listed below.

- The European pressurised reactors (EPRs) are an improvement on the pressurised water reactor and a huge improvement on the old Magnox and AGR systems. THE EPRs will be more efficient in producing energy and so need smaller amounts of fuel which will reduce the risk of a major accident.
- The floor of the reactors is on a base of 6m concrete with channels carved into it. In the event of a meltdown, this should stop the molten core burning through the floor and guard against leakage into the environment.
- Hinkley will have two concrete walls each over 1m thick. These are designed to protect the reactors and even to withstand aircraft strikes!

- In a direct response to the events at Fukushima and the importance of the cooling systems to safety, there will be two extra back-up generators in widely spaced, waterproof buildings.

In the next section, you will hear about how the developments will also improve the management of nuclear waste.

4.1.6 Nuclear waste

In the following audio, Adam Rutherford talks to Professor Sue Ion, former Director of Technology at British Nuclear Fuels.

She discusses how the modern design of Hinkley means a much smaller volume of nuclear waste of all categories.

Audio content is not available in this format.

Figure 8

In the next section, you will consider how important you think this development is.

4.1.7 Happy with Hinkley?

Figure 9

At the end of last week, you considered what you would want to be present in the design of a nuclear power station. How does what you said match to Hinkley C?

Activity 2

Think through these questions:

- Do you agree with the building of Hinkley C? Why or why not?
- Do you think the new safety measures are enough? Why or why not?
- Do you think that the lower volume of radioactive waste is significant? Why or why not?

In the next section you will look at one of the alternatives to fission of uranium or plutonium.

4.2 Thorium – nuclear fuel of the future?

Video content is not available in this format.

So far, the course has considered only uranium and plutonium as nuclear fuels.

However, thorium has been suggested as an alternative fuel because it is more abundant than uranium and has some advantages regarding safety.

The transformation of thorium-232 into a fissile isotope follows two β-decays:

$$^{232}_{90}\mathrm{Th} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow{\beta-decay} {}^{233}_{91}\mathrm{Pa} \xrightarrow{\beta-decay} {}^{233}_{92}\mathrm{U}.$$

Many research groups are actively pursuing thorium as a fuel. It is of particular interest to countries such as Norway and India which have large natural reserves of thorium.

The next sections consider a more radical change in nuclear fuel!

4.2.1 The Sun's energy source

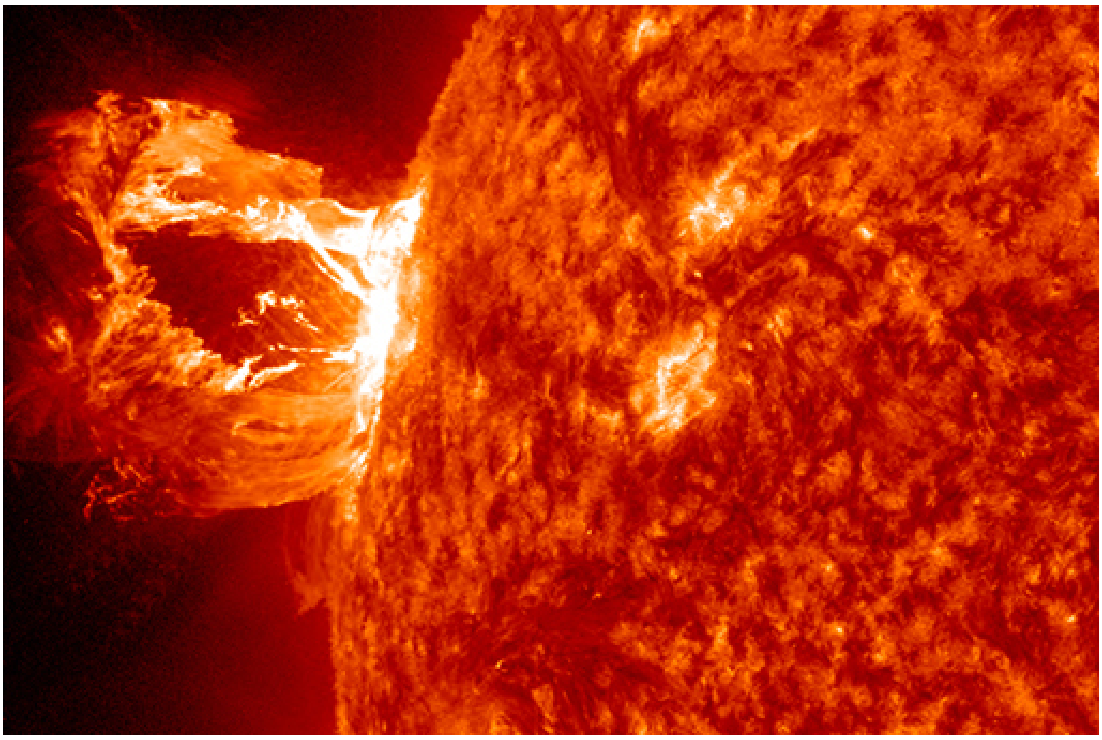

Figure 10

The origin of most of the energy sources on the Earth is the energy we receive from the Sun in the form of electromagnetic radiation.

