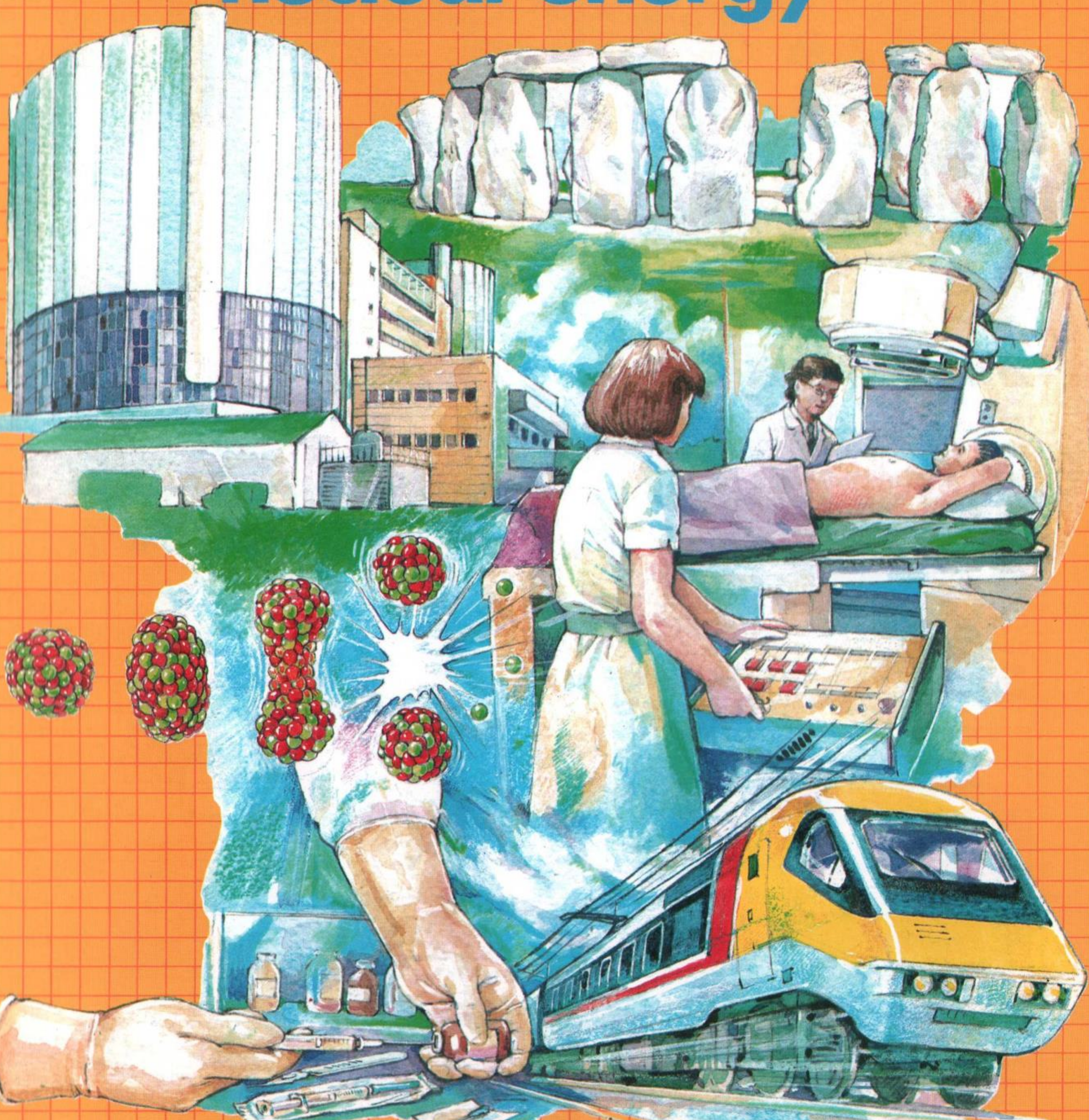
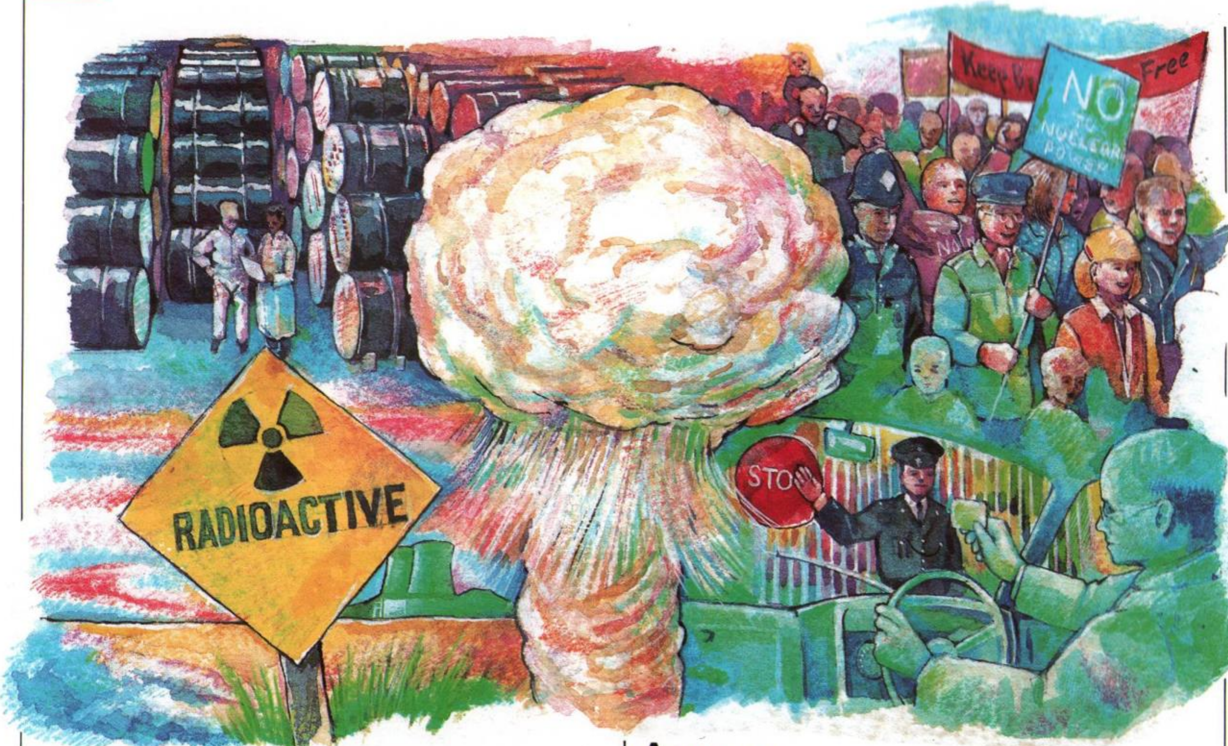
A Science and General Studies Resource Book for GCSE

Finding out . . .

About nuclear energy



1 Nuclear energy – friend or foe?



WHAT YOU CAN DO

1 The picture on the front cover illustrates some of the useful ways in which nuclear energy can be made to work for us. Name as many as you can.

2 On this page is the sort of picture an opponent of nuclear energy might paint. Can you explain what these illustrations are about?

3 Can you think of any other examples, for or against nuclear energy?

Nuclear power stations generate about one-fifth of Britain's electricity

Like it or not, nuclear energy is already with us. Apart from the power stations, energy from atoms is used in many different ways throughout industry, medicine and research laboratories.

- Are people right to be concerned?
- Could we manage without nuclear energy?
- Or should we welcome its development, because of its unique contribution to our way of life?

This book is to help you think about questions like these, by providing some of the facts and explanations.

A survey

It might be interesting to find out what your friends, family and neighbours feel about nuclear energy (or atomic energy, which is the same thing).

A survey might include questions like these:

	Yes	No	Don't know
• Do you think we need nuclear power stations in Britain?			
• Do you think we could do without them altogether?			
• Would you mind living next to one?			
• Would you mind working in one?			
• Do you have any idea how they work?			
• Can you name one other use of nuclear energy or radioactivity?			

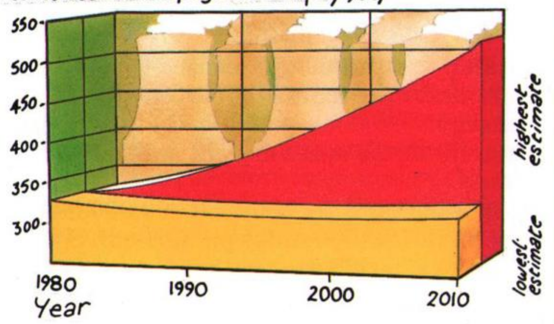
Facts about energy

Primitive man used about as much energy as a household light bulb (100 watts). He got it all from his food. In Britain today we each use as much energy as 60 light bulbs.

