HARWELL

Safety and Nuclear Power

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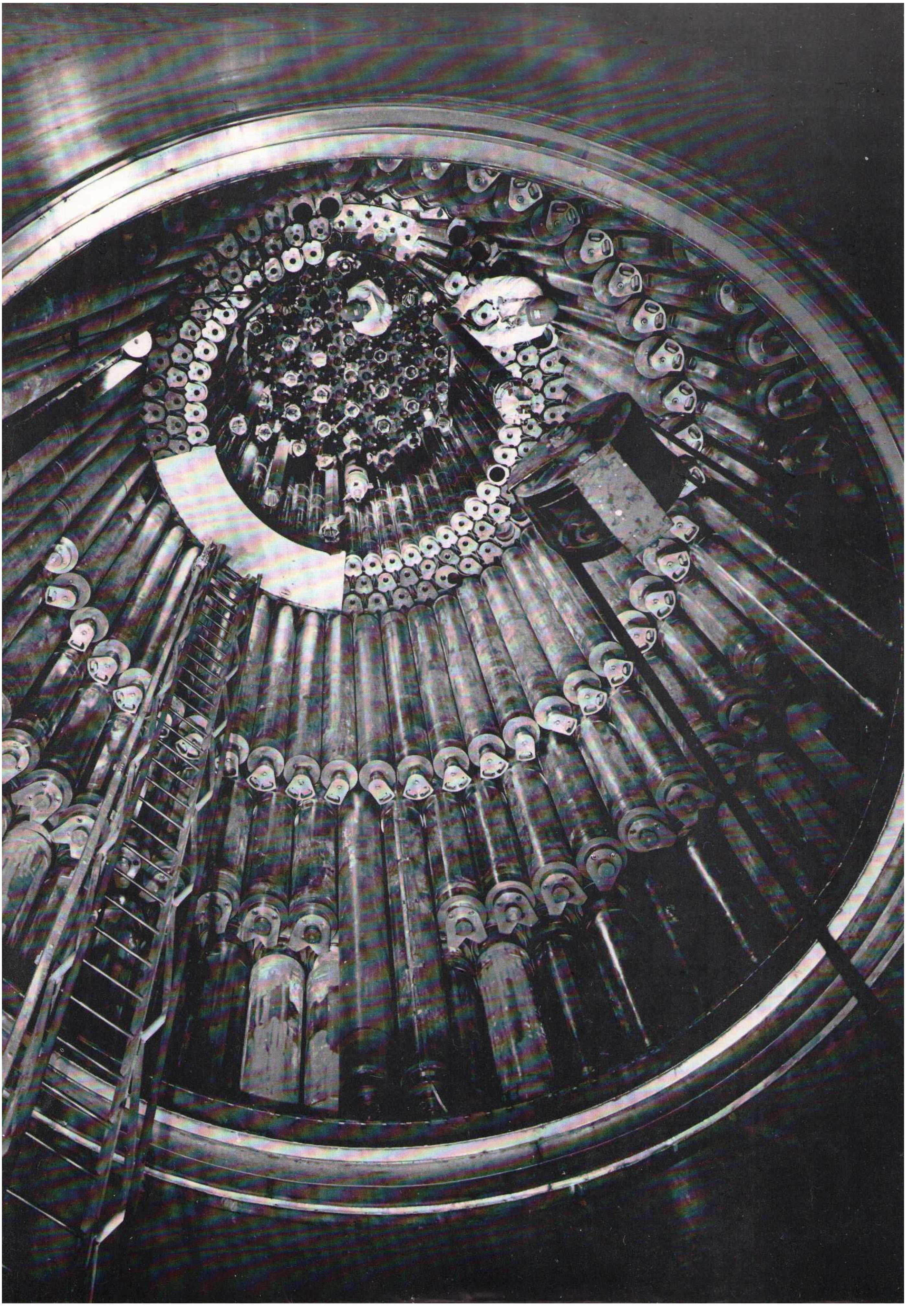


1 Nuclear Power and Society

There was a time when advancing technology was widely accepted as the main agent of social and economic development. This is not so today and there is no longer an unquestioning faith in its advantages. Society today is much more aware of the effects of technology and questions whether the benefits which it brings outweigh the detriments sometimes introduced. The choice of technology we should employ in the future has now become a matter of concern to a wider community of people than those working in industry and Government Departments. Nowhere is this more apparent than in the case of the further development of nuclear energy.

Looking into the core tank of the Prototype Fast Reactor at Dounreay, showing how a fuel sub-assembly is lowered into position.

Worldwide, the development of nuclear power in relation to its safety and environmental consequences is being publicly debated on an ethical as well as on a technical plane. How sure can we be that the power of the atom is being safely harnessed to produce electricity? Will the pollution now caused by burning fossil fuels in power stations be replaced by pollution from nuclear energy with attendant, but previously unencountered, problems in health and safety? Although the safety record of the nuclear industry has been exemplary, can we be sure that it will remain so as the use of nuclear power increases? No-one claims that nuclear power is entirely free from risk – if it were, it would be unique in this respect.

Yet industrial progress will still involve producing energy, particularly if progress means that poorer countries are helped to move nearer to their full potential, so reducing some of the world's inequalities. Therefore, we have to make a judgment. On the one hand, for the next few decades, nuclear power seems to offer the only practicable means of meeting the world's increasing demand for energy in the face of declining reserves of fossil fuels. On the other hand, a global commitment to the development of nuclear power on a massive scale involves accepting unfamiliar risks which may not immediately be easy to comprehend.

While economic, political and social considerations will ultimately play a part in resolving this dilemma, decisions cannot properly be taken without an understanding of the technology and of its potential benefits and risks. But to say that the issues are solely a matter for technical experts, because no-one else can understand the concepts and complexities of a highly advanced technology, must be wrong. Those who understand the concepts best have a responsibility to explain them in as straightforward a manner as they can. Only when the nature and extent of the risks involved are made clear will people be in a position to make up their minds about the advantages and disadvantages of nuclear energy in comparison with other sources of power.

This booklet is about the safety issues of nuclear power. Its aims are:

to review the technical facts which make up our existing knowledge about the potential risks;

to examine the extent of our knowledge, because this marks the boundary between what we can show to be true and what we have to assume by making extrapolations;

to put the risks into perspective with other hazards which are imposed upon us by nature or by society and with which we have already come to terms.

It is hoped that what follows will be helpful to the many people who are sincerely trying to understand the conflicting arguments and to reach a balanced view about the development of nuclear power.

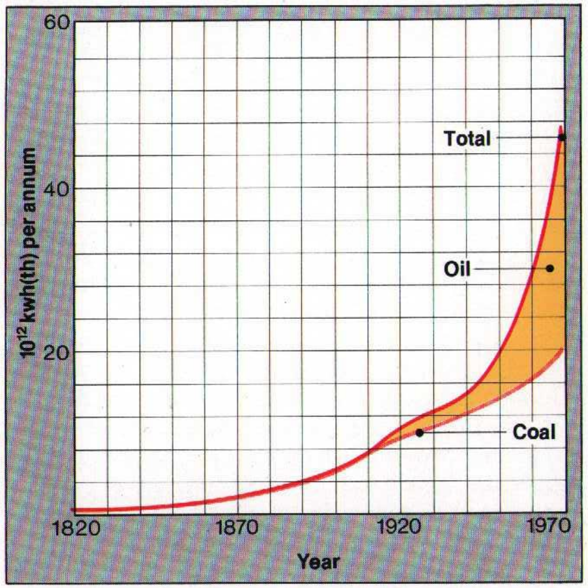
2 The Benefits of Nuclear Power

Conservation of Fossil Fuels

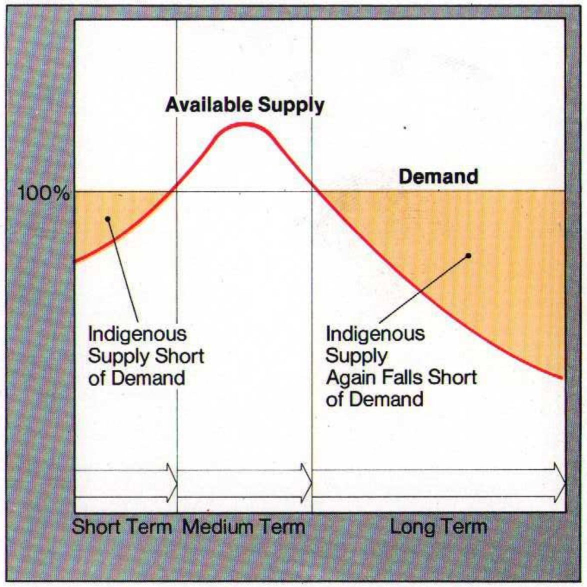
For several decades at least there is likely to be an increasing demand for energy, which the world's supply of fossil fuels will be unable to meet for long. Of other possible energy sources, nuclear energy alone can make a major contribution within a relatively short timescale, and it has conservation, economic and environmental advantages.

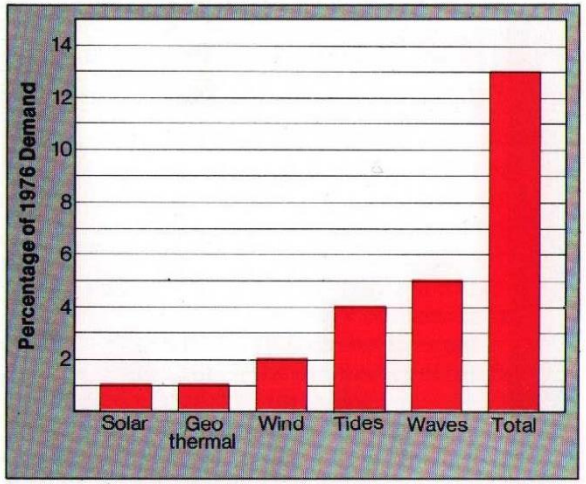
Throughout the history of civilisation, man's development has been associated with the search for new means of producing energy. He discovered how the water wheel could augment the strength of the human arm and how to release the solar energy stored in wood and plants by burning them. The Industrial Revolution was largely founded on coal, and in more recent years we have come to rely also on oil and natural gas. All these steps have raised man's standard of living and enabled the world to support its growing population. Industrial development has been associated with the consumption of increasing amounts of energy and during the last few decades the rate of growth of energy consumption has been increasing. Over the last 20 years, the world rate of population growth has averaged 2.3% a year, but the consumption of energy has increased by about 8% a year. The demand for energy is now so great that the estimated readily available reserves of fossil fuels are likely to be exhausted within a few generations. Even if the present demand for oil is moderated, most of the world's reserves will have gone within about 50 years. Although coal has the potential to supply all our needs for several

Growth of world energy demand.



Primary energy available from indigenous non-nuclear sources relative to total demand.





Tentative judgement of the Energy Technology Support Unit of the potential contribution of alternative energy sources to U.K. supplies by 2000 A.D.

centuries, its recovery at the necessary rate and price is uncertain. Many energy forecasts have indicated a shortfall in energy production around the end of the century, even making reasonable allowances for conservation measures and improvements in production. Were this shortfall to be met in the U.K. by nuclear technology, we could by then need more than 10 times our 1976 installed nuclear capacity.

Fossil fuels, particularly coal and oil, have been used in the past as cheap sources of electricity, but they also are important as fuels for transport and as feed-stocks for producing many vital chemicals, such as fertilisers, insecticides and pharmaceuticals. From now on it would be folly not to conserve fossil fuels for the purposes for which they are uniquely fitted; they should not be burned unnecessarily.

	Type	Rated output (MW)	First operation
Calder Hall	**Magnox**	**240**	**1956**
Chapel Cross	**Magnox**	**240**	**1959**
Berkeley	**Magnox**	**330**	**1962**
Bradwell	**Magnox**	**290**	**1962**
Dounreay (DFR)*	**FBR**	**15**	**1962**
Windscale	**AGR**	**40**	**1963**
Hunterston – A	**Magnox**	**330**	**1964**
Hinkley Point – A	**Magnox**	**540**	**1965**
Trawsfynydd	**Magnox**	**470**	**1965**
Dungeness – A	**Magnox**	**570**	**1965**
Sizewell – A	**Magnox**	**470**	**1966**
Oldbury – A	**Magnox**	**420**	**1968**
Winfrith	**SGHWR**	**100**	**1968**
Wylfa	**Magnox**	**990**	**1971**
Dounreay (PFR)	**FBR**	**250**	**1976**
Hinkley Point – B	**AGR**	**1320**	**1976**
Hunterston – B	**AGR**	**1320**	**1976**
Dungeness – B	**AGR**	**1320**	**1978/9**
Hartlepool	**AGR**	**1330**	**1979**
Heysham	**AGR**	**1330**	**1979**

* decommissioned early 1977

Power reactors operating, or soon to be operating, in the U.K. at the end of 1976.

With the world population increasing and many countries developing their own industries there will be greater demands for energy. This will be especially true in the case of the energy which is used for food production. Conservation of the remaining fossil fuels will be almost impossible unless a rapidly increasing proportion of the world energy is met from other sources.

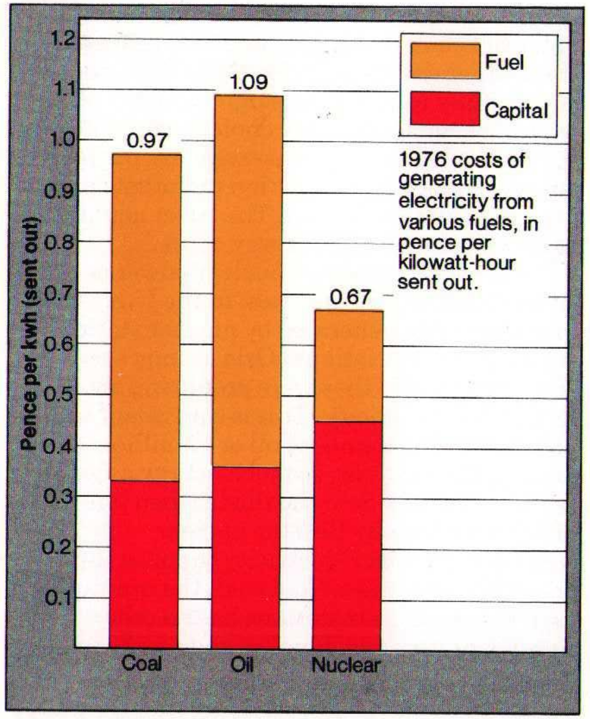
Alternative energy sources which could be developed for generating electricity (or as a substitute for electricity) are solar and geothermal energy and the power of the winds, waves and tides. One day it may be practicable to use these as substantial sources of energy. But these developments, even if they do prove to be environmentally acceptable, will take many years to come to fruition and are unlikely to be ready soon enough to do much for the conservation of fossil fuels, especially oil. The most recent prediction for the U.K. is that the potential contribution, some 25 years ahead, of these other energy sources, if all the options are successfully followed up, might be 6–8% of the overall demand. The only choices available now, if fossil fuels are to be conserved, are nuclear energy or a marked reduction in the rate of growth of our energy use. The latter might lead to radical changes in our way of life.