The Sun produces the whole of the electromagnetic spectrum (look back at Carbon emissions and global warming). The Sun's power output is 3.846×10^{26} W – this means it produces about 400 million billion billion joules of energy every second! It is clearly of interest to determine the Sun's own energy source.

The Sun is (as all stars are) composed mainly of hydrogen. The Sun is by far the largest object in the Solar System – it contains 99% of the mass of the entire Solar System. The large mass means that there are very large gravitational forces that pull the Sun together and create extremely high temperatures and pressures at the centre. These conditions allow **nuclear fusion** to occur.

Fusion involves combining, or 'fusing', two small nuclei into one larger one. It is the opposite of fission which, as you learned in Week 1, involves splitting large nuclei into two smaller ones. Like nuclear fission, fusion is a nuclear process because fusion reactions involve changes in the number of protons and neutrons within nuclei. These changes within the nucleus itself define nuclear reactions as opposed to chemical reactions. In both cases energy is released, considerably more in the case of fusion.

You will examine a bit more of the physics behind fusion in the next section, however all that you *need* to know is that the process of fusion produces a huge amount of energy.

4.2.2 What is nuclear fusion?

Figure 11

You will recall from Week 1 that the origin of the energy that is released is the change in mass and binding energy when a large nucleus splits into two lighter ones.

This works for massive atoms such as uranium, plutonium or thorium. You looked at the fission reaction:

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{93}_{38}\mathrm{Sr} + 3\,{}^{1}_{0}\mathrm{n}$$

The mass of the fission products and the three neutrons is less than of the U-236, although the number of nucleons is the same and this missing mass is released as energy due to equivalence of mass expressed by the equation E = mc^2.

We can also consider this in terms of binding energy – the energy released is due to the difference in binding energy of the nuclei involved.

Nuclear fusion

Let us look at a fusion reaction:

$$^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He}$$

Here hydrogen is fused with deuterium – the heavier isotope of hydrogen that contains one neutron to produce helium-3.

As with the fission reaction above, the number of nucleons is the same on each side but the mass of the helium nucleus is less than that of the hydrogen plus deuterium. This missing mass is converted to energy and released. In fact, the mass difference tends to be larger than with fission so that more energy is released in fusion reactions.

You may well be puzzling over how both splitting nuclei apart and fusing them together can produce energy. The full answer to this is beyond the scope of this course, but suffice to say that the physics within nuclei mean that the following is true.

- heavy nuclei with more than 56 nucleons release energy by undergoing fission
- light nuclei with fewer than 56 nucleons release energy by undergoing fusion.

This is shown in Figure 12.