The industrialised countries are using more and more energy. Most underdeveloped countries are heading the same way. And to make matters worse, the world's population is increasing rapidly.

How Britain's energy demand might change

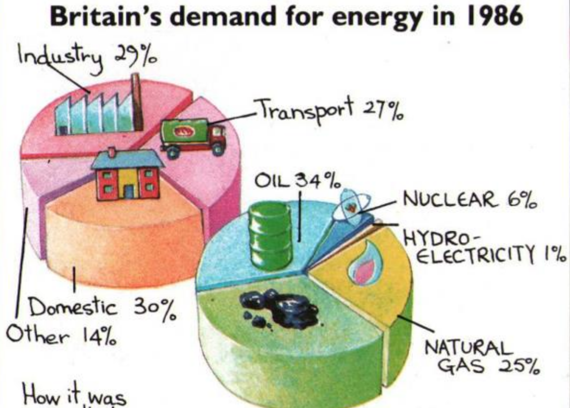
Annual Energy demand (in millions of tonnes of coal equivalent)
(Source: DoE evidence, Sizewell B Enquiry 1982)



Facts about fuel

Most of our energy is obtained by burning **fossil fuels**. Sooner or later they will become more difficult and expensive to extract. Britain's oil from the North Sea is probably quite near its peak production rate.

Britain's demand for energy in 1986



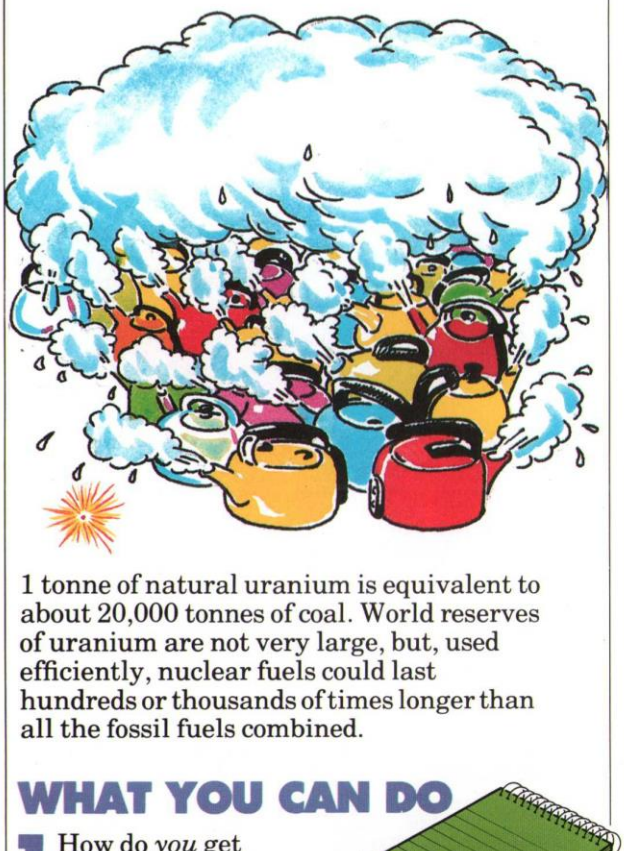
Coal may last	200 to 400 years
Natural gas may last	50 to 100 years
Oil may last	25 to 100 years

With falling reserves, increasing population and increasing industrialisation, we have to guard against the possibility of a major energy crisis in the years ahead.

Facts about uranium

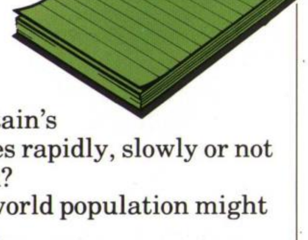
The uranium which reactors usually use is called uranium-235.

In a nuclear reactor, a pinhead-sized speck of uranium-235 can generate enough electricity to boil hundreds of kettles.



1 tonne of natural uranium is equivalent to about 20,000 tonnes of coal. World reserves of uranium are not very large, but, used efficiently, nuclear fuels could last hundreds or thousands of times longer than all the fossil fuels combined.

WHAT YOU CAN DO

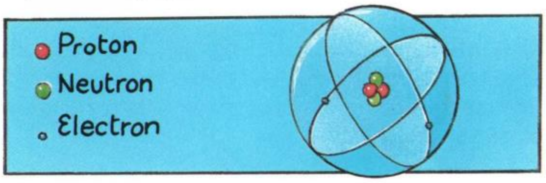


1. How do *you* get through as much energy in a day as 60 light bulbs?
2. What factors will decide whether Britain's energy demand increases rapidly, slowly or not at all in the years ahead?
3. Find out what the world population might be in the year 2010.
4. Imagine what would happen if the world ran out of fuel.

2 E = mc²

What are atoms?

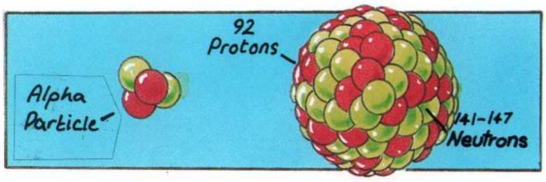
Everything in the universe is made of **atoms** (and that includes you). A thousand million atoms side by side might just stretch across a full stop on this page.



Positively charged **protons** and uncharged **neutrons** cling together to form a **nucleus**. Negatively charged **electrons** orbit the nucleus like satellites round the earth. But atoms are mostly empty space – an atom of helium enlarged to the size of a football field would have a nucleus the size of a flea.

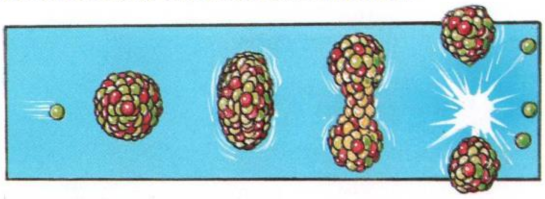
Uranium

Uranium is a heavy, silvery white metal. Its atoms can exist in several different forms, called **isotopes**, with different numbers of neutrons but always 92 protons. Very large nuclei like this are often **unstable**.

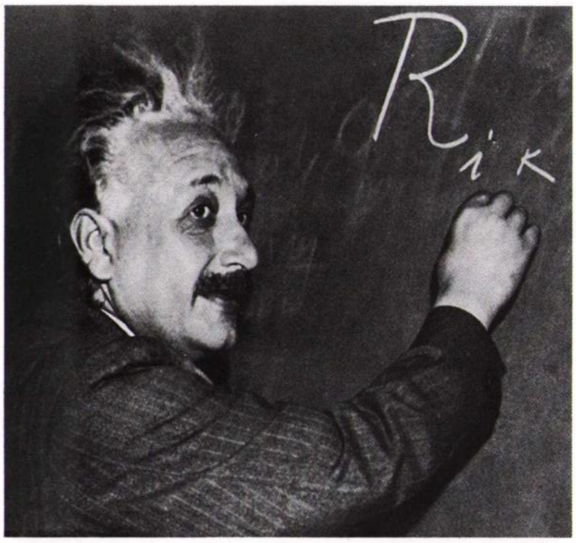


Fission

The uranium isotope with 143 neutrons, called uranium-235 or U-235 for short, has a nucleus very near the borderline between staying in one piece and flying apart. If we bombard a U-235 atom with neutrons and one of them buries itself in the nucleus, it is very likely to set it vibrating violently enough to split into two. The splitting of a nucleus is called **nuclear fission**.



The amount of matter in something is its **mass**. (The greater the mass of an apple, the more it weighs.) Something strange happens when a U-235 nucleus undergoes fission – *the two fragments have less total mass than the original nucleus*. This 'lost' mass has been converted directly into **energy**. Most of it appears as the kinetic (moving) energy of the two main fragments and of the two or three neutrons which often escape on their own at high speed.



Albert Einstein won a Nobel prize in 1921 for his work on relativity. Among other things, he made it possible to calculate just how much energy is released by nuclear fission with his famous equation

$$E = mc^2$$

E stands for the energy released
m stands for the mass 'lost', ie converted into energy
c^2 stands for the speed of light multiplied by *itself*

The speed of light is about 300,000,000 metres per second (186,000 miles per second). Squared, that gives a very large number indeed. Even for the small values of m, the energy released, E, is enormous.

The daily energy obtained from food by the whole population of the world could be released by a total nuclear mass loss of less than half a kilogram – the mass of three or four apples.