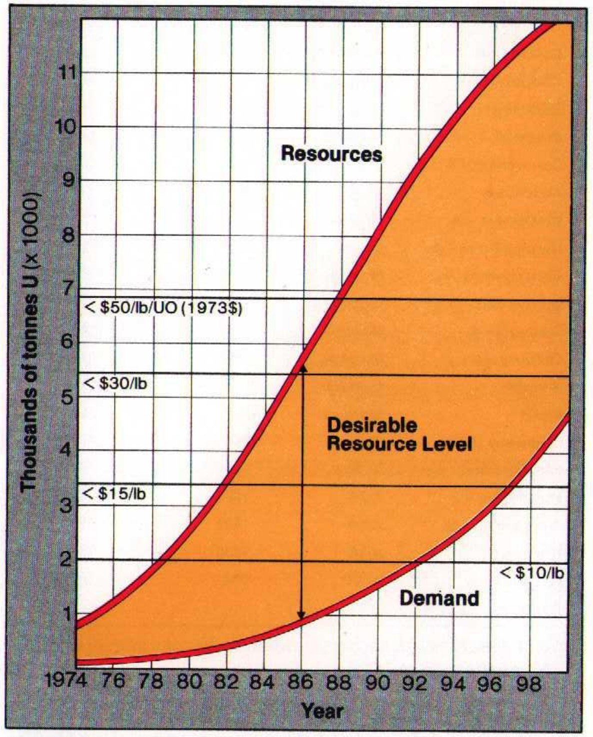
The development of nuclear power is well advanced in many countries. In the U.K., the first electricity generated by nuclear stations was fed into the National Grid as long ago as 1956. In mid-1976 they were producing about 12% of our electricity. This is equivalent to about 6 million tonnes of oil or 10 million tonnes of coal a year, as much energy as we shall get from the new Selby coalfield when it is in full production. By 1980 the nuclear contribution to our electricity supplies should reach 20%. Unlike oil and coal, the uranium used to fuel nuclear stations has no other significant uses and it makes good sense to use it instead.

Economic Advantages and Resources

The two main factors which determine the cost of electricity are the capital costs incurred in building the generating plant, and the operating costs which include the price of fuel. Although the capital costs of a nuclear power station are about half as much again as a coal or oil burning plant of similar output the fuel costs are much lower. As a result, the electricity is generated more cheaply in nuclear stations than in even the most modern coal fired stations. In the longer term nuclear power, by providing a large new source of energy, will help to keep all fuel prices down.

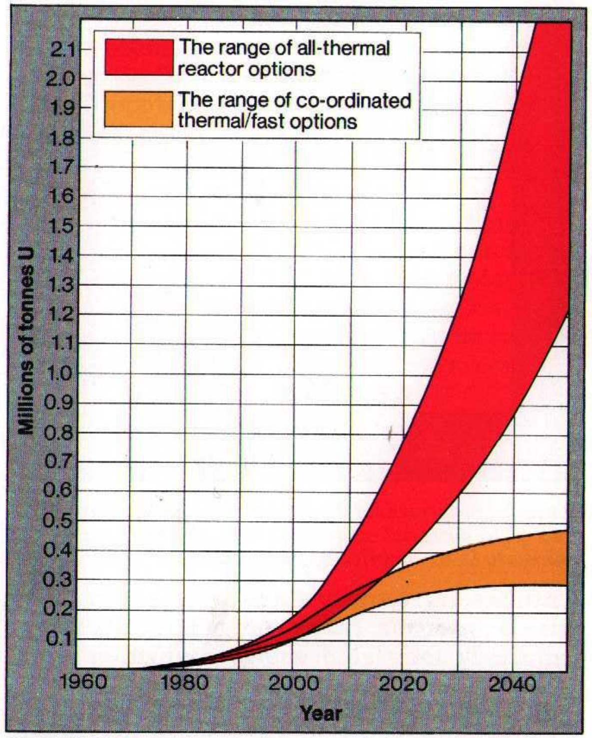
1976 costs of generating electricity from various fuels, in pence per kilowatt-hour sent out.





Level of reserves and potential resources of uranium needed to meet estimated world demand. (A reasonable resource level is assumed to be about four times the requirements of the following seven years.)

Less than one per cent of naturally occurring uranium (its fissile component) can be used to produce energy in present day reactors. The first generation reactors in this country, the Magnox reactors, use natural uranium as fuel. Later reactors, the Advanced Gas-Cooled Reactors (AGRs), and the Steam Generating Heavy Water Reactors (SGHWRs), use uranium which has been artificially enriched in the fissile component. But this leaves, at the fuel enrichment plant, large quantities of uranium depleted in its fissile



Total U.K. uranium requirements of alternative nuclear strategies.

component. By using this depleted uranium in fast reactors, which are being successfully developed in a number of countries including the U.K., it is possible to use its available energy far more effectively. With a system of thermal and fast reactors each tonne of natural uranium could be made to release about 60 times as much energy as in thermal reactors alone. The amount of depleted uranium already stored in the U.K., if used in fast reactors, would be equivalent in energy content to the entire U.K. technically recoverable coal reserves or ten times the amount of oil so far discovered under the North Sea.

Known uranium reserves, although substantial, are not unlimited. Indeed, if the worldwide development of nuclear power is on the scale currently forecast the present proven and probable uranium reserves may not be adequate to fuel, for their whole lifetime, thermal reactors being ordered now. A realistic view of future production of uranium suggests that without fast reactors it will meet only about one quarter of the predicted end-of-century energy gap. Prices would rise steeply in response to shortage.

In the long term the greatest resource may prove to be energy from nuclear fusion: the energy from which the sun derives its power. However, there are many scientific and technological problems to be overcome before a fusion power station can be designed and built. Energy from fusion cannot be available commercially until early in the 21st century. It would have immense benefits, but the realisation of its potential is not yet assured.

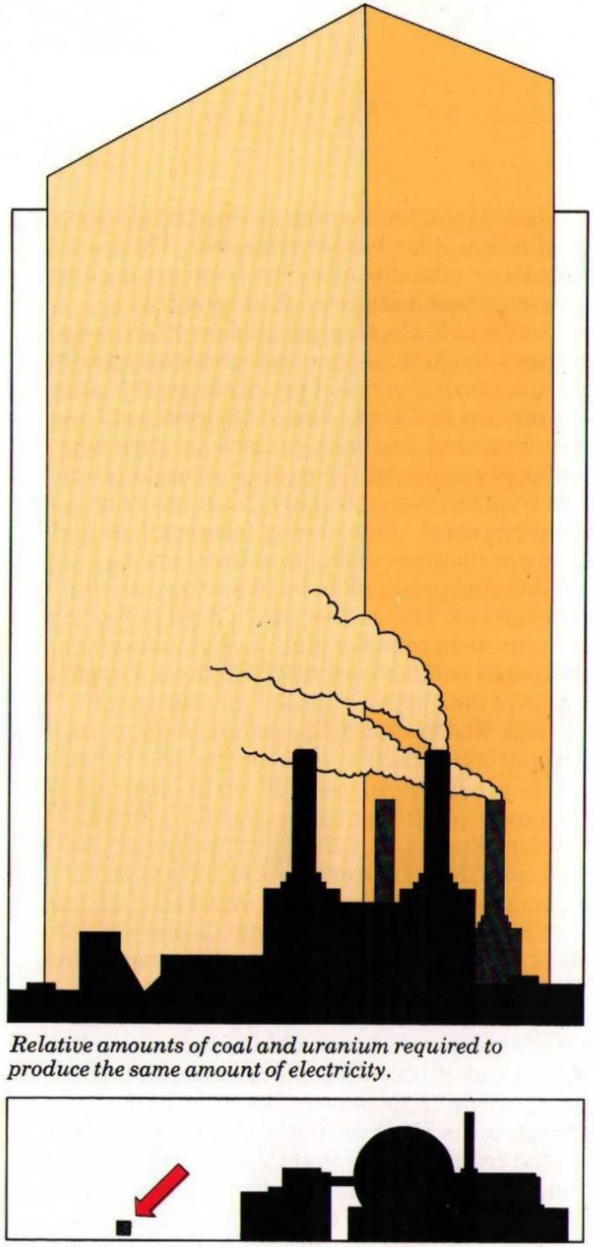
Environmental Benefits

In this country about 70 million tonnes of coal are used each year to generate electricity. This has an impact on the environment where the coal is mined, at the power station where it is burnt and on the surroundings over which the combustion products are dispersed. Each tonne of coal that is mined involves bringing to the surface a similar amount of 'spoil' which forms the pit-heaps which cover so much land in mining areas. Liquid effluents associated with the winning of coal add to pollution. Operation of a 2000 MW(e) coal fired station involves the arrival of 20 train loads of coal each day. The combustion of coal at the power station results in the discharge of contaminants to the atmosphere and the production of large volumes of solid waste.

In contrast, the environmental impact of nuclear power is small. The amount of spoil

Discharge rates of some pollutants from a modern 2000 MW(e) coal-fired power station.

Discharge	Tons per day
Fly ash	**20**
Sulphur dioxide	**500**
Carbon dioxide	**50,000**
Carbon monoxide	**4**
Nitrogen oxides	**160**
Radioactivity (Thorium and Radium)	**0.15 mCi per day**



Relative amounts of coal and uranium required to produce the same amount of electricity.

produced in uranium mining for unit electricity production is far less than for coal. The quantities of nuclear fuel involved are minute in comparison with fossil fuels and this contributes to the smaller land area taken up by nuclear stations. Even existing nuclear power stations derive as much energy from 50 tonnes of uranium fuel is as obtainable from a million tonnes of coal. In the fast reactor system now under development the equivalent amount of fuel required would be only about one tonne. As the generation of electricity from nuclear fuel does not involve combustion there are no combustion products to be liberated into the atmosphere. The wastes which need to be stored are minute in terms of mass and volume when compared with those from fossil fuels. Large tracts of land are not needed for storage of nuclear wastes and waste management costs will not significantly increase the price of the power produced. In the U.K. all nuclear fuel for the power programme is produced by British Nuclear Fuels Ltd. (BNFL) in one factory at Springfields in Lancashire and the spent fuel is reprocessed at their plant at Windscale on the Cumbrian coast. The Springfields factory, in addition, manufactures fuel for export and the Windscale plant also reprocesses spent fuel from abroad. With planned expansion, these two factories will be capable of processing the equivalent of 100 million tonnes of coal each year, within their present boundaries. In energy terms their output is almost equivalent to that from the National Coal Board's mines and, as we shall see later, burning the nuclear fuel has a far smaller environmental impact.

The Future Prospect

Man emerged from the primeval state because he was able to solve the problems of his environment and to adapt it to his own purposes. It is debatable whether during the last century or two this capability has always been used wisely but no-one can deny that it forms the basis of our present way of life. Our increasing demands for energy make it essential for us to come to terms with the fact that the earth's resources are limited or possibly suffer unpleasant consequences by exploiting them to exhaustion. Nuclear energy can play a major role in determining whether or not our present quality of life can be maintained for our children and later generations.

The benefits of nuclear power are these:

Nuclear power appears to be the only practicable means of meeting the energy shortfall predicted for the U.K. around the end of the century.

Our limited stocks of fossil fuels, particularly oil, are far too valuable as transport fuels and chemical feedstocks to burn them unnecessarily for power production.

Nuclear electricity, already cheaper in the U.K. than electricity generated from fossil fuels, will help to stabilise the cost of electricity as fossil fuels become more scarce and costly.

When our own off-shore oil reserves are exhausted, nuclear power will reduce our dependence on overseas supplies.

Successful development of fast reactor systems would allow uranium to be used far more efficiently than at present and reduce our import needs.

The environmental impacts from nuclear power are much less than those caused by the combustion of fossil fuels for the generation of electricity.

The mass and volume of nuclear wastes to be stored are so small that very little land will be taken up.

3 Benefit and Risk

The nuclear power industry has an exemplary safety record; there is no evidence that any member of the general public has been harmed by any of the nuclear power stations which are now in operation. But, of course, nuclear power, like any other industrial activity, brings with it some risk. It is how we see this risk and what we should do about it that has given rise to controversy. To reach a balanced judgment we need some means of measuring benefits and risks and weighing them against one another.

It is not difficult to quantify benefits in terms of material or monetary value – for example, the quantity of coal and oil which could be conserved by nuclear power, or the amount of foreign exchange which would be saved, or cheaper electricity. But this cannot be done in the same way for risks, particularly if human life is involved, because most of us would argue that a monetary value placed on human life is arbitrary. What we can do, however, is to compare the risks that arise from nuclear power with others to which we are exposed – risks with which society has already come to terms.

The Philosophy of Risk

A degree of risk has always been inseparable from normal living and we all accept some risks with little or no anxiety. Man has always rubbed shoulders with disease, accident and natural disaster, and for most of his history has accepted such things as being beyond his control. More recently, with the growth of science and technology, attitudes have changed. The development of medicine and public health measures has reduced the risks of death from disease and people expect to live longer. At the same time the populations of our towns and cities have grown much larger and to achieve economies of scale we accept bigger and bigger industrial plants and transport vehicles. This has brought with it an increasing likelihood of man-made catastrophies with casualties in the hundreds rather than in ones and twos. But people are becoming less inclined to accept these risks as beyond control and they are demanding that they be minimised.

It is almost impossible to avoid some of the risks to which we are exposed. Short of living underground we cannot get away from some hazards of the natural environment, such as being struck by lightning or a meteorite. We have learnt to live with these and largely to ignore them. We may also choose to accept other risks which we could avoid by a personal decision, for example those associated with driving, flying and the use of gas, electricity and oil in the home. But we normally accept such personal risks without concern, because they are sufficiently familiar for us to judge them from experience and to balance them against the benefits that these activities give us.

We are, however, far less willing to accept risks which are imposed on us by other groups in our society. We may have virtually no choice to accept or reject these, although we may have an opportunity to minimise them at some personal cost or inconvenience. Examples are pollution from road vehicles and factories, aircraft crashing on populated areas and the accidental release of dangerous chemicals during their transport or manufacture. These hazards face us in our everyday life and it is relevant to consider how society views and deals with them.

Approximate average chances of an individual dying from a given cause in any year.

Data from DHSS 1975 statistics except where otherwise stated.
(1) Registrar Generals Statistical Review
(2) Euratom Report EUR 5001 (1973)

Type of risk	Annual risk of death (chances per million)
Disease	**11,000**
Cancer of trachea broncus or lung	670
Leukaemia	60
Accident	**300**
Motor vehicle	120
Falls	100
Drowning	30 (2)
Electricity	20 (2)
Lightning	0.1 (1)
Pollution	
Discharges from oil or coal fired power stations	4 (2)

Levels of Risk

Annual death rates from various causes can be found in national and international statistics. These data, when viewed against the steps taken by society to reduce premature death, suggest that the extent of the preventative measures taken is related to the likelihood of the cause occurring. Risks which may cause the death of about one person in a thousand in any year are clearly unacceptable and all necessary steps are taken to eliminate them; an example is vaccination against smallpox. For relatively smaller risks which may affect about one person in 10,000 per year, the emphasis is on reducing the risk – so large amounts of public money are spent on traffic controls, and on the provision of ambulances and fire services. To counter risks of events which are likely to affect less than 1 person in 100,000 per year reliance is normally placed on individual persuasion, for example exhortations not to swim or walk in dangerous places. Annual risks of less than one in a million, such as being killed by lightning, appear to be of so little concern that only simple precautions, if any, are taken against such events. Certainly the estimated annual risk of 1 in 50 million of the world being engulfed by lethal levels of radiation from an exploding supernova is not something about which we worry very much.