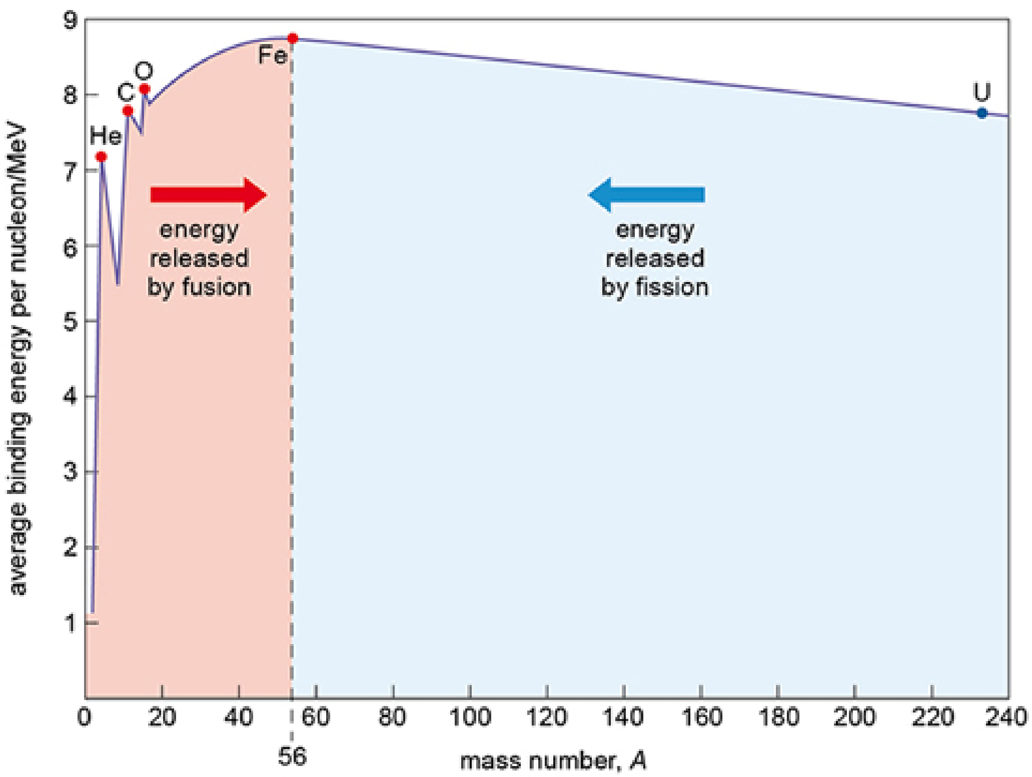

Figure 12 Energy released by fission and fusion

The advantages of fusion over fission

Nuclear fusion is often heralded as the ultimate future technology although this has been the case for some time! It is nonetheless pursued as it has significant advantages over fission.

- The fuel for fusion is hydrogen. Hydrogen is by far the most common element in the Universe and is plentiful on Earth. Water contains hydrogen, for example. The fuels used are often the isotopes of hydrogen called deuterium (hydrogen-2) and tritium (hydrogen-3). Deuterium can be extracted from water and tritium can be produced from lithium in the Earth's core. Both of these resources are plentiful and will last for millions of years.
- Unlike the radioactive products of fission, fusion produces no long-lived isotopes. Only plant components become radioactive and these will be safe to recycle or dispose of conventionally within 100 years.

- The process of fusion produces a huge amount of energy and only very tiny amounts of fuel need to be used. This means that nuclear incidents, such as those you heard about last week, are not possible with fusion.
- As with fission, there are no carbon emissions. The only by-products of fusion reactions are small amounts of helium, which is an inert gas that will not add to atmospheric pollution.

In the next section, you will consider the difficulties of achieving fusion.

4.2.3 Making use of fusion

In the following video, Professor Steve Cowley of JET explains the process of fusion and discusses the challenges of creating it on Earth.

You will learn more about the JET project at Culham later.

Video content is not available in this format.

In the next section, you will review the science behind it.

4.2.4 Challenges of fusing nuclei

The main challenge of achieving fusion on Earth, as described by Steve Cowley in the video, can be examined by looking at the fusion equation again.

$$^{1}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \rightarrow ^{3}_{2}\mathrm{He}$$

The hydrogen nucleus contains one proton and the deuterium nucleus one proton plus one neutron. Both of these nuclei are positively charged and will therefore repel each other. As we discovered in Week 1, it is the strong force that holds nuclei together and it is certainly capable of overcoming the electrostatic repulsion but only acts at extremely short range. To get the strong force to pull the nuclei together you need to get the nuclei very close. This is no mean feat as the nuclei are trying to push themselves apart!

If the nuclei are going fast enough they will be able to overcome the repulsion to get close enough for the strong force to allow fusion. The intense temperatures and pressures at the centre of stars make these speeds achievable but suitable conditions cannot be easily recreated on Earth.

The fuels used are generally deuterium (hydrogen-2) and tritium (hydrogen-3) – these each have neutrons in their nuclei that contribute to the attraction of strong force but not to the repulsion. Tritium and deuterium fuse to give helium-4 and one neutron. In order to enable nuclei to fuse, a plasma is used. A plasma is a gas that has had a significant proportion of its atoms ionised so that the positively charged nuclei and negatively charged electrons are dissociated from one another. In order to produce a plasma the gas needs to be extremely hot – over 100 million degrees Celsius!

The Joint European Torus (JET) uses magnetic fields to confine the enormously hot fuel, called a plasma. The fields are within a large donut-shaped device called a tokamak or torus.

Another approach is to use lasers to produce pulses of X-rays, fired at a small fuel pellet of tritium or deuterium. The pulses squeeze the pellet causing it to implode and briefly undergo fusion. The National Ignition Facility (NIF) project uses this approach and you will learn more about this later.

In the next section, you will test yourself on what you've learned about fusion.

4.2.5 Fusion

Test yourself on what you've learned about fusion in the following activity.

Activity 3

What do the processes of fission and fusion have in common?

- They both produce a great deal of long lived radioactive waste

The process of fission produces radioactive waste but the process of fusion does not. Think again about what fission and (hopefully one day) fusion are used for.

- Both processes produce a great deal of carbon dioxide

In fact, neither process produces a great deal of carbon dioxide. Think again about what fission and (hopefully one day) fusion are used for.