WHAT YOU CAN DO

1 Einstein once said about his work on nuclear energy: 'If only I had known, I should have become a watchmaker'. Do you think he was right to feel this way?

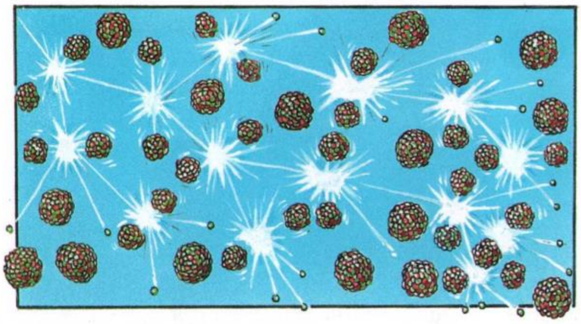
2 How many neutrons would the isotope U-238 contain?

3 Calculate the energy released by the fission of a single U-235 nucleus (mass loss = 3.6×10^{-28} kg, speed of light = 3.0×10^{8} m s^{-1}).

4 1 kilogram of U-235 contains about 2.5×10^{24} atoms. How much fission energy would they release altogether?

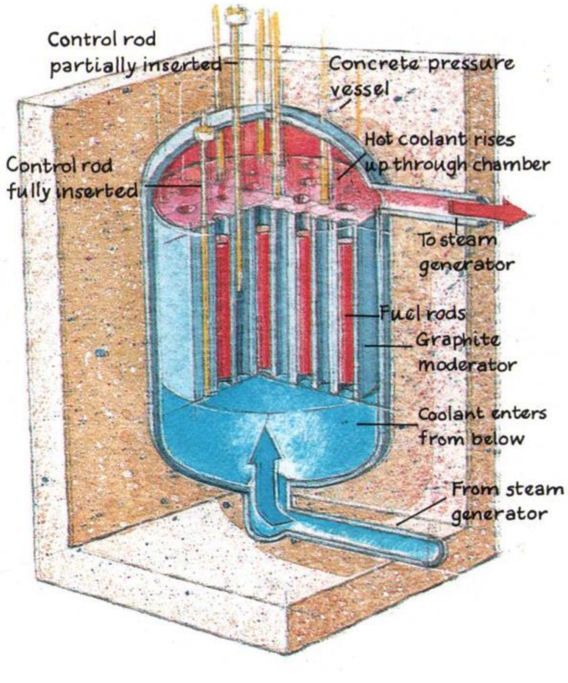
Chain reaction

Some of the neutrons emitted during the fission of a U-235 nucleus may go on to collide with other nuclei. If they cause these nuclei in turn to split up, we have the beginnings of a fission **chain reaction**.



The nuclear reactor

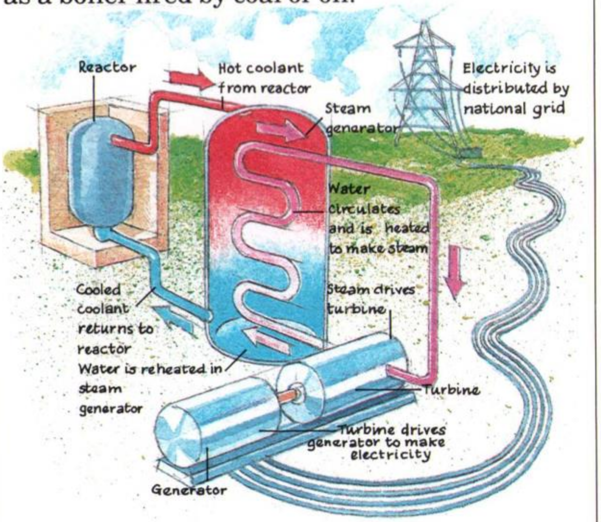
Getting a chain reaction going is not as easy as it sounds. There are three main problems. Firstly, the piece of uranium must be greater than a certain size and mass, called the **critical mass**. Secondly, natural uranium contains only a small fraction (0.7%) of U-235. The rest is U-238, which is much less likely to undergo fission. And finally, high speed neutrons tend simply to bounce off U-235 atoms and get absorbed harmlessly by U-238 atoms, or to escape altogether. We therefore have to slow the neutrons down, which makes them much more likely to be absorbed by U-235 atoms and cause fission. Materials which can slow neutrons down without stopping them completely are called **moderators**, and include ordinary water, heavy water and graphite.



A nuclear reactor depends upon a continuous chain reaction taking place in its uranium fuel. It is started up by gradually withdrawing the control rods upwards from the reactor core. Fewer neutrons are then absorbed, so more become available to cause fissions. Eventually a point will be reached where *one* neutron from every fission goes on to produce *one* new fission, on average. The chain reaction can then go on indefinitely, and the reactor is said to have **gone critical**. Constant adjustment of the control rods keeps it exactly in that condition. In an emergency, they can all be dropped back into the core to stop the chain reaction.

Getting power from the reactor

The fragments resulting from the fission of U-235 atoms have a great deal of kinetic energy, which they quickly give up in the form of heat. The reactor core gets hot, and the coolant takes the heat away to where we can make use of it, producing steam which drives a turbine. The turbine drives a generator producing electricity to be distributed on the national grid system. So the nuclear reactor is used in just the same way as a boiler fired by coal or oil.



WHAT YOU CAN DO

1 Sketch the first few stages of a chain reaction in which two neutrons from each fission cause further fissions.

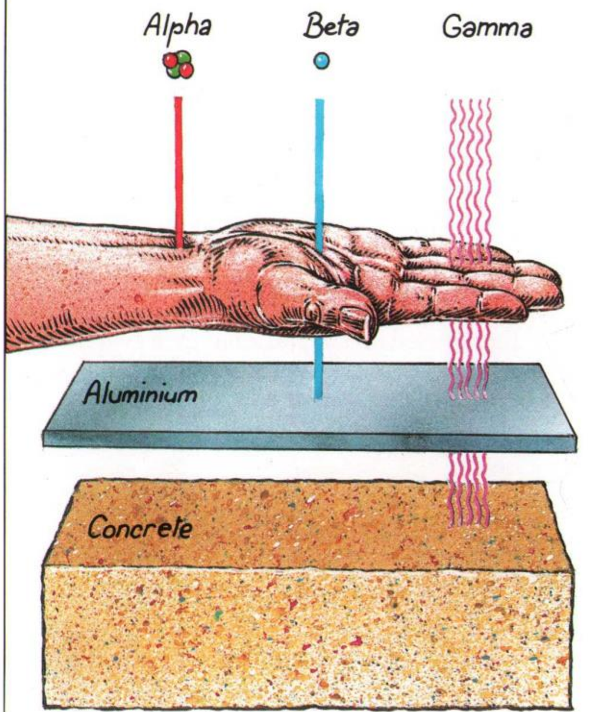
2 Although an atom bomb also works by a chain reaction, a nuclear reactor can *never* turn into a bomb. Can you suggest a reason why not?

3 Electrical substations convert the high voltages of the national grid to lower ones for local distribution. Find out where your local substations are.

3 Radioactivity

U-235 and U-238 are different forms of the same element, and are called **isotopes**. The other elements have isotopes too, and many of these emit **radiation** – they are **radioactive** and are therefore known as **radioisotopes**. When a U-235 nucleus splits into two in a nuclear reactor, the two fragments are usually very radioactive indeed.

There are three common types of radiation with very different properties:



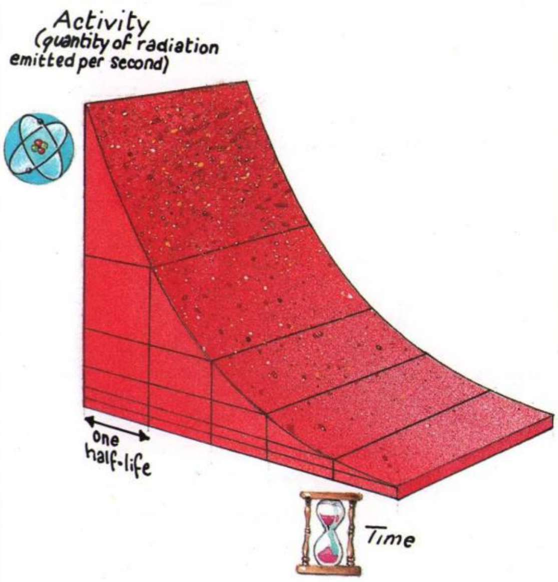
- alpha radiation consists of streams of fast-moving particles ejected from atomic nuclei. They are soon stopped but can cause a lot of damage to living cells.
- beta radiation also consists of particles, but much smaller and lighter ones (electrons). They can travel further, causing less damage but over a longer path.
- gamma radiation is very penetrating indeed, like an extreme form of X-ray.