Smoking $1\frac{1}{2}$ cigarettes
Travelling 50 miles by car
Travelling 250 miles by air
1-2 weeks' typical factory work
20 minutes being a man aged 60

Examples of activities giving statistically a one in a million chance of death.

So we can sum up the way society deals with risks as follows:

the acceptance of risk by individuals is inseparable from living; in each case the risk taken is set against the benefits that would otherwise be lost;

society seeks to minimise risks by a variety of means but may not choose, or be able to eliminate them entirely;

the response to specific risks is related to their magnitude; society prefers to concentrate its resources on eliminating or reducing the major ones to which people are exposed, rather than the very small ones.

Within this framework we can begin to identify and assess the risks that may be associated with nuclear power.

4 The Risks of Radiation

Apprehension about the possible impact of any major new technology is understandable and in recent years there has been increasing expression of concern over the risks associated with the production of electricity from nuclear energy. This concern may have been heightened by a lack of information about nuclear power and about the nature of its potential hazards. If this is so, it is hoped that what follows will help to improve understanding and to put the risks which do exist in the proper context of our overall radiation environment. This chapter deals with the sources of natural and man-made radiation, its nature and its biological effects.

There are many forms of radiation; some, such as visible light, heat and sound have always been known to man; others, such as radio-waves, ultra-violet light and X-rays, have been discovered and used in more recent times. In this booklet, 'radiation' refers to that form which can cause electrical effects known as ionisation – the so-called "ionising radiation".

Natural Radiation

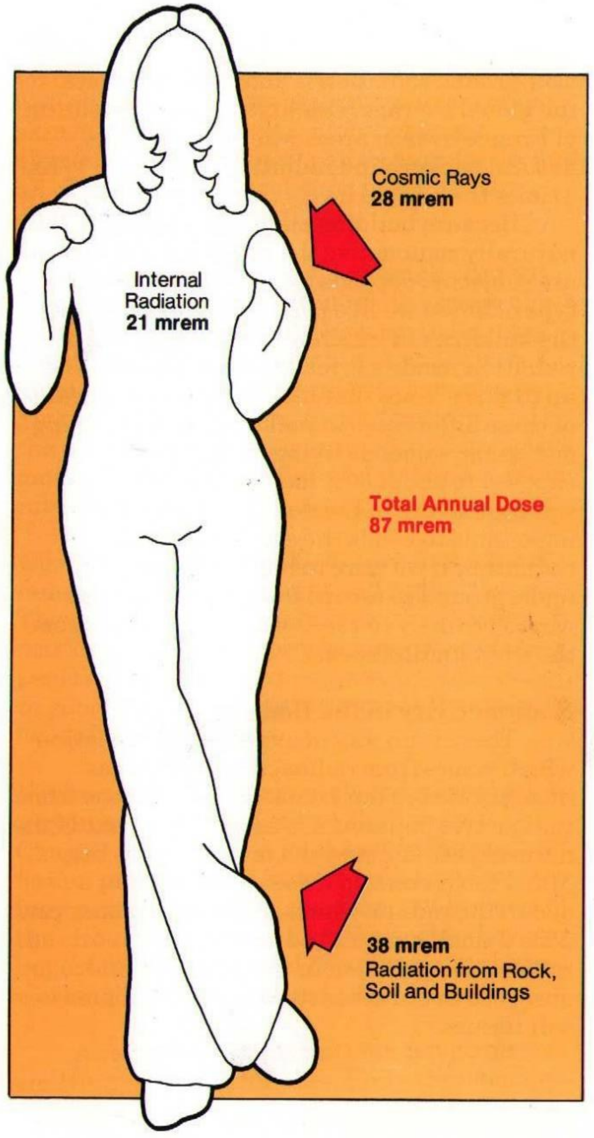
Radiation and radioactivity are inseparable from the natural environment. Life on this planet has evolved in naturally radioactive surroundings, and man has always been subject to radiation from many natural sources. This "background" radiation comes from cosmic rays which bombard the earth from the sun and outer space; from radioactive materials which are produced as the cosmic rays pass through the atmosphere; and from natural radioactive materials in the earth's crust. It also comes from radioactive constituents of our own bodies

Cosmic Rays

Radiation from cosmic rays stays more or less constant at any particular place on the earth's surface, but its level does change a little with latitude and much more with altitude. Thus, those living in high places and those who do much flying receive considerably more cosmic radiation than most of us.

Terrestrial Radiation

At or around sea-level, where most of the world's population lives, the largest part of the radiation received comes from natural radioactive materials in the earth's crust, such as uranium and thorium. Even over quite small distances, variations in the intensity of the radiation from this source are quite large, owing to differences in rock and soil composition. In a few localities of the world, such as small areas of Brazil and India, the natural



Average individual yearly dose from natural sources in the U.K.

background radiation is about twenty times the global average. One sixth of the population of France lives in areas where the average natural background radiation is between 1½ and 3 times the normal levels.

Because building materials are also naturally radioactive the radiation to which we are subjected depends to some extent on the type of house we live in and the construction of the buildings in which we work. The level of radiation inside a brick or stone house can be up to three times that in a wooden one. Because of these differences in rocks and local building materials, someone living in Aberdeen is exposed to about 50% more radiation than someone living in London. It is virtually impossible to evade the earth's natural radiation. If we were to burrow deep underground to escape from cosmic rays we would be likely to receive more radiation from the surrounding rocks.

Radioactivity in the Body

There is no way of avoiding the radiation which comes from radioactive substances incorporated in our bodies. Most of this is from radioactive potassium, a small ingredient of the natural potassium which is essential to life. Many foods contain traces of naturally occurring radium which is retained in bone and adds a small amount to our internal radioactivity. Radon in the air becomes absorbed in our bloodstream and irradiates soft tissues.

Man-made Sources of Radiation

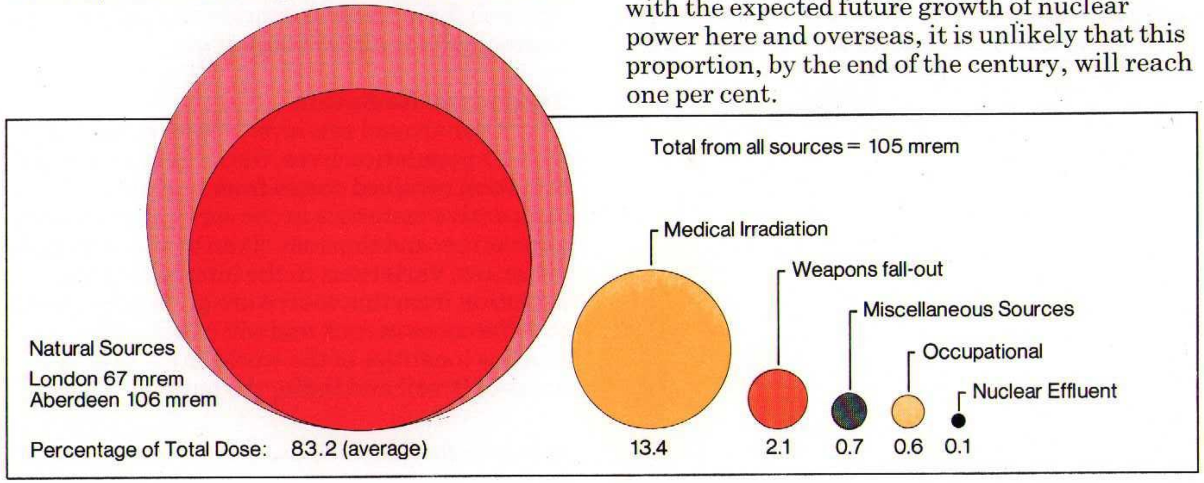
In addition to these natural sources, which account for 83% of the radiation to which man is exposed, there are a number of man-made sources. Of these, by far the most important is application in medicine. This includes diagnostic radiology, radiation therapy and the use of radio-pharmaceuticals. In this country, approximately 14% of all the radiation received by the population as a whole, including that from natural sources, comes from medical uses.

Another source of man-made radioactivity is the fall-out from nuclear weapon tests in the atmosphere. The tests carried out before 1963 still represent the largest series of events leading to global radioactive contamination. Most of the debris injected into the stratosphere has by now been deposited on the earth's surface and the radiation levels from fall-out have considerably decreased since their peak in 1963.

Some other miscellaneous sources of radiation make a small contribution to people's average exposure. These include consumer products which contain radioactive materials (such as luminous dials of watches and clocks) and colour television tubes which emit very small amounts of X-rays.

The operations of the nuclear industry lead to radiation exposure of people working in nuclear plants. They also include some processes in which controlled discharges of radioactivity are made to the environment. Although exposure of the population to radiation is thereby increased, this additional radiation amounts, in this country, to only about one tenth of one per cent of that received from the other sources described above. Even with the expected future growth of nuclear power here and overseas, it is unlikely that this proportion, by the end of the century, will reach one per cent.

A comparison of average U.K. exposure from man-made sources of radiation with exposure from natural sources.

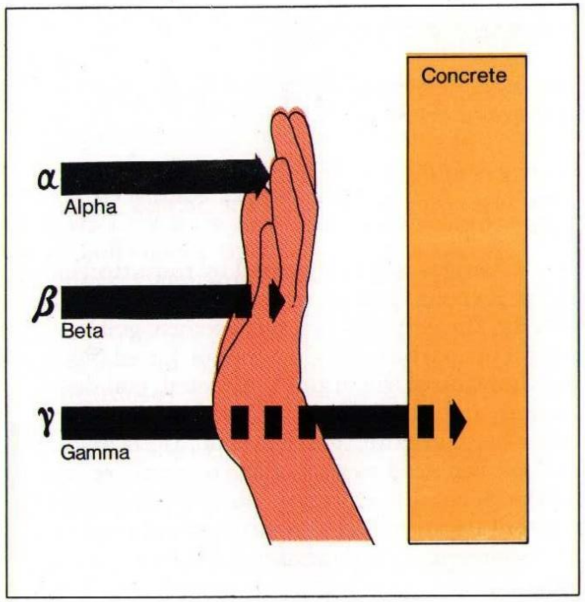


Nature of Radiation and Radioactivity

Man's knowledge of ionising radiation began with the discovery of X-rays by Röntgen in 1895. In the same year, Becquerel, working in Paris, discovered that uranium compounds were capable of fogging photographic plates. This effect was shown to be due to the spontaneous emission of radiation. The fundamental property which causes this emission is known as *radioactivity*.

All material is made up from *elements* – about a hundred elements are now known. The basic unit of any element is the *atom*. An atom consists of a *nucleus* around which orbit a number of negatively charged particles called *electrons*. The nucleus itself is made up of positively charged particles (*protons*) and others with no charge (*neutrons*). It is the number and arrangement of these various particles within the atom which determine the properties of the element – which, for instance, make iron different from copper.

Penetrating power of different forms of ionising radiation.



Atoms are identified by their chemical names and by their mass; for example, carbon-14 refers to a carbon atom which has a mass 14 times that of the lightest atom – hydrogen. Atoms like carbon-14 and carbon-12 which are identical chemically but have different masses are called *isotopes* of the element.

Because of their structure some atoms (like carbon-14) are unstable and change spontaneously into other kinds of atoms, often atoms of other elements. These new atoms may be stable or unstable, but eventually all unstable (radioactive) atoms turn into stable ones. In changing into another form, the unstable atoms emit energy in the form of radiation which can be one or more of five main types – alpha, beta, gamma, X-ray and neutron emissions.

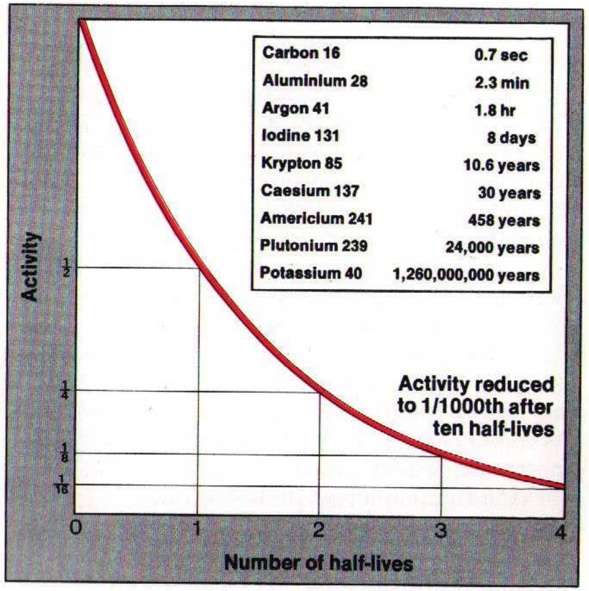
Alpha radiation is the emission of a particle the mass of which is four times the mass of the hydrogen atom. In passing through matter, alpha particles give up their energy and become helium atoms. They cannot penetrate far into solids and liquids; an ordinary sheet of paper will stop them. Because of their short range, alpha particles outside the body do not constitute a hazard to human beings as they are absorbed in the outer insensitive layers of the skin. On the other hand, alpha emitting elements inside the body can be harmful because all of their energy is released in such a short distance within living tissue.

Beta radiation consists of very small charged particles (electrons). Although the range of beta particles is greater than alpha particles, they are stopped by relatively thin layers of water, glass or metal. The range of beta particles is great enough, however, to penetrate beyond the outer insensitive layers of skin. Beta active materials may also be harmful if they are taken into the body.

Gamma radiation and X-rays are in the same family of radiation as light and radio-waves. They penetrate relatively great thicknesses of matter before being absorbed. Because of their penetrating power, over-exposure of the body to gamma rays originating outside the body can cause internal damage.

Neutrons have approximately the same mass as a hydrogen atom and, as we shall see in Chapter 6, they play a vital part in the nuclear fission process. Like gamma radiation they are very penetrating and damaging, but because of the circumstances in which they arise they are important as a potential hazard only to those working in the nuclear industry.

A radioactive material does not go on emitting radiation for ever. From the moment it is formed its activity diminishes as it progressively decays away. This process cannot be speeded up or delayed. For each substance the activity disappears at a characteristic rate; its 'half-life' is the time taken for its activity to fall to a half. For example, if a substance has a half-life of one day then its activity is reduced to half after one day, to one quarter after two days, one eighth after three days and so on. After ten half-lives only about a thousandth of the original activity remains. Although for any given substance the half-life is always constant, the half-lives of different substances vary enormously between fractions of a second and millions of years.



Carbon 16	**0.7 sec**
Aluminium 28	**2.3 min**
Argon 41	**1.8 hr**
Iodine 131	**8 days**
Krypton 85	**10.6 years**
Caesium 137	**30 years**
Americium 241	**458 years**
Plutonium 239	**24,000 years**
Potassium 40	**1,260,000,000 years**

Half-life or rate of radioactive decay.