- They both occur within the Sun

Nuclear fusion occurs in the Sun but fission does not. Think again about what fission and (hopefully one day) fusion are used for.

- Fusion and fission release a proportionally large amount of energy

This is true for both processes. Fission is the process used in nuclear power stations to create energy and fusion will hopefully be able to be used for this process in the future.

Why is nuclear fusion difficult to achieve?

- The fuel used is very rare on Earth

The fuel, deuterium, is found in water which is readily available on Earth! Think of the process involved in achieving fusion.

- The nuclei are negatively charged and repel each other

This is not true. The nuclei are both positively charged and repel each other. Think of the process involved in achieving fusion.

○ Very high temperatures are required

Nuclear fusion is difficult to achieve because very high temperatures are required – of the order 200 million ^{o}C.

○ The reactor is likely to go into meltdown

The reactor is not likely to go into meltdown with a fusion reactor as the mass of the fuel is so small and fusion is difficult to achieve.

4.2.6 Fusion at JET and ITER

Video content is not available in this format.

In the video Steve Cowley explains the experiments conducted at JET (Joint European Torus) in inducing nuclear fusion and looking to the future at the tokamak being built at ITER, (International Thermonuclear Experimental Reactor).

One of the main challenges in the development of fusion is creating a reactor that is commercially viable. At the moment, the fusion at JET can only occur for a matter of seconds. The energy achieved is about the same as that put in, to achieve the contained plasma or a little more. This means that the tokamak at JET is not commercially viable.

The successor to JET is ITER, a new tokamak that is being built in France. This should be able to produce 500 MW of fusion power.

Next, read about the National Ignition Facility (NIF).

4.2.7 The National Ignition Facility

In the following video, Brian Cox looks round the National Ignition Facility (NIF) and observes laser-induced fusion.

NIF has been running since 2009 and is still a way from producing fusion that maintains an overall gain in energy on a large scale.

However, since 2014 they have been able to produce more energy than that required to start the reaction. If you want to read more about this development, read this article from *New Scientist* (Aron, 2014).

Video content is not available in this format.

4.3 Nuclear energy debate

Now that you have explored the science behind nuclear power and all the key issues surrounding its use, take time to reflect on the arguments for and against nuclear power.

Listen to the debate. You may feel that you agree with some of the points that they raise, perhaps even points from both sides.

Video content is not available in this format.

In the next section, you will be invited to consider your views on nuclear power.

4.3.1 What are your views on nuclear power?

Figure 13

Now you have a chance to bring together the ideas that you have examined throughout this course.

Activity 4

Consider the following questions:

- What are the main arguments for investing in nuclear energy at the present time?
- How convinced are you that nuclear energy should form part of the energy mix for the future?
- Have your views changed through your study? If not, how have they been reinforced?

4.4 End-of-course quiz

Review your learning throughout the course in the end-of-course quiz.

End-of-course quiz.

Open the quiz in a new tab or window and come back here when you are done.

4.5 Summary of Week 4

Figure 14

At the moment, most of our power comes from the burning of fossil fuels, which release carbon dioxide and water when burnt.

These are greenhouse gases and contribute to the greenhouse effect and global warming. Because of these environmental concerns and the finite nature of fossil fuels, alternative resources are being pursued, one of which is nuclear energy.

In order to meet the UK's energy requirements, a new nuclear power station is being constructed at Hinkley Point in Somerset. It has enhanced safety features in order to protect the core and to contain it in the event of a meltdown. It is also expected to produce significantly less nuclear waste compared to older type reactors. Research is being done elsewhere on using thorium as a nuclear fuel rather than uranium or plutonium. This would particularly advantage countries that have reserves of thorium.

Another technology that is being pursued is nuclear fusion. Like nuclear fission, this also involves changes within the nucleus itself but involves bonding light nuclei together rather than splitting heavy nuclei apart.

Fusion reactions power the stars but it is very difficult to achieve on Earth as the two nuclei are both positively charged and require very high energies to overcome the repulsion. To date, nuclear fusion has not attained the status of a workable energy resource but research is progressing at NIF in the US and ITER in France.

Complete our survey

We would love to know what you thought of the course and what you plan to do next. Whether you studied each section or dipped in and out, please take our Open University end-of-course survey. Your feedback is anonymous but will have massive value to us in improving what we deliver.

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Further reading

Look up the periodic table.

Find out more about Marie Curie by listening to the BBC programme *In Our Time: The Curies*.

Compare different sources of radiation at the UK Government site.

Review a list of the uses of radioactive isotopes.

There is more information from the World Nuclear Association about Fukushima.

There is much more information from the World Nuclear Association about Chernobyl.

Read more about Hinkley C from EDF Energy.

Look again at The National Grid status from Week 2.

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