Half-life

Each atom in a piece of radioactive material emits radiation only once. It has then changed into a different kind of atom. As the atoms gradually get 'used up' the total amount of radiation being emitted decreases.

The half-life of a radioactive substance is the time taken for its activity level to halve.

How radioactivity decreases with time



A graph like this is called a decay curve.

Half-life is always the same for a particular radioisotope, but varies widely for different ones:

isotope	half-life
polonium-212	less than a millionth of a second
iodine-137	23 seconds
caesium-137	30 years
plutonium-239	24,000 years
uranium-238	4,500 million years

Half-life is an important factor in deciding how to use a radioisotope.

It is also important in deciding whether it can safely be released into the environment.

WHAT YOU CAN DO

1 Alpha, beta and gamma rays can be imagined as golfballs, footballs and laser beams. Which do you think is which?

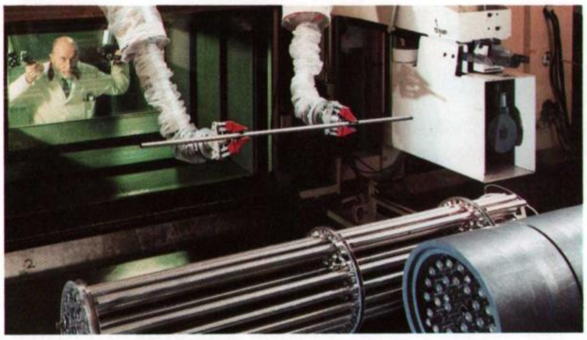
2 Look at the decay curve above. Can you think of any other graphs which would look like this?

3 How long would it take for the radioactivity of a piece of caesium-137 to decay to (a) one-half (b) one-eighth of its original value?

4 The earth is about 4500 million years old. How much of the original uranium-238 is left?

Is radiation likely to be harmful?

Radiation can be harmful because it can damage living cells. It does this by causing changes to the DNA or 'biological code' found in all cells. A very large amount of radiation actually kills many cells and causes radiation sickness. With smaller amounts, the body can usually repair the damage. If the damage is not repaired it can cause cancer. It is therefore important to protect people from radiation. This is done by shielding.



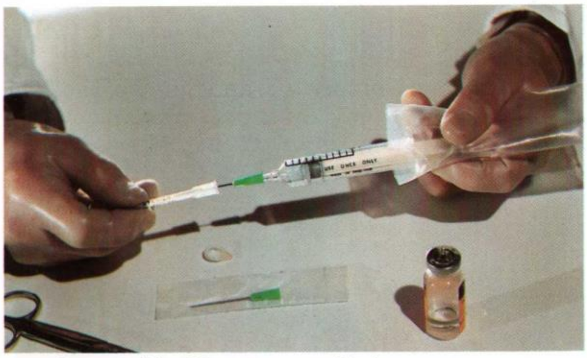
Why is radioactivity so useful?

1 Because radiation carries energy. For example:

- a tiny pellet of plutonium-238 has been used to power a heart pacemaker
- luminous paints contain a fluorescent material mixed with very small quantities of a radioisotope
- gamma radiation can produce shadow photographs, as X-rays do.

a nuclear battery for heart pacemaker

2 Because radiation can destroy living cells. For example, intense beams of gamma radiation can destroy cancer tumours or be used to sterilise medical equipment.



a syringe sterilised by gamma radiation

3 Because radiation can easily be detected. A small quantity of a short-lived radioisotope injected into the bloodstream enables the blood flow to be traced round particular organs of the body. Industry uses radioactive tracers as well, for studying everything from plant nutrition to ocean pollution.

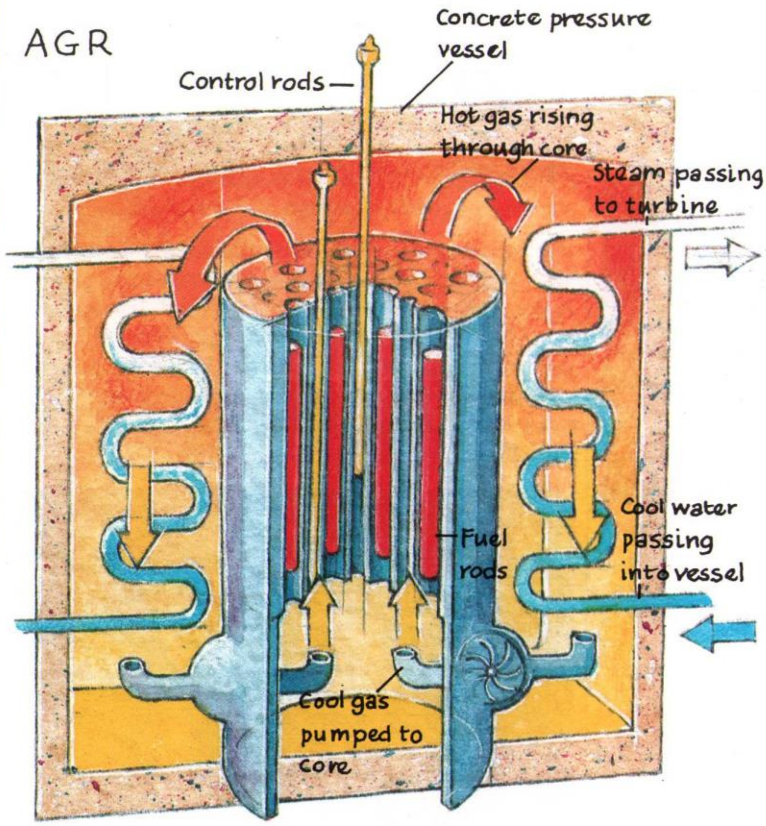
medical use of radioactive tracers

4 Because radioactivity decreases with time. Granite contains a little U-238, with a half-life of 4.5 thousand million years. It ends up finally as lead. Measuring the proportions of uranium and lead enables the age of the rock to be calculated. Radioactive carbon-14 can be used in a similar way to date ancient furniture, clothing, documents or even human remains.

the Lindow Moss Man

4 Choosing a reactor

Many kinds of reactor have been developed. The first type developed in Britain was the Magnox. Improved types developed subsequently include the **advanced gas-cooled reactor (AGR)** and the **pressurised water reactor (PWR)**.



Advanced gas-cooled reactor (AGR)

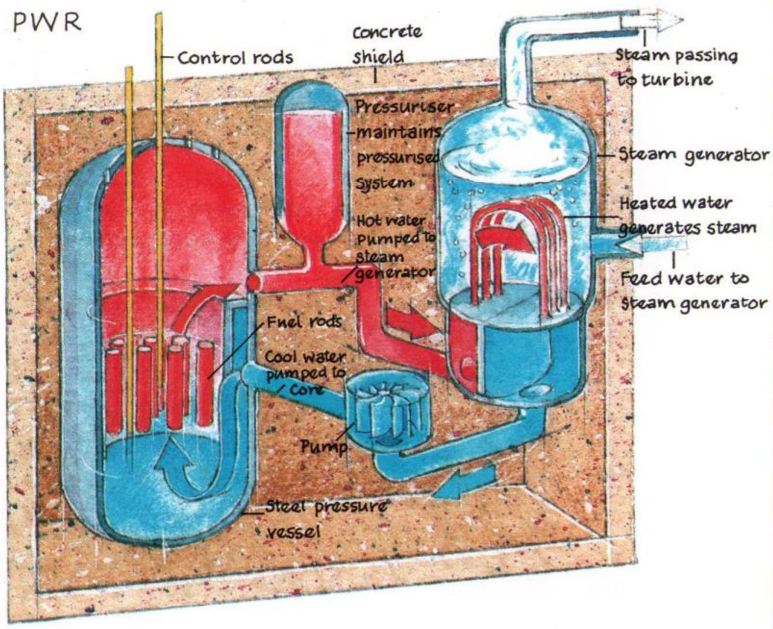
Developed in Britain from the magnox reactor. The improvement is mainly in the fuel – ceramic pellets to withstand much higher temperatures, with the proportion of fissile U-235 increased from 0.7% to 2.3% **(enrichment)**.
Present number 10, all British

Advantages

- high temperature provides hotter steam to drive modern efficient electricity generators
- 1 tonne of uranium 'burned' in an AGR is equivalent to 5 tonnes burned in a magnox reactor

Disadvantages

- future research and development costs would be carried by Britain alone
- costs more than a PWR



Pressurised water reactor (PWR)

Developed in the USA and USSR originally as a marine propulsion unit.