Measurement of Radiation

The radiations described above cannot be sensed directly. They can only be detected by means of instruments, which can also be made to indicate the quantity of radiation received, that is, the exposure or dose. When living tissue is exposed to radiation, energy is transferred to the tissue; as we shall see in the following section, this may have adverse effects on the tissue's normal functions.

Despite the diversity of types of radiation, the likelihood of harm can be estimated by assessing the dose to the tissue, i.e. the energy absorbed by it. The tissue of interest may be the whole body, part of the body or a specific organ. However, some types of radiation have a greater damaging effect than others. For example, for the same amount of energy absorbed, alpha or neutron radiation is ten times more harmful than beta or gamma radiation or X-rays. These differences are taken into account by measuring exposure in '*rems*', the unit of 'dose equivalent'. One rem of any type of radiation is equivalent in damaging effect to one rem of any other type of radiation. (A millirem is one thousandth of a rem).

The Biological Effects of Radiation

Radiation can cause changes in living cells – that is what makes it dangerous. Depending on the dose of radiation and the nature of the cells affected, these changes can affect the health or survival of the individual or his or her offspring. Our knowledge of the effects produced, and the influence of dose on both the type and the likelihood of occurrence of their effects, has come from several sources. In particular, it has come from studies of:

animals experimentally exposed to radiation

persons exposed in the course of their work before the harmful effects were fully appreciated (e.g. those pioneering the use of X-rays and painters of luminous dials)

patients given radiation treatment for non-malignant diseases

survivors of the atomic bomb attacks on two Japanese cities at the end of the Second World War.

Changes in a cell caused by radiation can affect its behaviour in a number of ways. Firstly, the cell may die, but because generally a high proportion of cells must be killed before the function of the organ is affected, cell death is likely to be important only at high radiation doses (say, greater than 50 rems). Cells also die and are replaced as part of the normal process of life. Secondly, changes caused in the cell may prevent its normal division or may prevent the development of its daughter cells. Here again, effects on the body are only significant if large numbers of cells are affected following radiation doses much higher than those with which we are concerned in discussions about nuclear power. Thirdly, at lower doses, the cell, although damaged by radiation, may survive and be capable of producing viable daughter cells.

In this third case two possible consequences are important. If the affected cells are in the ovary or testes and subsequently form fertilised ova or fertilising spermatozoa, abnormalities produced in the cells may be transmitted to the offspring of the irradiated person. This may lead to consequent illness or clinical abnormality (which may vary from severe to inconspicuous) in his or her children or in a later descendant – a "genetic" effect; or it may cause failure of the ovum to develop into a viable foetus.

If, on the other hand, the irradiated cells are in some other body organ or tissue, or in the developing foetus, any effect is limited to the person (or foetus) irradiated, i.e. it is a "somatic" effect. In this case, changes induced in such cells may sometimes result in their abnormal division and cause subsequent abnormal development of the foetus or induction of cancer. The mechanisms of these effects are complex and not fully understood. It is known that large doses of radiation can give rise to tumours in most body tissues. In epidemiological studies of people exposed to lower, but still abnormally high doses of radiation and in experimental animals a detectable increase in the frequency of occurrence of some types of cancer has been demonstrated statistically. Of particular importance is the increased induction of thyroid tumours and leukaemia in survivors of the Japanese nuclear explosions. In only one or two instances (exposure of the foetus and thyroid gland during medical procedures) has an increase in the incidence of tumours been detected following doses comparable with those received in a lifetime from natural sources. In a high proportion of cases thyroid tumours can be cured.

Mammalian cell damage by high dose γ-radiation.
(a) dicentric (b) tricentric (c) tetracentric Photo N.R.P.B.

Radiation is not alone as a potential cause of cancer and genetic effects. We are increasingly aware that cancer may be produced by many other agencies including ultra-violet light and common non-radioactive materials such as asbestos, vinyl chloride, some oils and tobacco smoke. Many carcinogenic (cancer producing) chemicals can also produce genetic changes.

From the evidence we have we can estimate the frequency of cancer production following average radiation doses of a few hundred rems and in certain cases of a few rems. The frequency and even the occurrence of cancer production at the levels of natural radiation (one to two tenths of a rem per year) or at the average population exposure levels associated with nuclear power (less than one thousandth of a rem per year) can only be inferred by making assumptions.

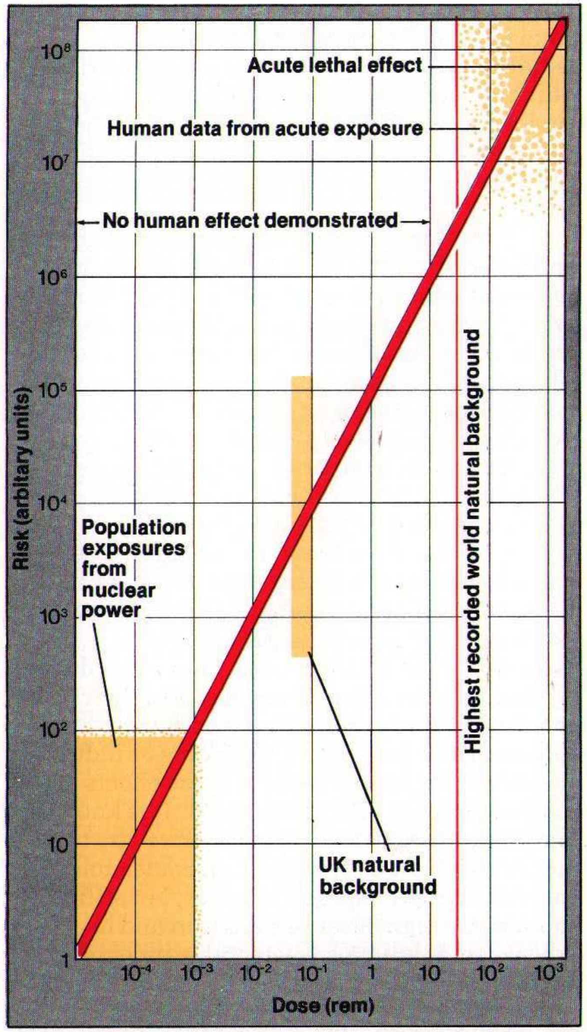
These assumptions allow us to make estimates of the somatic and genetic effects which might be expected following the widespread development of nuclear power. This is further considered in the next two chapters.

5 The Basis of Radiological Protection

Since the 1920s, *our growing knowledge of the biological effects of radiation and radioactive materials has enabled standards of health protection to be formulated. These apply both to people who are exposed in the course of their work (such as radiographers and those working in nuclear plants) and to members of the general population. Around the world these standards are based on recommendations of the International Commission for Radiological Protection (ICRP), an independent body of experts which, working under the aegis of the International Congress of Radiology, has since* 1928 *kept under review all aspects of the effects of radiation on man. In the United Kingdom the Medical Research Council and the National Radiological Protection Board advise the Government on the application of these recommendations.*

The aims of radiological protection are to prevent acute effects and to limit the occurrence of delayed effects to an acceptable level. The recommendations of the ICRP are based on the cautious assumption that any radiation exposure carries with it some risk of somatic or genetic effect. It is assumed that even from the very lowest doses the risk of a harmful effect increases in proportion to the dose received. On a number of grounds such an assumption is liable to overestimate the harm caused by low doses of radiation; but it remains the most suitable basis for radiological protection purposes in that it represents an upper limit to the possible harmful effects. Adoption of the hypothesis that there is no "safe" dose below which there is no risk makes inevitable the need for a judgment about the acceptability of risks.

The recommendations of ICRP are founded on a wealth of past and continuing research. They comprise a comprehensive system of exposure limits designed to restrict the risk to individuals and populations to a level which should be generally acceptable. They refer only to exposure from sources other than natural background radiation and radiation received by patients in the course of medical and dental procedures. The recommendations distinguish between two types of individuals – adults exposed in the course of their occupation (with special consideration for women of reproductive capacity) and members of the public. As the latter include children and others who might be subject to an increased risk, and as they are not



The linear hypothesis relating radiation dose to risk which is used as the basis of radiological protection.

Gonads and red bone marrow and, in the case of uniform irradiation, the whole body	**5 rems**
Skin; thyroid; bone	**30 rems**
Hands and forearms; feet and ankles	**75 rems**
All other organs	**15 rems**

Maximum permissible annual doses recommended by the ICRP for workers.

subject to special supervision as are occupational workers, in general they are limited to doses ten times less than those permitted to radiation workers. The Commission has also made recommendations to limit the average dose to populations so as to control the burden to society of any possible increase in genetic mutations.

The recommended maximum permissible annual dose for radiation workers is 5 rems. There are higher limits for certain organs and for body extremities. Concentration limits of radioactive materials in air and water to achieve these basic individual standards are also given by the ICRP.

The effect on a population is measured in terms of its "collective dose" (in man rems), i.e. the number of people considered multiplied by their average dose. For large populations an average limit of 5 rems per generation (30 years) is recommended; this is equivalent to an average annual dose of 0.17 rems. For the population of Britain, irradiation at this limit implies an annual collective dose of just under one million man rems.

Within these limits the ICRP highlights the need to avoid any unnecessary exposure, to keep all doses to the lowest levels reasonably achievable (having taken economic and social considerations into account) and to be able to justify the doses in terms of the benefits that would not otherwise have been achieved.

The next chapters discuss the operation of our nuclear industry and how strict implementation of radiological protection standards has kept exposures of members of the public, even those most highly exposed, well below the allowable levels. Indeed, it will become clear that the safety criteria and regulations applied to the nuclear industry are quite different from those applied to other and older industries.

Note: Since going to press some of the ICRP recommended maximum permissible annual doses detailed in the Table in Chapter 5 have been revised in ICRP Publication 26, Pergamon Press, 1977. The maximum permissible annual dose to the whole body for occupational exposure remains at 5 rems.

P16 + 17

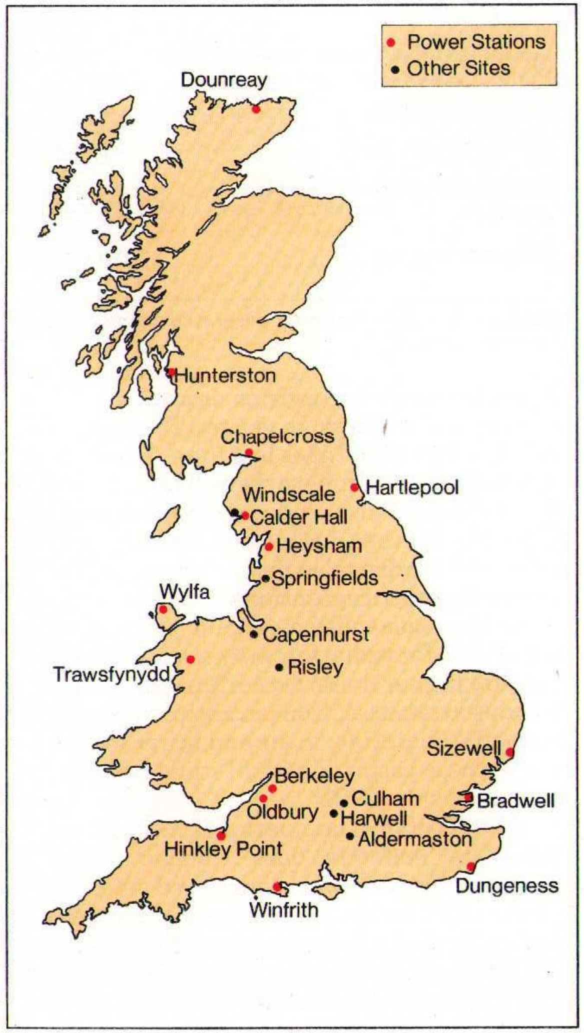
6 Nuclear Power and the Nuclear Fuel Cycle

Except for their heat source, power stations based on fossil fuels and uranium have much in common. Both use boilers to convert the heat into steam which is fed to turbines where it is used to drive the electricity generators. The principal difference is the way the heat is produced. The nuclear station uses the energy available in atoms of uranium instead of the combustion energy of coal or oil.

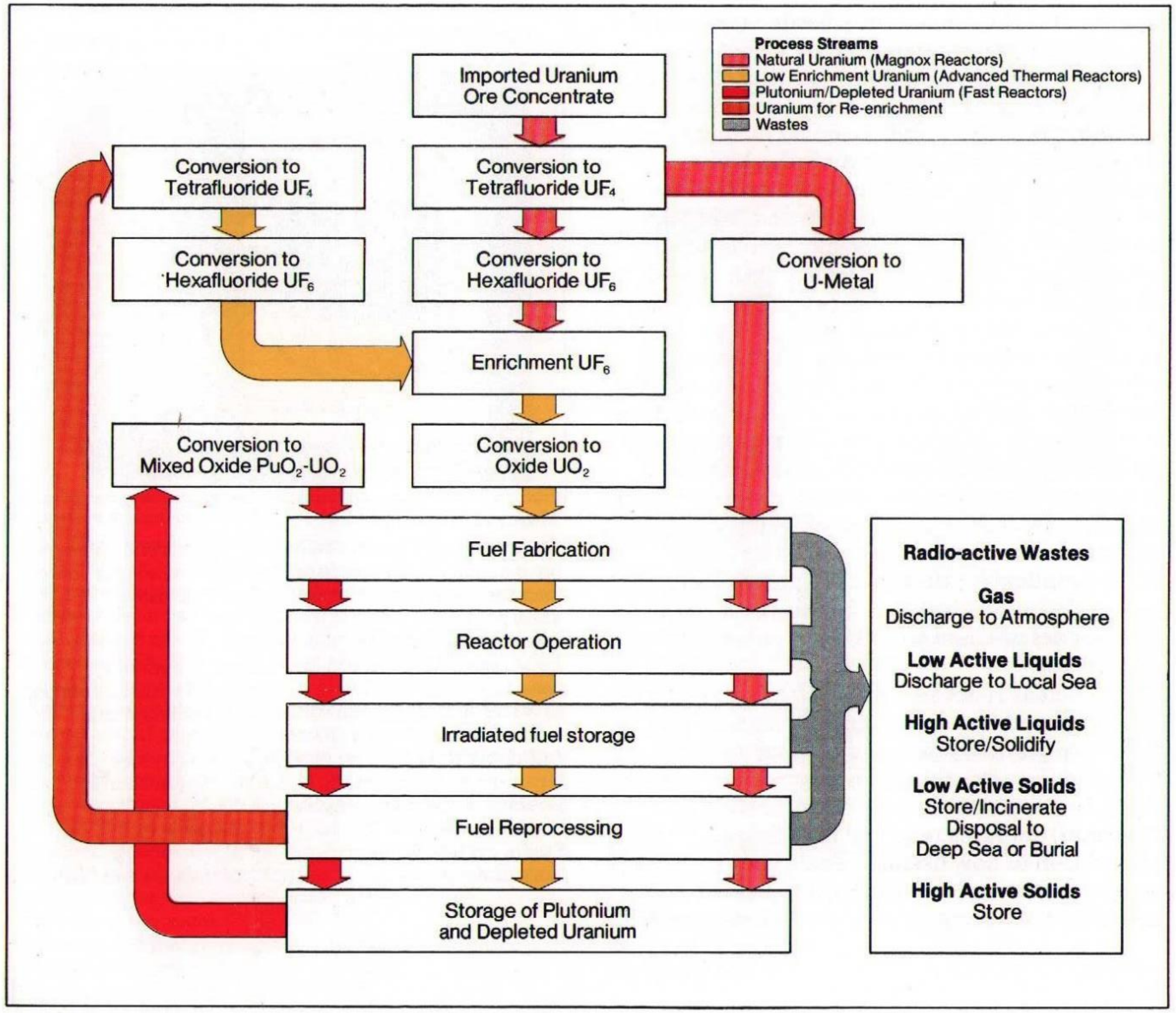
The term 'nuclear fuel cycle' refers to the process through which the fuel passes: mining and extraction of uranium, enrichment and conversion to fuel; fabrication of fuel elements, 'irradiation' (burning in the core of a nuclear reactor); separation of the by-products from the spent fuel; and reconstitution of the unused fuel. These various stages are described briefly in the following paragraphs.