Present number worldwide

- over 200 on land – more than half of all reactors – and more than 600 at sea. 20 British PWRs are in use in our submarine fleet

Advantages

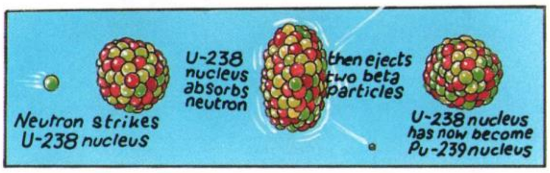
- high output from relatively small size
- little development work needed, saving money

Disadvantages

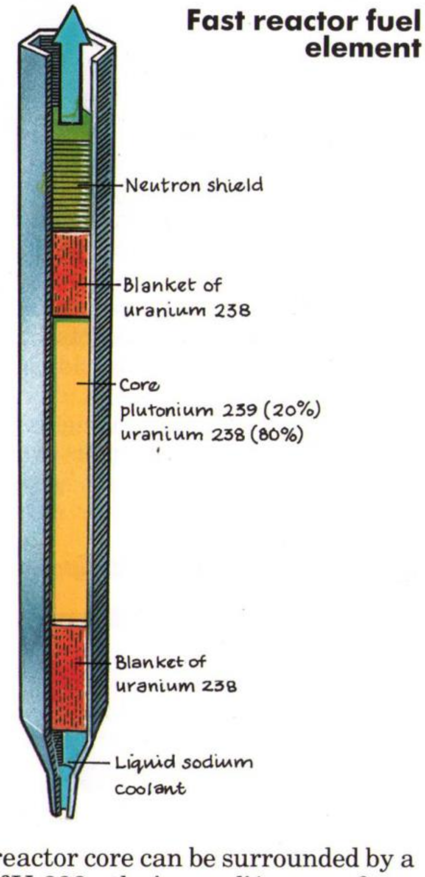
- slightly higher fuel consumption than the AGR
- requires annual shutdown for refuelling

The fast reactor

Conventional reactors use only the U-235 isotope in their uranium fuel. The 99.3% of natural uranium which is the U-238 isotope is not used at all. However, some of the U-238 atoms are changed in these reactors, by absorbing a neutron. They become atoms of a different element, plutonium (Pu-239).



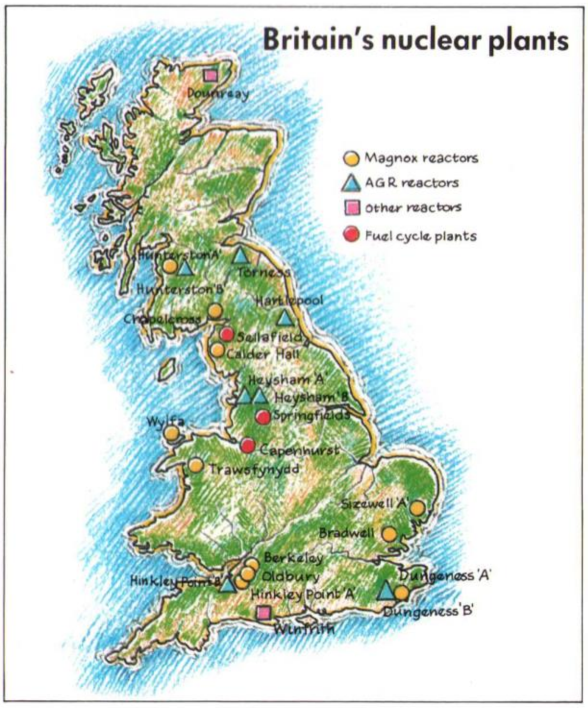
Plutonium-239 is fissile like uranium-235, but conventional reactors are unable to use it efficiently. The fast reactor can, and if required it can produce more fuel than it burns – a very clever trick.



The fast reactor core can be surrounded by a blanket of U-238 – the 'wasted' isotope of natural uranium – which soaks up many of the fast neutrons escaping from the core. Its atoms change into Pu-239 which can later be used as fuel for another fast reactor. Used in this way, the reactor 'breeds' fuel. It is often called the **fast breeder reactor**. It can also be used as a plutonium **incinerator** simply by leaving out the U-238 blanket.

Britain's prototype fast reactor at Dounreay started producing electricity in 1975.

- Breeding fuel is slow – enough for another reactor takes 20 or 30 years
- But fast reactors can eventually extract 60 times more energy from natural uranium



WHAT YOU CAN DO

1 Write out the really important differences between these reactors. Which design would *you* choose?

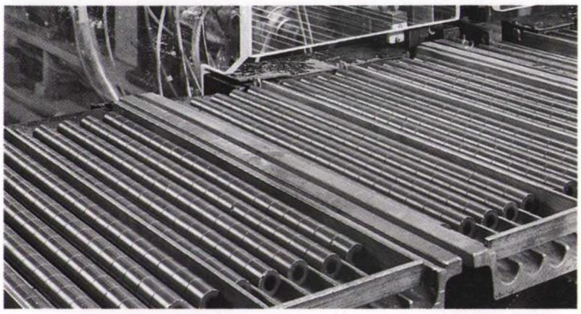
2 A reactor which costs more to build may cost less to run – the economics of nuclear power are very complicated. How important do you think economic considerations are, when making choices?

3 Why do you think reactors are often near the coast?

4 Will the local biosystem (plants and animals) be affected, for better or worse?

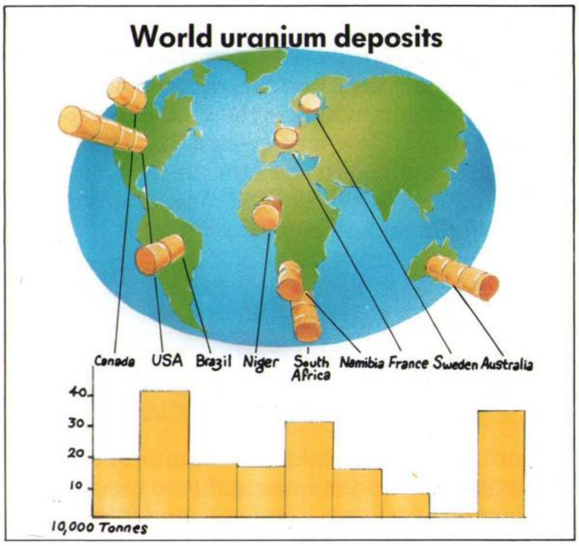
Where does uranium come from?

Uranium is widely distributed around the world – many granites contain traces of it. Not many deposits are economically recoverable, though. The most important suppliers are Australia, Canada, the USA, Namibia and South Africa.



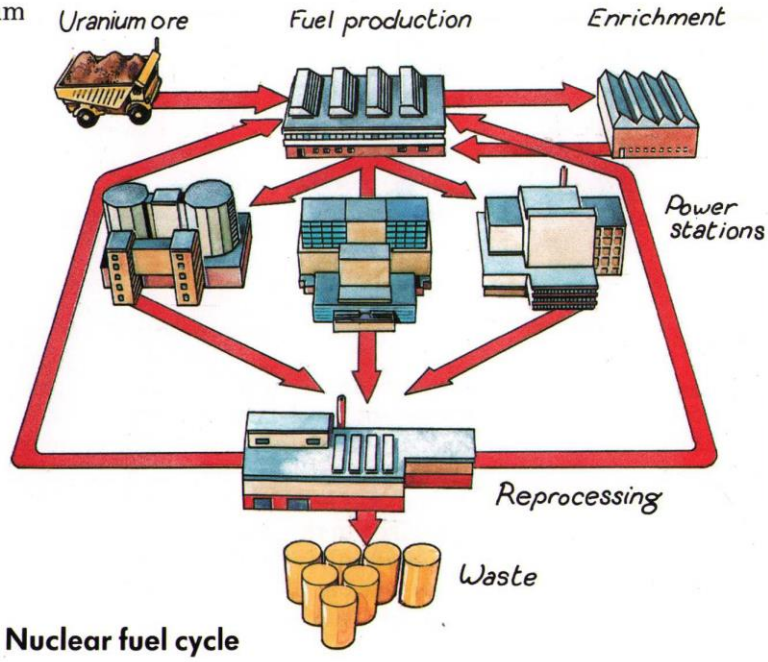
The uranium fuel is enriched, formed into rods or pellets and encased in a jacket of alloy or stainless steel for easy handling and efficient heat transfer in the reactor.

Spent fuel elements are reprocessed to extract any unused uranium and plutonium for use in future reactors. The waste fission products from the U-235 nuclei are also extracted.



WHAT YOU CAN DO

1. Why do spent fuel elements have to be handled by remote control?
2. Do you think uranium mining might be more dangerous than coal mining or oil drilling?
3. Look at the map of uranium deposits. Are we likely to find politics entering our decisions, now or in the future?
4. About 2 million tonnes of uranium could be economically mined. At present we use about 30,000 tonnes a year worldwide. How long will it last at this rate?
5. How long would it last using only fast reactors, which are 60 times more efficient?

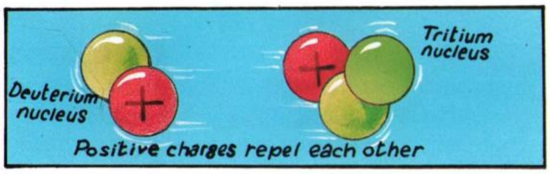


Nuclear fuel cycle

Fusion

Fission means the splitting of a heavy nucleus into two lighter ones. **Fusion** means bringing two light nuclei together to create a heavier one. In both cases, large amounts of energy are released. The sun gets its energy from fusion – can we do the same on earth?

The most promising fusion reaction is that between two isotopes of hydrogen – **deuterium** and **tritium**. When they fuse together, forming helium and a neutron, there is a small loss of mass. The 'lost' mass has been converted into energy – mostly the kinetic energy of the neutron which is absorbed in a moderator blanket of lithium.



The deuterium and tritium nuclei cannot get close enough to fuse unless they approach at enormous speed. Inside the sun, the temperature of around 20 million degrees Celsius gives the nuclei enough energy to fuse together. In the hydrogen bomb, the right conditions are created by using a fission (atomic) bomb to set off the fusion reaction. For controlled fusion, we need temperatures of over 100 million degrees – hotter than the centre of the sun.

Britain is involved with eleven other countries in operating the world's largest fusion experiment, at Culham in Oxfordshire, called the Joint European Torus (JET).

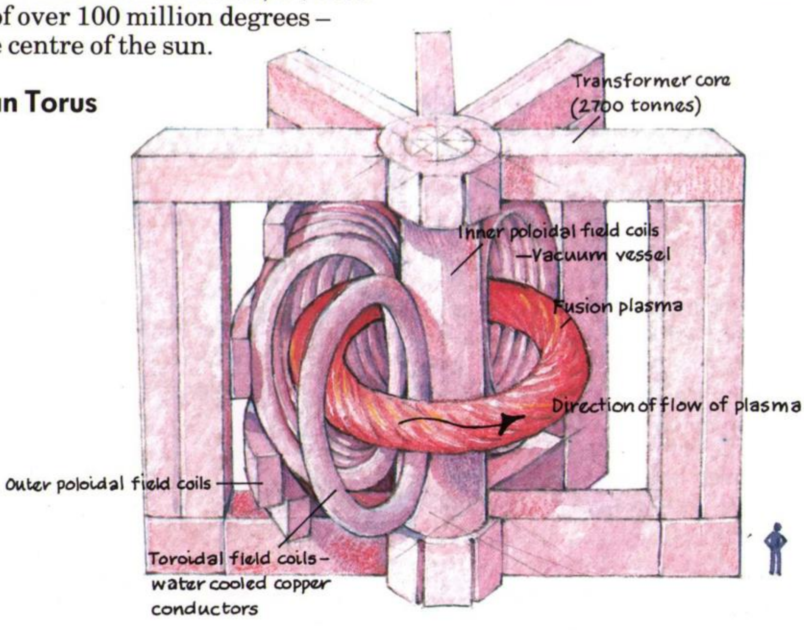
In JET, small amounts of deuterium and tritium gas are heated to form a high temperature **plasma** (a mixture of nuclei and free electrons). The plasma is held away from the walls of the containing vessel (a **torus**) by magnetic fields, and is heated by a large electric current to 30 million degrees. Additional heating systems will then raise the temperature sufficiently for fusion reactions to take place.

The fuel

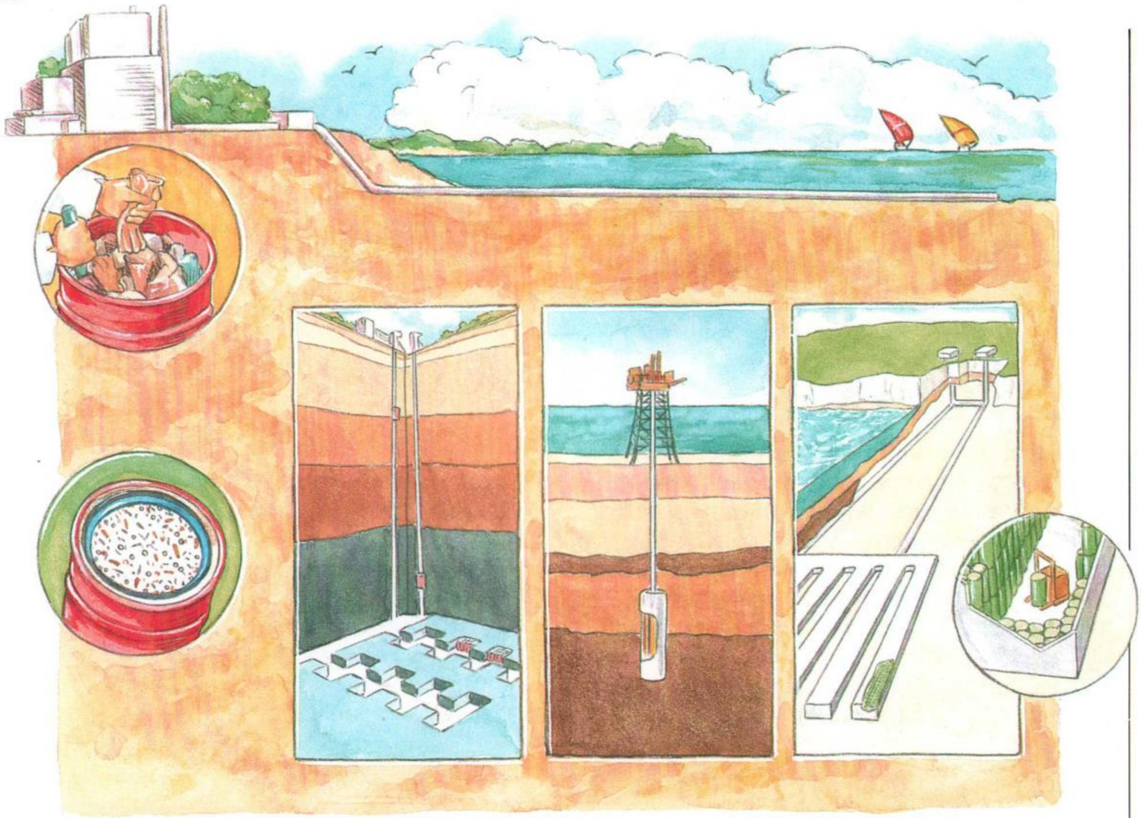
Deuterium can be extracted easily from sea water, and is virtually unlimited. Tritium can be bred (by neutron bombardment) from lithium, a light metal found in the Earth's crust. The total world reserves of lithium, if used in fusion reactors, represent an energy output comparable with that from our fossil fuel reserves. Future reactors might use only deuterium, in which case our energy problems would seem to be over.

- Nuclear fusion power might be available in another 30 or 40 years
- Fusion fuel is at worst plentiful, and at best, virtually unlimited
- The waste product is helium, a harmless gas (although parts of the reactor will become radioactive and will need to be disposed of safely)

Joint European Torus



5 What can we do with the waste?



Low and intermediate-level radioactive wastes *will be disposed of either deep underground, or under the seabed with access from the shore or from an artificial platform.*

Like many other industries, the nuclear power industry produces waste products. Although they are small in volume compared with, say, the ash from coal-fired power stations, they require special treatment because they are radioactive.

Two factors are of major importance in deciding how to deal with radioactive waste material: the half-life – which may be fractions of a second or hundreds of years – and the level of radioactivity. Wastes are classified as being of **low, intermediate or high-level activity.**

95% of the radioactivity is in the high-level waste.