Uranium Mining and Extraction

Uranium is a relatively widely occurring material although it forms only about 2 parts per million of the earth's crust. The largest resources (excluding the USSR, China and eastern Europe) are in North America, southern Africa, Australia and Sweden. There are some low grade deposits in Britain but these are not exploited. The mining methods employed to extract uranium depend upon the characteristics of the ore deposit. Generally, deposits lying less than about 150m below the surface are mined by open pit methods. Underground mining is carried out using conventional techniques. Present commercial ores, which typically contain between 0.1 and 0.3% of uranium, are converted by a chemical process into a concentrate known as 'yellowcake' which is mainly uranium oxide. This is the form in which we import it.



Nuclear sites in Great Britain.



Enrichment

Only about 0.7% of the uranium which occurs in nature is fissile; this fraction is known as uranium-235. The remainder is mostly non-fissile uranium-238. Some power reactors, for example the British first-generation Magnox reactors and the Canadian CANDU reactors, have been designed to operate with natural uranium fuel, but in other reactor types, to reduce capital costs, the uranium-235 content is increased or 'enriched' up to a few per cent. Enrichment is now carried out by a diffusion process after conversion of the uranium to a volatile compound (the hexafluoride). An alternative process being developed commercially uses the gas centrifuge.

A simple diagram of the nuclear fuel cycle showing the main categories of waste.

Fuel Fabrication

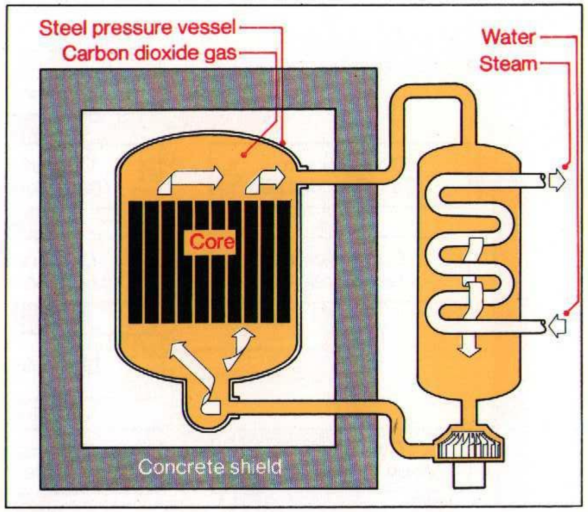
The uranium from yellowcake, or the uranium hexafluoride after enrichment, is converted by a series of chemical reactions into the metal or the oxide. In one or other of these forms it is loaded into metal tubes (magnesium or zirconium alloy or stainless steel) which are filled with gas and sealed. The filled tubes, either singly or in clusters, are assembled into fuel elements for inserting into the nuclear reactor.

Completed S.G.H.W.R. fuel element.

Power Reactor Operation

In a reactor the nucleus of a fissile atom, such as uranium-235, when struck by a neutron divides into two fragments. Splitting (fission) can occur in many different ways to produce a whole range of lighter chemical elements (the 'fission products') most of which are radioactive. This process is accompanied by the release of energy, which appears as heat, and more neutrons. Under appropriate conditions some of these neutrons can react with other uranium-235 atoms thereby setting up a chain reaction which continues as long as the conditions remain favourable. The fission products are retained inside the metal cladding. In another type of reaction in the fuel, neutrons can be captured by uranium-238 atoms thereby producing atoms of elements heavier than uranium. These heavier elements, the so-called transuranic elements, many of which emit alpha radiation, are of special importance in the nuclear industry; they include plutonium, a material which has been highlighted in the nuclear debate, and which is the subject of a later chapter.

Nuclear reactors fall into two categories – 'thermal' and 'fast'. In thermal reactors, the fuel elements are separated by 'moderating' material (e.g. graphite or heavy water) to slow down the neutrons to the comparatively low (thermal) energies required for efficient production of new fissions. Fast reactors have no moderator and are designed to utilise neutrons travelling at very much faster speeds.



Magnox Reactor

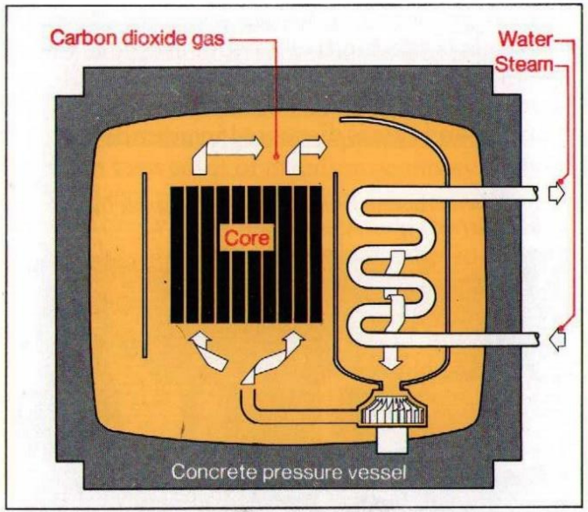
Fuel: Uranium metal. To conserve neutrons and allow natural uranium to be used, the fuel is clad in a magnesium alloy (Magnox) with low neutron absorption.

Moderator: Graphite.

Heat extraction: Carbon dioxide gas is heated by passing it over the fuel in the core and transfers its heat to water in a steam generator; the steam drives a turbine coupled to an electric generator.

Indicative data for a reactor of 600 MW(e) size:

Uranium enrichment (% U.235)	0·7% (natural)
Coolant outlet temperature	400°C
Coolant pressure	300 psia
Steam cycle efficiency	31%
Core dimensions	14 m dia. × 8 m high



Advanced Gas-cooled Reactor (AGR)

Fuel: Uranium dioxide in stainless steel cans. The fuel can operate at higher temperatures and heat output rates than Magnox reactor fuel, giving a smaller size of reactor core and a more efficient steam cycle. To achieve these advantages and a greater heat rating, the proportion of U.235 in the fuel has to be increased (enriched uranium).

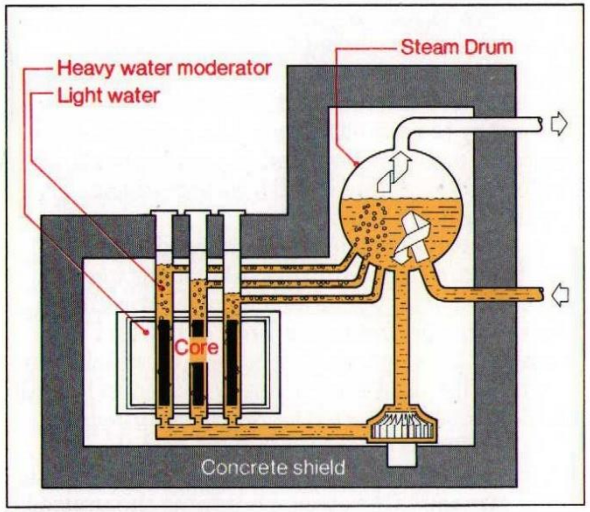
Moderator: Graphite.

Core layout: Clusters of fuel elements are joined together end-to-end in a stringer, placed in vertical holes in the graphite.

Heat extraction: Carbon dioxide gas is heated by passing over the fuel in the core and transfers its heat to water in a steam generator; the steam drives a turbine coupled to an electric generator.

Indicative data for a reactor of 600 MW(e) size:

Uranium enrichment (% U.235)	2·3%
Coolant outlet temperature	650°C
Coolant pressure	600 psia
Steam cycle efficiency	42%
Core dimensions	9·1 m dia. × 8·5 m high



Steam Generating Heavy Water Reactor (SGHWR)

Fuel: Uranium dioxide in Zircaloy cans.

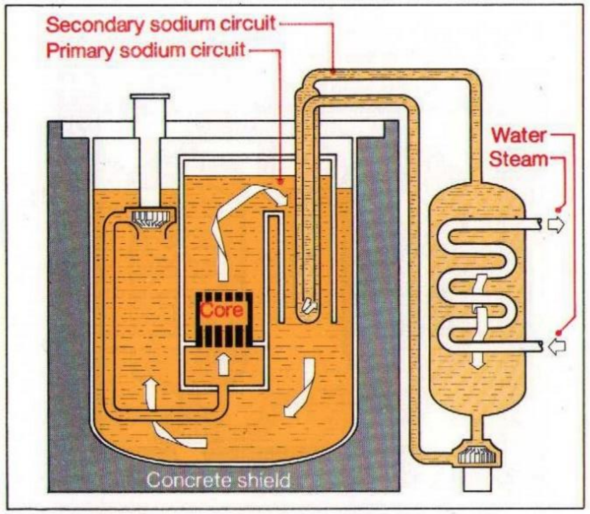
Moderator: Heavy water (D_2O).

Core layout: Each cluster of fuel elements is in a separate pressure tube; the pressure tubes are in a tank of heavy water. Heavy water is the most efficient moderator and compensates for the neutron absorption in the pressure tubes.

Heat extraction: Light water (ordinary water, H_2O) at pressure is heated by passing over the fuel in the pressure tubes and allowed to boil; the steam from the boiling coolant drives a turbine coupled to an electric generator.

Indicative data for a reactor of 600 MW(e) size:

Uranium enrichment (%U.235)	2·24%
Coolant outlet temperature	272°C
Coolant pressure	900 psia
Steam cycle efficiency	32%
Core dimensions	6·5 m dia. × 3·7 m high



Fast Reactor

Fuel: A mixture of plutonium and uranium dioxides in stainless steel cans.

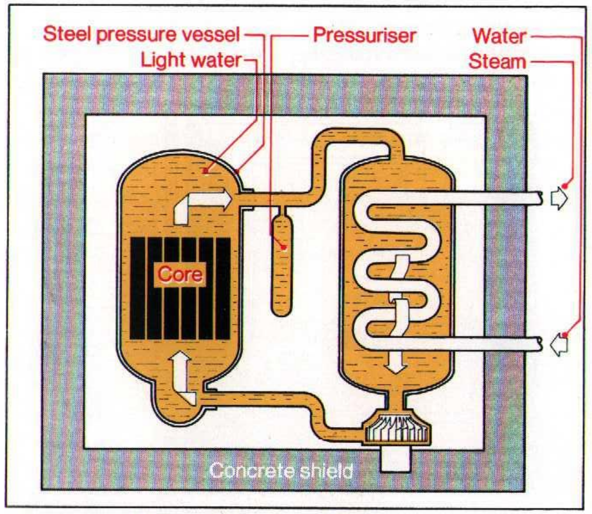
Moderator: None.

Core layout: Assemblies of fuel elements are placed inside a tank containing the liquid sodium coolant. The core is surrounded by a "blanket" of uranium in stainless steel cans.

Heat extraction: The sodium is heated by the core and pumped through an intermediate heat exchanger where it heats sodium in a separate secondary circuit. The sodium in the secondary circuit transfers its heat to water in a steam generator; the steam drives a turbine coupled to an electric generator.

Indicative data for a reactor of 1300 MW(e) size:

Fuel enrichment (% Pu)	20%
Coolant outlet temperature	620°C
Coolant pressure	5 psia
Steam cycle efficiency	44%
Core dimensions	2·3 m dia. × 1·1 m high
Core and blanket dimensions	3·1 m dia. × 2·1 m high



Pressurised Water Reactor (PWR)

Fuel: Uranium dioxide in Zircaloy cans.
Moderator: Light water (ordinary water, H_2O).
Core layout: Fuel pins, arranged in clusters, are placed inside a pressure vessel containing the light water moderator, which also is the coolant.
Heat extraction: The light water in the pressure vessel at high pressure is heated by the core. It is pumped to a steam generator where it boils water in a separate circuit; the steam drives a turbine coupled to an electric generator.

Indicative data for a reactor of 700 MW(e) size:

Uranium enrichment (% U.235)	3·2%
Coolant outlet temperature	317°C
Coolant pressure	2235 psia
Steam cycle efficiency	32%
Core dimensions	3·0 m dia. × 3·7 m high

Fuel Reprocessing

In a thermal reactor, as the uranium-235 gets used up and is replaced by fission products which absorb neutrons, the fission process becomes less efficient and it eventually becomes necessary to renew the fuel. The irradiated fuel contains uranium depleted in uranium-235, the fission products and small amounts of the transuranium elements.

Spent fuel elements discharged from reactors are stored for several months under water in special ponds at the power stations. During this period the activity of the fuel elements falls naturally to a level at which they can be safely and economically moved in heavily shielded containers to the reprocessing plant. Here the fuel is dissolved in acid, and the solution is treated chemically to separate it into three streams. One stream contains the unused uranium which is recovered to make new fuel. The second stream contains the bulk of the plutonium which is kept for future use in fast reactors. The third stream contains the fission products and most of the other transuranic elements; this is highly radioactive waste.
The separation process is carried out remotely in plant situated behind massive concrete walls.

Waste Management

As in all industrial processes a variety of waste materials is produced at various stages of the fuel cycle. Their safe management is an important responsibility of the nuclear industry and this is discussed in more detail later.

Plutonium extraction from irradiated magnox fuel at Windscale fuel reprocessing plant.

Other Fuel Cycles

It has often been suggested that the relatively abundant element thorium be used to replace uranium in thermal reactors (particularly in High Temperature Gas Cooled Reactors). Although at first sight this appears attractive from the viewpoint of uranium economy, detailed examination does not support this view. Moreover, new fuel technologies would have to be introduced to deal with the high levels of radioactive thorium-228 which would be produced in the reactor and remain with the recovered fuel after reprocessing. Little, if any, overall environmental benefit would accrue from adoption of the thorium fuel cycle.

The Safety Issues of Nuclear Power

If we are to be convinced that nuclear energy as a source of power is as safe as, or safer than other sources, we need answers to the following questions:

What are the effects on the public and on workers in the nuclear industry of the normal operation of power reactors and the remainder of the nuclear fuel cycle? In particular, to what level of radiation are people being exposed by disposal of radioactive wastes to the environment?

How is the nuclear industry intending to deal with the increasing amount of radioactive waste which will accumulate as the use of nuclear power grows? Can it ever be disposed of safely or will it remain as a burden on future generations?

How likely is a serious accident; and what might be the consequences?

Does the fast reactor now under development introduce any additional dangers?

Can we safely handle and adequately safeguard the growing amounts of plutonium which will be used, stored and transported in the future?