Disposal routes

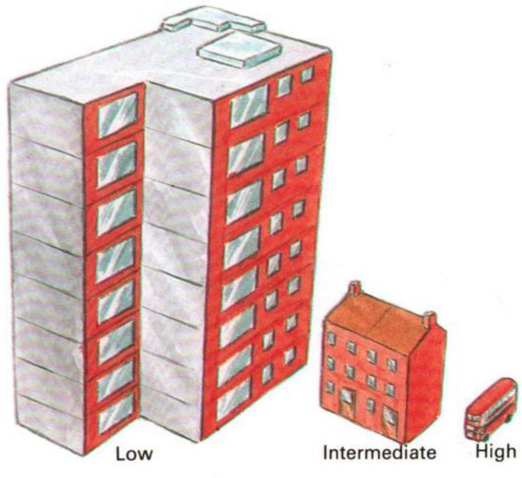
Although most of this waste is only mildly radioactive, or only remains so for a fairly short period of time, some does remain radioactive for many years. We have to be sure that no significant radioactivity ever returns to the human food cycle after disposal, so it is important to choose a disposal site which is suitable geologically and has very little ground water movement.

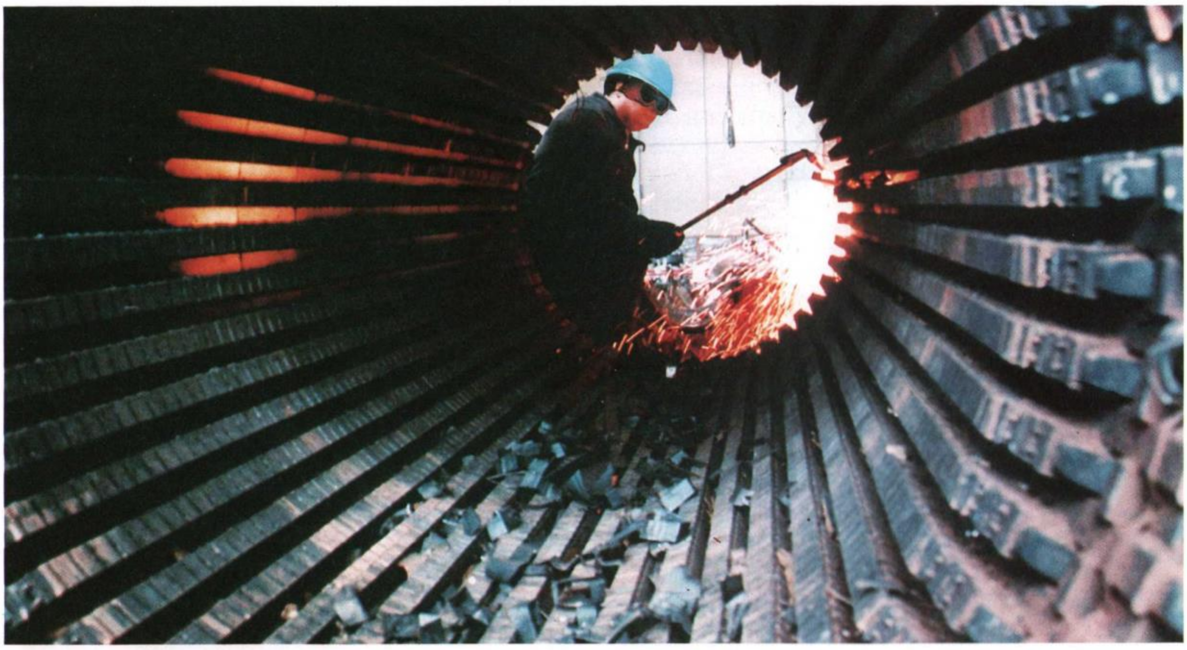
Some very low activity levels of liquids and gases are diluted and dispersed into the sea and the atmosphere.

High-level wastes come only from spent or used fuel elements, which are reprocessed mainly at Sellafield. These wastes will eventually be **vitrified** (glassified) and disposed of deep underground. However, disposal will not take place for 50 to 60 years, when the heat output has fallen considerably so the wastes are easier to handle.

How big is the problem?

This picture illustrates the relative amounts of radioactive waste produced by Britain's nuclear power industry each year





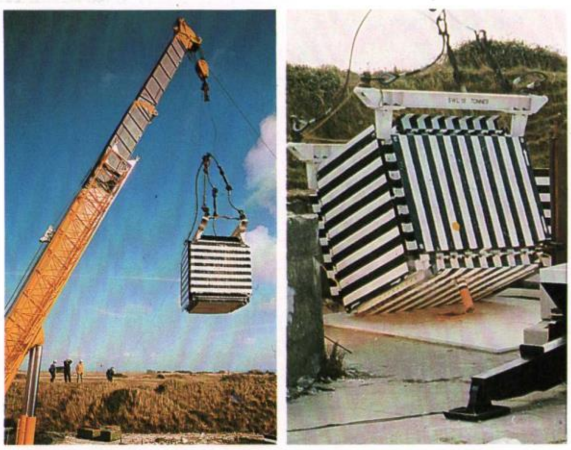
a stage in decommissioning

Transport

Low-level waste is packaged into steel drums and can be transported safely in ordinary freight containers of the sort seen every day on the roads.

Intermediate-level waste needs to be shielded to protect the public from the radiation. It consists mainly of metal fragments and chemical sludges, which are mixed with 'setting' materials such as concrete and packed in steel drums. The drums will be transported, when this becomes necessary, in large steel boxes which are designed and tested to withstand very severe transport accidents.

Spent fuel, of which only 3% is waste, is transported by sea and rail in much heavier steel containers because it is many times more radioactive.



transport containers are tested to ensure safety in all possible traffic accidents

What happens to old reactors?

Reactors have longer lives than was at first predicted, but generally will not be useable much beyond 30 years because their core materials gradually deteriorate.

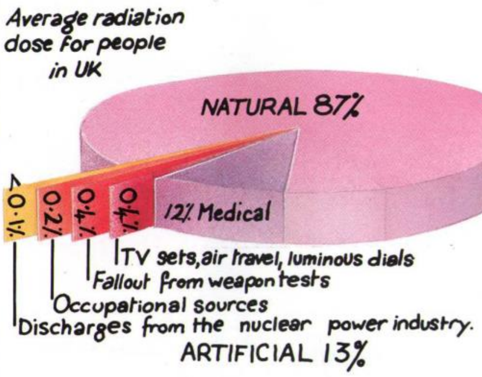
They then have to be **decommissioned** – shut down, relieved of their fuel and coolant, and eventually dismanted. Everything will be removed except perhaps the core and shielding, and studies have suggested that even these could be removed by remote handling equipment.

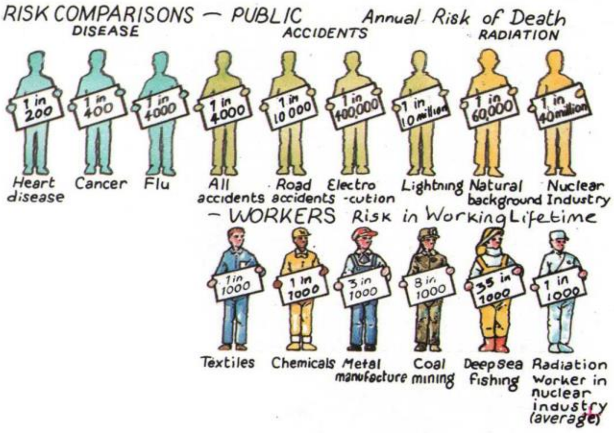
WHAT YOU CAN DO

1. Other industries have waste problems too – asbestos or highly toxic chemicals, for instance. Can you think of other examples?
2. How do you think the nuclear industry's waste problems compare with those of other industries?
3. Do you think radioactive waste would be best disposed of under the ground or under the seabed, or stored on the earth's surface? Do you have any other ideas?
4. People sometimes show more concern about 'waste trains' passing through cities than about petrol tankers, say. What do you think?
5. Is it best for the world's reprocessing to be confined to a small number of large plants, carefully monitored? And should Britain take on this job?

6 Is the flame worth the candle?

We have to balance any real or theoretical risks in the use of nuclear power against its benefits. You might find the following information interesting.





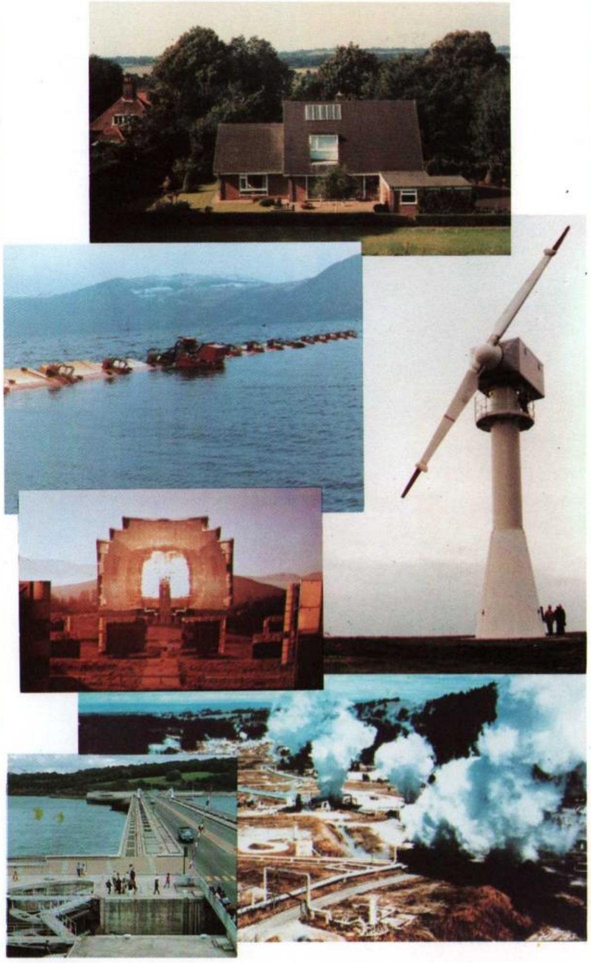
WHAT YOU CAN DO

In the table below are some of the charges often made against the nuclear power industry, together with arguments in its defence. Say which side you agree with in each case.

Can you think of other possible criticisms, and give both sides?

Against	Are you for or against?	For
Reactors are dangerous. They might release radioactive material after a human error, an earth tremor or an aircraft crash.	1	They are engineered to extremely high safety limits, and, in the West, are designed to withstand any conceivable misfortunes.
What about Chernobyl, where in April 1986 an accident released massive amounts of radiation, causing 31 deaths and many more at risk of cancer?	2	Human error, and the worst incident yet. But it was a unique USSR - designed reactor, which would not have been allowed in Britain. (Details of the accident have been studied worldwide.)
The nuclear industry constantly pollutes the environment, the worst offender being Sellafield reprocessing plant.	3	All routine releases are very small and subject to strict control. Sellafield is now taking steps to reduce its radioactive releases to negligible levels. And on average only about 0.1% of the radiation to which we are exposed comes from the nuclear industry.
Storage and transport of radioactive materials invites trouble, either from accidents or from deliberate attacks by political, or other, extremists.	4	Transport flasks can withstand extremely severe impacts. Storage facilities are small, few in number and very well guarded. Deliberate assault could at worst cause only local contamination, the greatest risk being to the attackers.
Reactors produce plutonium which can be used to make more and more nuclear weapons. And stocks of plutonium are another invitation to extremist groups.	5	Civil and military plutonium cycles can be completely separate. Stocks of plutonium are carefully safeguarded and their use is the subject of international treaties.
The nuclear industry represents a health risk both to its workers and to the general public.	6	Its health and safety record is much better than that of many other industries — look at the tables at the top of this page.

What are the alternatives?



Could renewable energy sources supply our needs?

Some only supply **heat**. Others could be used to generate **electricity**, but could they generate sufficient?

Power stations are rated in megawatts (MW); modern ones are normally 1000 MW or 2000 MW. (One megawatt will supply 1000 electric bar fires.)

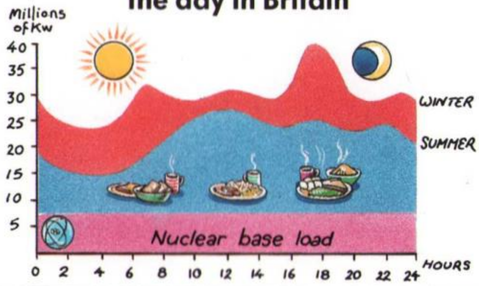
To generate 1000 MW you would need approximately:

- 300 windmills on land or sea with rotors 100 m across
- a large tidal barrier
- a very large dam for hydroelectric generation
- 40 square kilometres of solar collector
- 100 kilometres of ocean wave energy converters
- 10 ocean thermal energy converters
- 20,000 tonnes of biomass (plant crops or waste) per day.

Only the first two at present seem to be serious possibilities for Britain.

One major difficulty is that our demand for electricity varies both seasonally and daily; we need steady power sources to supply the base load, and easily adjustable ones for the peaks. Many renewable sources are intermittent, depending on tide or weather for instance, and although they could save fossil fuels when operating, we would still need the conventional power stations as a back-up.

How electricity demand varies during the day in Britain

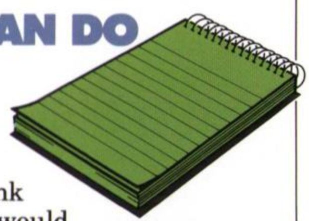


Nuclear energy

Bear in mind, for comparison, that nuclear power stations:

- cover the electrical base load reliably
- emit no sulphur dioxide which may cause acid rain
- are already developed and available
- do not emit gases to add to the 'greenhouse effect'.

WHAT YOU CAN DO



1 People often say we should conserve energy instead of generating more. How much energy do you think *you* could save, and how would you do it?

2 Should we limit our use of electricity to cases where there is no alternative?

3 Look at the pictures to identify the different sources of energy. Pick two of them, and answer as many of these questions as you can:

- how much energy could they supply in Britain?
- is their output constant, variable daily or yearly, or erratic?
- are they best suited for local or national supply?
- are they safe?
- do they emit pollution?
- are there other unwelcome environmental effects?
- would they be large or ugly or a nuisance?
- would they cost a lot to build?
- would they cost a lot to run?

Titles in the Finding Out series are:

Finding Out . . . What Happens When I Drink Designed for biology, human biology and general studies students, this thought-provoking book encourages young people to examine their own views on alcohol.

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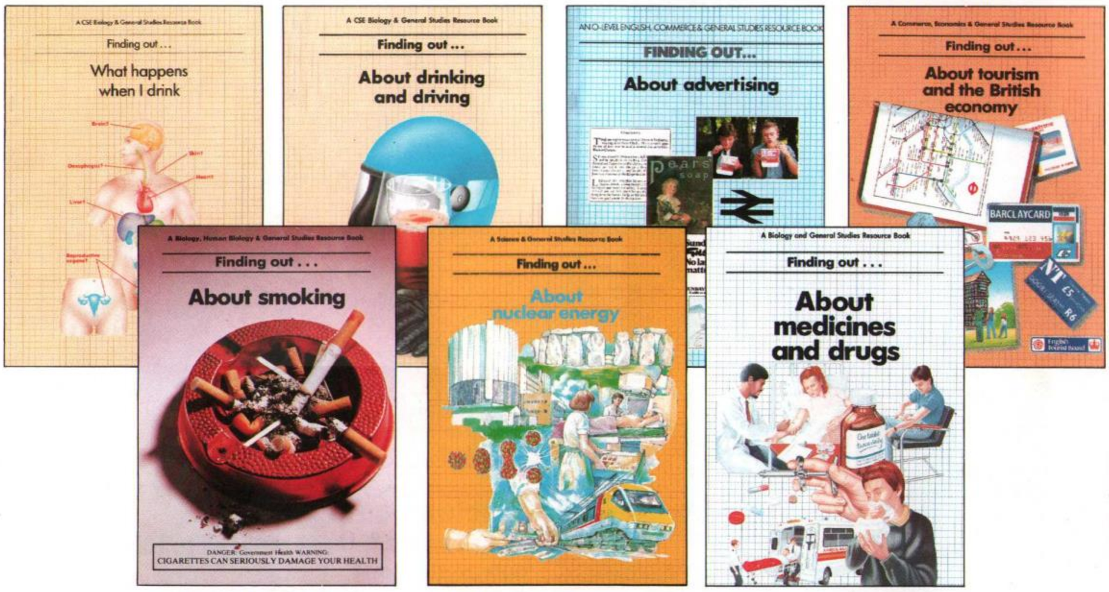
Finding Out . . . About Tourism and the British Economy For commerce, economics and general studies students, this book uses colourful illustrations and planned classroom activities to explain the role and importance of tourism.



Finding Out . . . About Smoking This book looks at the reasons why people smoke, the effect it has on the body and suggests ways to give up or avoid starting to smoke.

Finding Out . . . About Nuclear Energy This book looks rationally at the advantages and disadvantages of nuclear energy and provides facts and information to help students to draw their own conclusions.

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All books can be ordered from Learning Materials, Hobsons Publishing PLC, Bateman Street, Cambridge CB2 1LZ or telephone 0223 314640 (24 hours).

Contents

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