The remainder of this booklet will be addressed to these questions.

7 Control of Nuclear Plant Operations

The high standards of safety and consideration for the environment, adopted by the nuclear industry from the outset, have an internationally accepted quantitative basis in the recommendations of the International Commission for Radiological Protection (ICRP). These recommendations and the philosophy behind them are the foundation for legislation and codes of practice which serve to protect both members of the public and people exposed to radiation in the course of their work.

It would be hard to name any other public health issue that is as well understood and controlled as that related to the nuclear industry. Close attention is paid to various ways in which radiation can reach man. Those who are occupationally exposed are under careful supervision, their conditions of work are controlled and their exposure is regularly measured to ensure that they do not exceed the limits laid down by law or in codes of practice. This thorough supervision contributes to their excellent health record. Data for the Atomic

Cause of death	Actual	Expected	Percentage of total expected
All causes	2,730	3,652	75
All neoplasms	730	858	85
Leukaemia	11	23	48
Circulatory system other than blood	26	34	76
Bone cancer	4	4.2	95
Lung cancer	291	406	72
Circulatory system	1,497	1,651	91
Coronaries	1,066	1,181	90
Strokes	219	309	71
Respiratory system	173	437	40
Digestive system	65	90	72
Reproductive and excretory systems	26	47	55
Accidents, violence	153	197	78
Road traffic	71	68	104

Number and causes of death of male employees and pensioners of the Atomic Energy Authority and British Nuclear Fuels Limited, from 1962 to 1974.

Radiation and contamination monitoring at the entrance to a controlled area at Winfrith.

Energy Authority and British Nuclear Fuels covering the period 1962/1975 shows that for every cause of death (except for road accidents) atomic energy workers have a lower mortality rate than would be expected for a corresponding cross-section of population in general. This enviable record extends also to working time lost from illnesses and accidents.

For members of the public direct measurement of radiation exposure from operations of the nuclear industry is not practicable. Protection must therefore rely on effective control of the source of the exposure, the main source being discharges of radioactive materials to the environment either as airborne effluents to atmosphere or as liquid effluent to the seas or inland waters. A further source of exposure, albeit extremely small, arises through the transport of radioactive materials by road, rail or sea. Radiation from these sources will not reach all members of the population equally, e.g. those near the source of airborne effluent will in general receive more exposure than those further away. Following some discharges, particularly of materials with a long half life, radioactive materials may travel large distances in air or water. So, in assessing the safety of various existing or proposed operations we have to consider not only the dose to local individuals but also the collective dose to national, regional and global populations.

Legislation and Advisory Bodies

Nuclear operations in this country are closely governed by a comprehensive framework of legislation. Under the *Nuclear Installations Acts* no nuclear reactor or other plant may be built or operated (other than by the UKAEA or Government Departments) or later modified, without the approval of the Health and Safety Executive. Conditions under which the plant may be operated are imposed by licence granted by the Executive and enforced by its Nuclear Installations Inspectorate. The UKAEA and Government Departments are required to observe as far as is practicable the safety requirements ordinarily imposed on licensed operators. The Nuclear Installations Acts impose an absolute duty on licencees, the UKAEA and Government Departments to prevent any personal injury or damage to property arising from nuclear operations.

Persons employed in factories and other places to which the *Factories Act* applies are protected against exposure to ionising radiation by very detailed Regulations made under the Act which specify the conditions of work and the required medical and other controls. Certain health and safety legislation including the Factories Act and relevant parts of the Nuclear Installations Act will be replaced in due course by Regulations and Codes of Practice approved under the *Health and Safety at Work Act*.

Carriage of radioactive materials by air, sea, road, rail and postal services is controlled by *Transport Regulations* made under appropriate Acts. They apply standards recommended by the International Atomic Energy Agency concerning packaging and other conditions of transport.

It is an offence to dispose of radioactive waste without an Authorisation issued by relevant Government Departments under the *Radioactive Substances Act*. (This Act exempts certain minor uses and commonplace items which would not normally be regarded as radioactive.) Authorisations are issued as appropriate by the Department of the Environment, the Ministry of Agriculture, Fisheries and Food, the Scottish Development Department and the Welsh Office, following consultation with appropriate local authorities. It is also an offence to exceed the quantities stipulated in the Authorisation.

Under the Euratom Treaty, we will have to comply with those matters which will, in time, become uniform throughout the Community. The new *EEC Directive* concerned with radiological protection standards, like U.K. legislation, is closely modelled on the ICRP recommendations.

A broadly based *Advisory Committee on Safety of Nuclear Installations* has recently been established to advise the Health and Safety Commission and, where necessary, the Government on nuclear safety matters.

The *National Radiological Protection Board* was established by the Radiological Protection Act 1970. Its principal duties are to help to advance the acquisition of knowledge on protection from radiation hazards and to provide information to those in the U.K. with responsibilities related to radiation protection of the community. It offers services to users of radiation and radioactive materials who do not have their own specialist teams and it administers the emergency network known as the National Arrangements for Incidents involving Radioactivity (NAIR).

From the start of the power programme, *Local Liaison Committees* have been set up at nuclear plants. These Committees include members and officials of county and local authorities, representatives of local organisations including the police, water authorities and agricultural and fisheries interests and representatives of the site operators and the authorising Ministries. At the meetings of these Committees information is supplied on the operations of the site and the significance of the measurements made related to protection of the public. They also provide a forum for the discussion of schemes for the protection of the public in the event of a serious accident.

Control of Waste Discharges

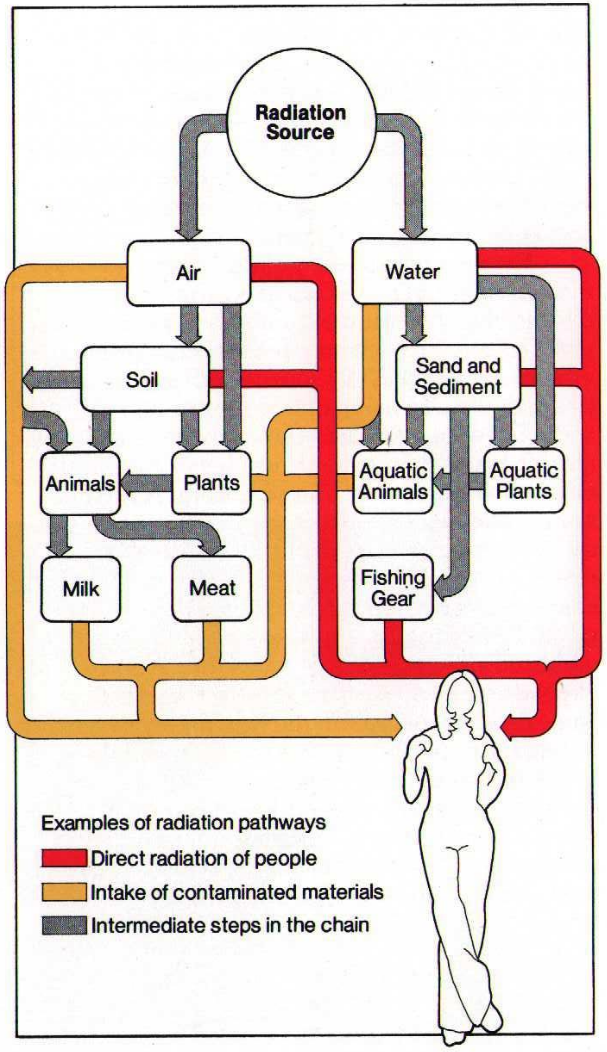
In 1959 a Government White Paper (now under review) laid down the principles on which the control of radioactive waste should be based and these have been followed since then. They are:

to ensure, irrespective of cost, that no member of the public shall be exposed to a radiation dose exceeding the ICRP limit,

to ensure, irrespective of cost, that the whole population of the country shall not receive an average dose of more than 1 rem per person in 30 years, and

to do what is reasonably practicable, having regard to cost, convenience and the national importance of the subject, to reduce doses far below these levels.

Radioactive substances released to the environment may come into contact with man through many different routes or 'pathways'. 'External' radiation may arise either from material in the atmosphere or on the ground. Or there may be 'internal' radiation if airborne material is taken into the body by breathing or if contaminated food or water is consumed. The resulting exposure will depend firstly on the quantities, nature and conditions of the discharge, particularly on the materials involved, and on the initial and eventual dilution in the air or water to which the discharge is made. Equally important in



Some examples of radiation pathways to man.

assessing the safety of any proposed discharge of radioactive effluent is the identification of the various routes or pathways by which, in that particular situation, the radiation might reach man. Many detailed studies have to be made, for example, of the expected movement of the released material through the atmosphere or biosphere, its possible concentration in flora or fauna, the age structure of the relevant population, their dietary, occupational and domestic habits and their recreational activities. Generally it is found that one or two of the materials to be released and one or two pathways will contribute most of the exposure and these are referred to as being 'critical'. The population affected may be a small group of people – even one person. The capacity of the environment to receive the waste is based on these critical groups and critical pathways and is calculated with reference to the internationally accepted exposure limits. Even when the upper limit to the discharge has been determined in this way, the Authorisation granted by Government Departments is normally restricted to a lower amount still, depending on the demonstrable need for the discharge to be made.

The best example of this type of 'critical pathway' analysis, well illustrative of the need to keep local situations under continual review, concerns the discharge of low level wastes from Windscale in Cumbria to the Irish Sea. Following detailed studies it was found that the critical group was not in the population living around the plant but people in South Wales who consume a local speciality called 'laver bread'. This is made from a type of seaweed which used to be collected from the shore near Windscale and which concentrates radioactivity. The permissible discharge from the Windscale plant was determined to ensure that these people were not exposed beyond the recommended limits. In the early 1970's, however, the three harvesters retired and their work was not taken up by others. As seaweed from the Cumbrian coastline was no longer gathered, different pathways and new groups of people became 'critical' – those involved in fishing pursuits in the Ravenglass Estuary (who are exposed to external radiation from radioactive materials taken up by coastal sediments) and those who eat fish caught off the Cumbrian beaches.

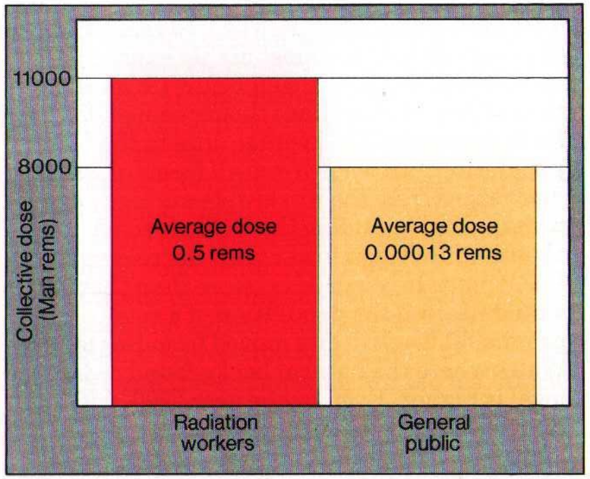
Other critical pathways identified, although ones giving only very low exposure of the population, include the consumption of oysters from near Bradwell in Essex, and of fish from the lake at Trawsfynydd in North Wales (both near nuclear power stations), handling of fishing gear near the experimental establishment at Dounreay in the far north of Scotland, and water consumption from the River Thames which receives very low active liquid waste from a number of establishments.

Any pathway identified as being important is extensively monitored by staff from the organisation responsible for the discharge in a way approved by the authorising Departments who also make independent checks. The results of the measurements made and their interpretation in terms of dose to people are regularly published.

Achievements and Predictions

This philosophy and these procedures have kept exposure of even the most highly exposed members of the public well below (in most cases tens of times lower than) the recommended limit for individuals. The average dose to the U.K. population as a whole from all forms of waste discharged from the worldwide nuclear power programme, including the U.K., is some thousands of times lower than the relevant ICRP limit. It is indeed no more than that which would result if the population of a small provincial English city moved from England to Wales where the natural background radiation level is higher. Even by the year 2000, without making any allowance for expected improvements in control procedures, it is predicted that the average population exposure from nuclear waste discharges would still be less than 1 per cent of the limit imposed by Government policy.

Because some of the materials discharged to the environment have extremely long half lives, they will be present in the biosphere for a very long period. Taking this into account, a detailed assessment has been made of the possible ultimate health effects of all the various aspects of worldwide nuclear power production including mining, construction and operation. The results of the study have recently been published by OECD. If one million people consumed electricity at an average rate of 1 KW each for one year (about twice the present U.K. rate of consumption) and if this were all nuclear, the study concludes that its production might result in about one death from radiation induced malignant disease and one case curable



Collective and average whole body U.K. exposure from nuclear power in 1975 with a 5 GW(e) installed capacity.

"... Quantitative analyses of the effects of the nuclear power industry on the health and well being of individuals and populations must be made in comparison with the corresponding effects of alternative energy sources (present and future). In such assessments data should be treated on an equivalent basis, that is for equal energy output and for the complete cycle of operations. Since knowledge of the health effects of alternative sources of energy (e.g. fossil fuels) is generally less precise than that of radiation effects, it is recommended that available information be critically reviewed and appropriate research be conducted on the health effects of alternative energy sources".

Extract from summary of a publication on Health Implications of Nuclear Power Production by the WHO Regional Office for Europe.

Plant Type	Fatalities per Year	
	Workers	Public
Coal Fired	**2.6-4.0**	**5-100**
Oil Fired	**0.35**	**3-60**
Gas Fired	**0.20**	**—**
Nuclear	**0.1-0.4**	**0.1**

Summary of estimate by the Energy Research Group Inc. in the U.S.A., of mortality rates for a 1000 MW(e) power plant.

by operation. In addition, there could be about one fatal and fifty other disabling conventional accidents. After many generations about one to one and a half cases of slight or severe genetic defects might appear each year. On this basis the predicted rate of development of nuclear power in the U.K. and worldwide would be unlikely to cause the present incidence of cancer in this country to increase by as much as 0.01% by the end of the century. Such a small increase would be statistically undetectable. This is also true of the increase which might be expected in the incidence of genetically related disease.

But even these very small levels of exposure could be reduced using existing technology; deciding if and when to impose further restrictions is a matter of balancing cost against risk. In making such a judgment a number of factors have to be borne in mind. Firstly, the collective dose received by the relatively small number of workers in the nuclear industry is considerably higher than the collective dose received by the rest of the population at large and introduction of any new process to reduce discharges might well increase further the collective dose to workers in the industry as well as produce other forms of waste. Secondly, because an increasing fraction of the dose to the U.K. population will come from effluent discharges from plants in other countries, proportionately less benefit will be achieved by U.K. action alone. Thirdly, greater benefit might be obtained if we were to spend our limited resources on reducing some of the considerably greater risks associated with other industries and activities.

The few comparative comprehensive studies of health risks that have been attempted in relation to the production of electricity by alternative technologies show uranium in a favourable light compared with fossil fuels, particularly coal. Evaluations as detailed as those which have already been made for nuclear energy are necessary before the risks associated with producing energy by the various alternative routes can properly be seen in perspective. This need has recently been recognised and emphasized by a Working Group of the World Health Organisation.

8 Radioactive Waste Management

Nearly all industries produce wastes, in a variety of physical and chemical forms, each of which needs special consideration. So it is with the nuclear industry. There are only two acceptable ways of dealing with wastes of any kind if they cannot be destroyed or are economically not worth recycling. Either they may be stored *in a safe and well managed way or they may be* disposed of *to the environment. In the latter case physical barriers and natural processes, e.g. dilution effects or chemical changes, may assist in reducing the impact on life to an acceptable level and in protecting the value of the environment. Both storage and disposal are practised in the case of radioactive wastes.*

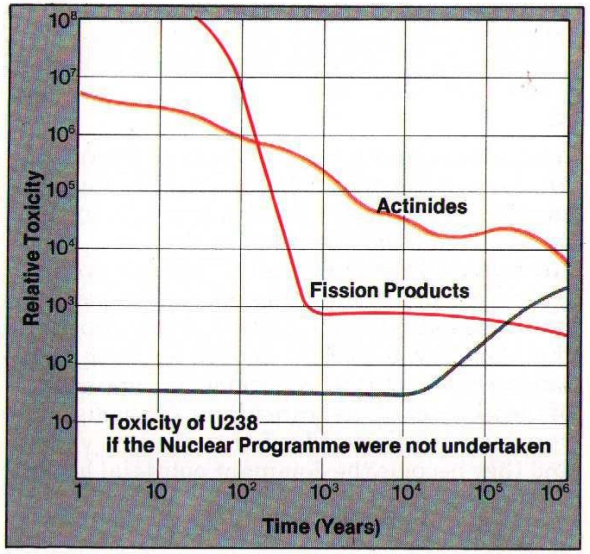
In all that follows, a clear distinction must be made between the terms 'storage' and 'disposal'. Storage signifies the supervised retention of material, isolated from human and other forms of life, but under such conditions that it can be recovered when necessary. Disposal implies the discarding of material to the environment in a controlled manner with no intention of it ever being recovered; this may be achieved either by deliberate dispersion in the atmosphere, the sea or fresh water, or by burying it in such a way that nobody can ever be harmed by it. Sometimes it might be acceptable to ensure its isolation for long periods followed by slow dispersion when the initial high levels of radioactivity have substantially decayed away. Storage always involves supervision; disposal may involve some more limited supervision of the disposal site. There is no technological reason why well engineered storage of radioactive materials should not be continued indefinitely. But there may well be economic and social reasons why eventually some method of disposal will be desirable or even necessary, so as to remove any risk, however remote, which might come from the stored waste in the distant future.

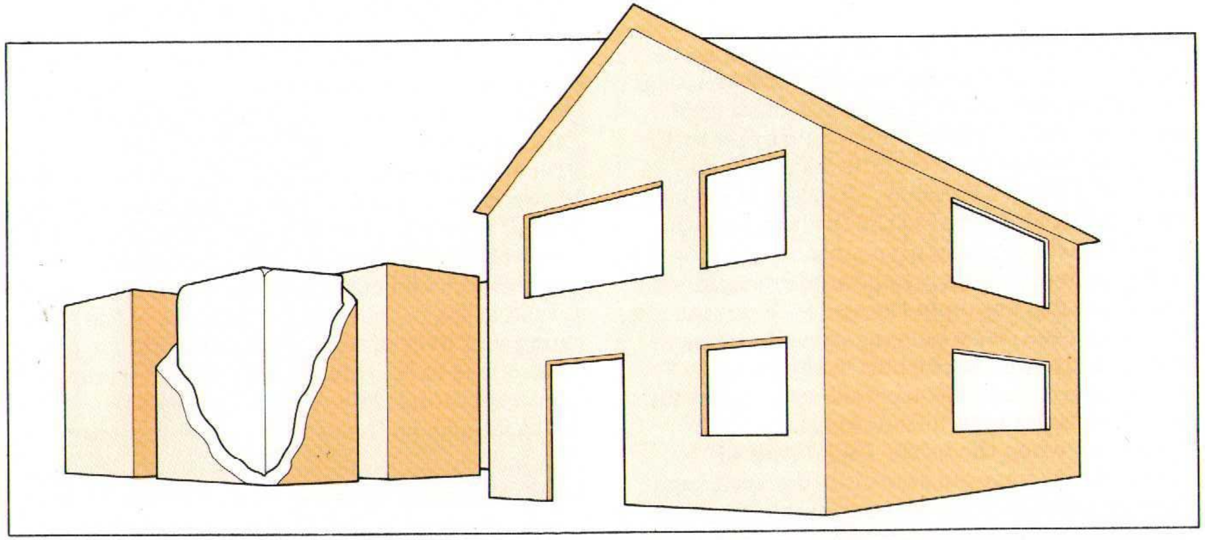
For convenience, the terms 'high', 'medium' and 'low' will be used to refer to the level of radioactivity in the waste, although these terms do not refer to precisely defined waste categories. The wastes which have given rise to most concern are the most highly radioactive ones, particularly those in liquid form, so we shall start by considering this category.

Highly Active Liquid Waste

Nearly all the highly active waste arises from reprocessing of nuclear fuels. The liquid waste concentrate from the reprocessing plant after the uranium and plutonium have been recovered contains about 99.9% of the residual total fission product activity. It also contains small amounts of unrecovered plutonium and other transuranic elements (particularly americium and curium) formed during irradiation in the reactor. Because of the very long half lives of some of its components, the waste has to be isolated from the environment for a very long time. When the waste is separated from the uranium and plutonium,

Relative ingestion toxicity of components of highly active waste from fast reactors.

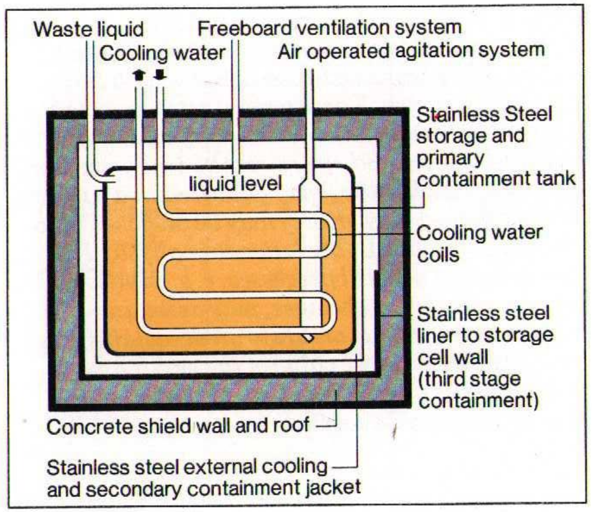




The highly active waste from the whole U.K. reactor programme which started in 1952, is only equal in volume to an average family house.

nearly all of its activity is due to the fission products. Although at first this falls quite rapidly, as the shorter lived isotopes decay, the longer lived fission products such as strontium-90 and caesium-137 (which have half lives of about 30 years) demand containment for several hundred years. After this time, however, their levels would be low enough for them to be safely released to the environment. But many of the isotopes of the transuranic elements have very long half lives indeed, thousands of years, and they become the dominant potential hazard after the activity of the fission products has decayed to very low levels. So man must be protected for periods of time longer than those already covered by the history of his civilisation.

Nearly all the highly active liquid wastes so far produced in this country are stored at Windscale in cooled, stainless steel tanks, the later ones having double walls. The tanks are themselves enclosed in stainless steel lined concrete silos. The containment and cooling water circuits are monitored so that any leak would rapidly be detected and the liquid could be transferred to spare tanks which are always available. This method of storage could be continued for a very long time; twenty five years' experience, during which time there have been no leaks of radioactivity from the tank systems confirms that this confidence is well founded.



Principle of the highly active waste storage tank.

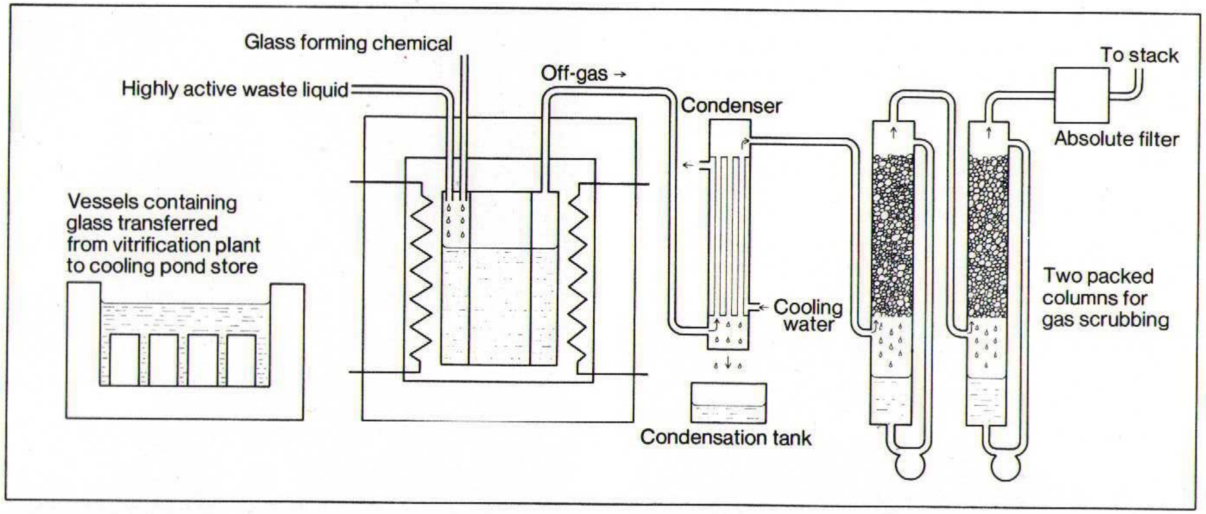
The amount of waste is often misunderstood. The present volume of fission product waste concentrate from the whole U.K. reactor programme (since 1952) is only about 600 cubic metres, equivalent to about the size of an average family house. By the year 2000 the total accumulated waste from the envisaged power programme would have increased by at most ten times.

Any storage system requires surveillance. But the degree and importance of surveillance could be reduced, and the storage of the high level wastes made even safer, if the liquid were converted to a stable solid. One such process turns the wastes into insoluble blocks of glass which have been shown to be very resistant to chemical attack and high levels of radioactivity. The feasibility of this process was proved at Harwell some 10-15 years ago on a pilot-plant scale; further developments are now in hand for a full scale plant to be operating at Windscale in the mid-1980s. Stainless steel containers, filled with the glass, could then be stored in a controlled environment such as under water in special ponds. If all the electricity consumed were nuclear, its supply to a town the size of Nottingham would give rise, each year, to less than a cubic metre of glass waste. All the highly active liquid wastes likely to be produced in the U.K. by the end of the century if converted into glass form would occupy about 3000 cubic metres and could be stored in an area of ground 100 metres square – no bigger than the size of two football pitches.

Even though such methods of supervised storage could be confidently applied for a very long time, it would obviously be better if the waste could be removed once and for all from man's environment. So studies are being made in this country and internationally to find the best way of doing this. These include examination of burial in deep, stable geological formations, such as salt domes, clay or hard rock and disposal on or in the deep ocean bed. Geological stability is, of course, vital, but areas have been identified which have been stable for many millions of years. Indeed, a convincing argument comes from a recent discovery that 2000 million years ago high uranium concentrations in the earth in the African state of Gabon initiated a natural 'reactor' which operated for about a million years. Evidence on the migration of the tonnes of products of the reactor away from its site holds no surprises; the elements which from their chemistry would have been expected to stay had done so and those which would be expected to be mobile had moved. Plutonium-239 appears not to have migrated during its lifetime. And the circumstances were less favourable than would be expected in a carefully selected disposal site.

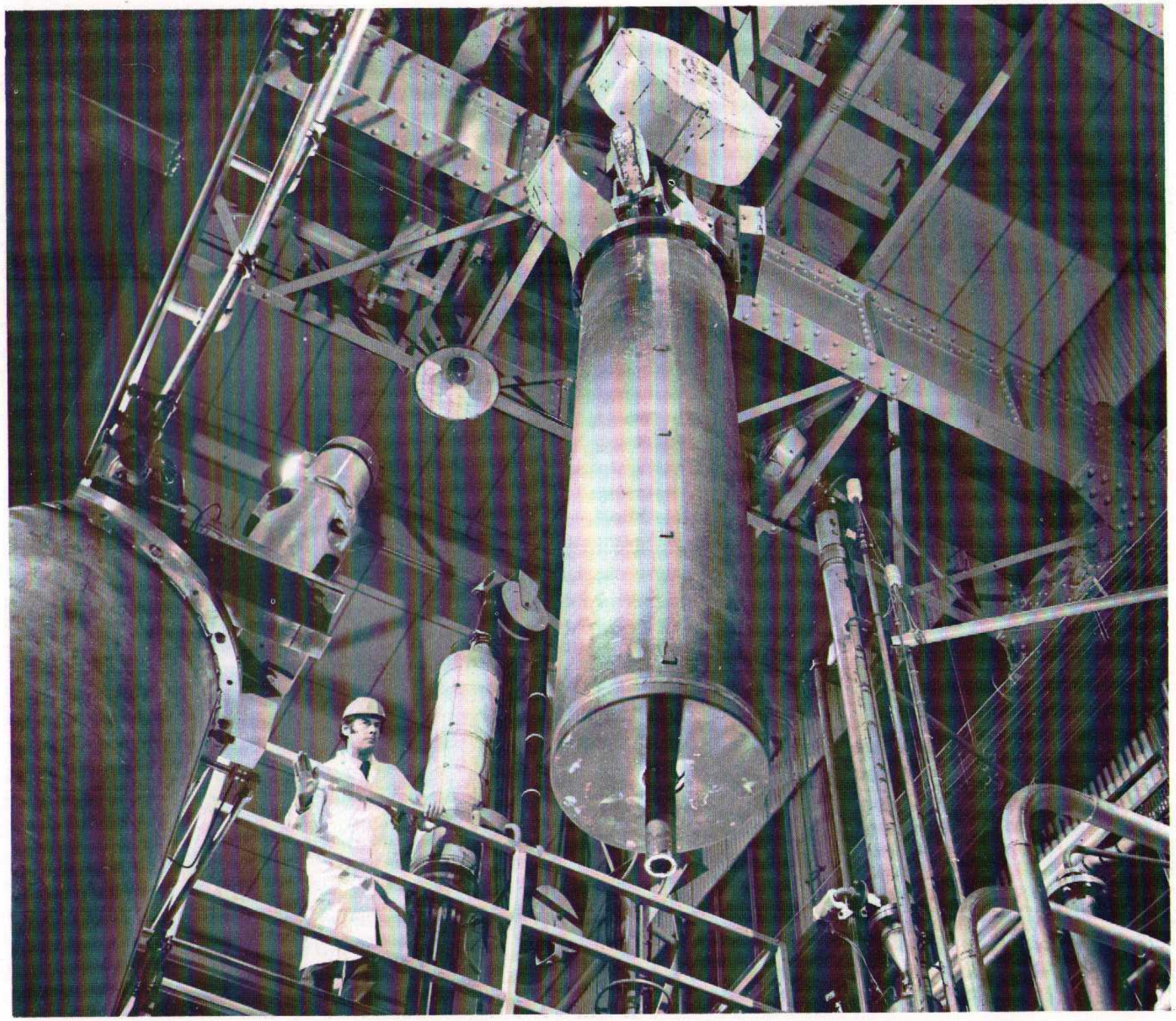
In principle, elimination of the long lived component of the waste would be very attractive. If we could separate the transuranic elements from the fission products and use them as fuel in a reactor (and they would make very good fuel), they would eventually be converted into shorter lived fission products. Although this approach is theoretically feasible for eliminating our long lived waste, its development would be a long and expensive business. The application of the process would probably involve an increase in the number of people operating nuclear plants and hence an increase in the total occupational exposure. Even so, it is being examined in the U.K. and a number of other countries.

We are not left, therefore, just with a hope that one day we may find a suitable and safe method of disposing of our highly active wastes; rather we will have to take a decision on the best of a number of options. Our present and proposed methods of storage will allow us the



A simple flow diagram of the Harvest/Fingal process for converting the highly active mobile liquid into an immobile solid.

time to make the best choice. It is important that premature and irreversible decisions are not taken before the necessary thorough research has been done.



An 18-inch diameter stainless steel vessel, used for experimental glass-making as part of Harwell's Harvest Project for liquid waste disposal.

Section of a stainless steel vessel containing vitrified waste with simulated fission products.

Medium and Low Activity Liquid Waste

Medium and low activity liquid waste streams are dealt with in various ways depending on their nature and radioactivity content. Those medium level wastes that are relatively free of dissolved materials can be evaporated and the concentrate can be stored with the highly active liquid waste. Other wastes, which on evaporation would yield concentrated solutions or sludges, are currently stored until their activity has decayed sufficiently for them to be treated as low level waste.

Very low activity liquid waste, after treatment, is discharged directly to coastal or inland waters within the terms of authorisations granted by relevant Government Departments. Discharges are made through long pipelines to sea from the BNFL site at Windscale, from the UKAEA establishments at Dounreay in Scotland and Winfrith in Dorset and from most of the nuclear power stations. From the power station at Trawsfynydd in Wales discharges are made to a lake and from a number of establishments in the south of England to the River Thames. The principles for assessing safe limits and for monitoring after discharge have already been described. As the nuclear industry grows, and the amount of fuel increases, maintenance of the present low levels of exposure will demand improved decontamination of some of these liquid effluents. Developments are being undertaken which will achieve these improvements.

Highly Active Solid Waste

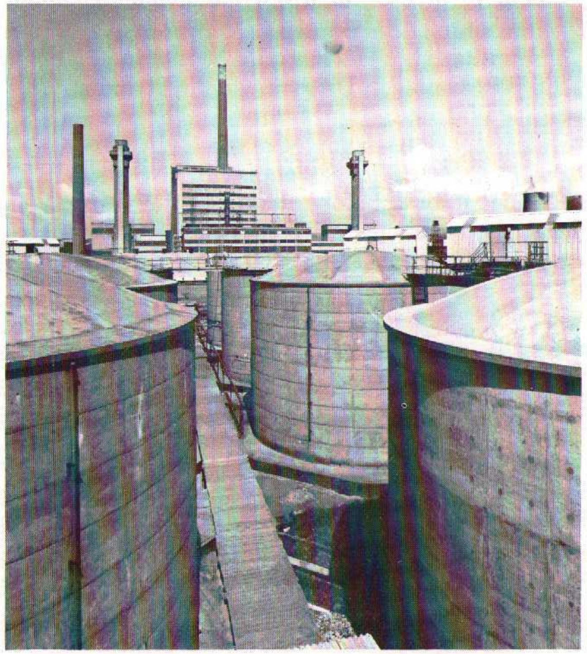
Much of the highly active solid waste consists of contaminated swarf or metal cladding removed from irradiated fuel before it is dissolved at the start of reprocessing. These and certain other highly active wastes are stored in concrete silos; the present silos contain water, but newer designs are dry and permit retrieval of the waste should it become necessary. The major source of the activity is small amounts of irradiated fuel which adhere to the swarf and chopped cladding. A special problem in highly irradiated fuels, e.g. from the fast reactor, are the small amounts of certain fission products (particularly rhodium and palladium) and plutonium, which remain with the cladding after dissolution of the fuel. Technically the management of this stored waste is not difficult, but ways are being examined for converting it into a form more suitable either for long term storage or for disposal. This would involve recovering the valuable plutonium and reducing the volume of the residual wastes.

Medium and Low Activity Solid Waste

At all plants and laboratories there is a miscellaneous collection of solid waste of medium and low activity such as contaminated apparatus, swabs, towels and clothing. At power stations active sludges and ion-exchange resins arise from the treatment of liquid effluent and cooling pond water.

Medium active waste is either stored in a retrievable way, or packed into drums, concreted, sealed and dumped in the deep parts of the Atlantic Ocean. The dumping is

View of low activity liquid effluent storage tanks at the Windscale fuel reprocessing plant.



conducted under the surveillance of the Nuclear Energy Agency of the OECD and is strictly controlled in respect of packaging of the material, the quantities, the dumping area, the safety precautions during transportation etc. The scale of sea dumping is well below currently approved international limits which themselves have large factors of safety built into them. Current and predicted future discharges to sea make only a minute addition to its natural levels of radioactivity.

Low active solid waste containing small but significant amounts of the transuranic elements is packaged and stored. Low level waste which does not contain significant amounts of these elements is buried in pits at the BNFL sites at Drigg in Cumbria and at Ulnes Walton in Lancashire, and at the Dounreay establishment of the UKAEA. Some of the low level wastes can be considerably reduced in bulk before disposal by burning them in special incinerators designed to prevent the release of radioactivity to the atmosphere.

Airborne Effluents

The environmental impact of radioactive airborne effluents is largely associated with fuel reprocessing plants. Here the most volatile fission product elements contained in the fuel after its decay period are likely to be released during fuel dissolution.

The main source of gaseous effluent from power stations arises in the early Magnox stations from irradiation of the air which cools the concrete shielding. Although the amount of the radioactive isotope argon-41 produced is large, its short half life, 1.8 hours, and rapid atmospheric dispersion after discharge combine to make the radiological effect insignificant. Discharges of argon from later Magnox stations are much lower because of differences in design.

The discharges to atmosphere which will be of greatest importance in the nuclear industry consist of long lived hydrogen-3 (tritium), carbon-14, krypton-85 and iodine-129. It is unlikely that krypton-85 will need to be removed from gaseous discharges before the end of the century on the grounds of hazard to the local, U.K. or world population. However, if a decision is made to reduce the levels of discharge, the necessary technology for doing so is available.

Tritium is formed in reactors in many different ways; its quantity and distribution among the various waste streams depend on the reactor type. Dilution in the sea would have a lower radiological impact than discharge to atmosphere, giving rise to only insignificant exposure for several decades. Separation of tritium from liquid effluents could be based on techniques for producing heavy water, but it would be expensive. Studies are in hand to minimise the quantity of water that would need to be processed.

Iodine-129 has a very long half-life (17 million years) but its activity per unit mass is extremely low. Radiological protection authorities do not expect it to be necessary on health grounds to make further provision for removing it from airborne effluents for many years. But, if a decision is taken to reduce the present very small discharges then methods for doing so already exist.

It is possible that in the very long term carbon-14 may make the largest contribution to the population dose from airborne effluents arising from nuclear plants. This is because of its ready incorporation into biological materials. Studies are currently being undertaken, both in this country and abroad, to evaluate its effect, and methods for reducing its release are being developed.

9 Redundant Nuclear Installations

Most of the sites licensed for nuclear power plants were chosen for features which provide a strong incentive for their continued full use. It would therefore be desirable for plant at the end of its life to be dismantled as far as is necessary and as quickly as is consistent with safety, to make way for new plant which can use existing site facilities.

Some nuclear installations, including a number of small research reactors and other plant, have already been successfully dismantled. This experience includes the recent decontamination of a large section of the fuel reprocessing plant at the UKAEA establishment at Dounreay prior to its reconstruction for handling fuel from the prototype fast reactor. Dismantling has not yet been necessary for large power reactors. Many reactor components and structures will have become radioactive as a result of their intense irradiation by neutrons and some will have become contaminated. Their dismantling will require special techniques and will create thousands of tonnes of waste material of various levels of radioactivity. In the steel structures the activity will at first be dominated by relatively short-lived isotopes of iron and cobalt. Later, however, the longer lived nickel-63 becomes most important and after 40-50 years the activity of the steel will decay with a half life of about 100 years.

For a number of years the nuclear industry has been examining the problems and costs of decommissioning redundant nuclear plant, particularly reactors. Three stages are envisaged:

Stage 1 *Permanently taking the installation out of service, without dismantling it, and putting it into a state in which it would be safe under routine surveillance. For reactors this would involve removal of all the fuel.*

Stage 2 *Reduction of the installation to minimum size without penetrating highly irradiated or contaminated parts, for example those associated with the reactor core.*

Stage 3 *Complete removal and disposal.*

Decisions on how far to proceed will depend, in part, on future policies on the disposal of radioactive waste. But whatever is decided it will be important for the layout, design and construction of nuclear plant to incorporate features which would aid their eventual decommissioning and dismantling.

10 Transport of Radioactive Materials

Our fuel manufacturing and fuel reprocessing plants serve the needs of a number of U.K. and overseas reactors and new and irradiated nuclear fuel has to be transported between the reactors and these other plants. Because of the very high levels of radioactivity the transport of spent fuel entails special precautions.

Whether carried by road, rail or sea spent fuel is contained in massive steel containers weighing tens of tonnes and designed to withstand extreme accidents without releasing any of the contents. The containers must pass stringent tests including a drop from nine metres onto concrete and exposure to fire. Although accidents have occurred involving such containers, there has never been a release of radioactivity. The conditions of packaging and transport required by law ensure that there is no significant radiation exposure of the general public. These requirements are based on standards set by the International Atomic Energy Agency. At present about 400 movements of spent fuel containers take place each year. Although this number will increase as the nuclear power programme expands, the more advanced reactors will require far fewer fuel transfers per unit of power sent out.

Construction of integrated nuclear sites with fuel fabrication and reprocessing plants situated alongside a number of power reactors, would further reduce (though not altogether eliminate) the need for transport of nuclear materials. This concept is being studied here and in other countries as are the interrelated economic, technical and environmental issues.

Top *A Magnox fuel flask being delivered to the 600 MW (e) power station at Oldbury.* **Middle** *A fissile material transport container undergoing an intense fire test.* **Bottom** *Another transportation container undergoing drop testing.*

11 Nuclear Accidents

From the outset, the development of our nuclear industry has been undertaken with full recognition of the dangers associated with radiation and with the greatest care for personal and environmental safety. Although the possibility of an accident affecting the public is very remote, detailed emergency plans have been prepared at all nuclear plants with the collaboration of local and national authorities; these plans are kept under review by Local Liaison Committees (Chapter 7) and they are regularly tested in realistic exercises. The first nuclear power stations were constructed in remote areas, but following improvements in design, construction is now permitted nearer to urban areas. But in safeguarding the health of the population, remote siting can never be an acceptable substitute for a high standard of design, construction and operation of the plant.

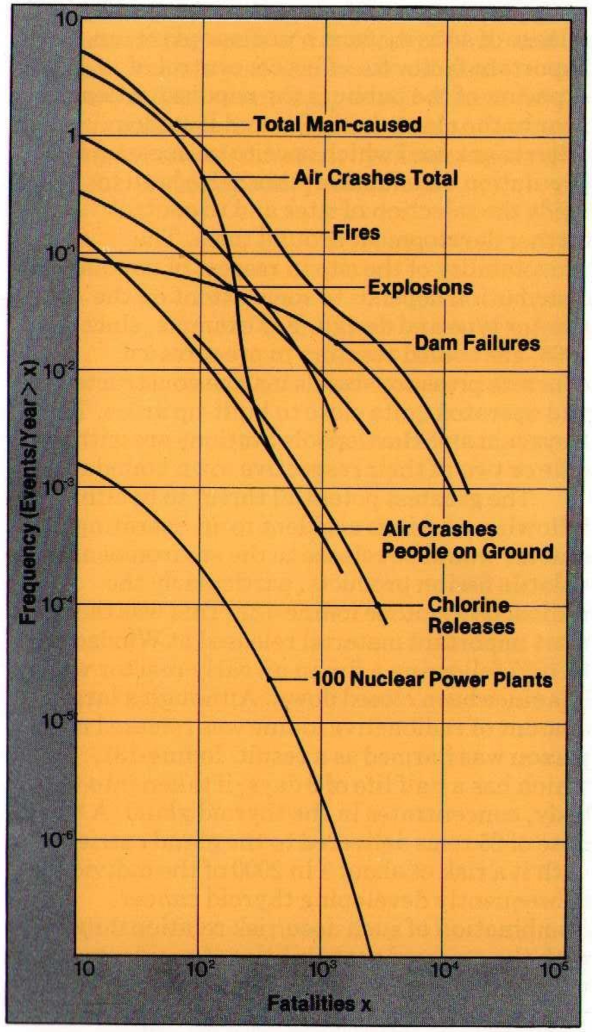
A Philosophy for Reactor Safety

Ultimately the safety of a nuclear reactor, like any other industrial plant, depends on its reliability and on the efficient operation of its built-in safety devices. But no design of any complex plant can eliminate completely the risk of an accident. In a reactor, removal of heat from the core is necessary for its safety while it is operating and after it is shut down. So comprehensive systems of instrumentation and control ensure that at all times there is an effective balance between the heat produced and the heat removed by the liquid or gaseous coolant. Independent safety circuits are designed to shut down the reactor if, for example, the temperature or the pressure or the flow of coolant deviate from safe values and to cover the possibility of human error or improbable faults. But, in spite of the diversity and multiplication of safety systems, and of quality assurance during manufacture, it is always possible in any reactor to imagine ways in which a number of unlikely events might occur in sequence. They could lead to a severe local overheating and melting of the fuel and release of fission products. The industry has therefore been at great pains to understand the behaviour of reactors under a large variety of unusual conditions. They are designed and operated in such a way as to make serious failure a very remote possibility and to ensure that the likelihood of any accident, small or large, is acceptable in relation to its anticipated consequences.

Accidents and Reactor Siting Criteria

In the unlikely event of an accidental airborne release of activity from a nuclear plant, an important factor for effective control of exposure of the public is the population density near to the plant. In the United Kingdom criteria are used which specify an acceptable population distribution; this helps both to guide the selection of sites and to control further development around them. The acceptability of the site in respect of population distribution depends to some extent on the reactor type and design. For example, since 1968, gas cooled reactors in pre-stressed concrete pressure vessels may be constructed and operated quite close to built-up areas. The Heysham and Hartlepools Stations are within a mile or two of their respective town boundaries.

The greatest potential threat to health following a serious accident to an operating reactor would be release to the environment of volatile fission products, particularly the radioactive isotope iodine-131. This was the most important material released at Windscale in 1957 following a fire in an early reactor which has since been closed down. Although a large amount of radioactive iodine was released no person was harmed as a result. Iodine-131, which has a half life of 8 days, if taken into the body, concentrates in the thyroid gland. A total dose of 25 rems delivered to the gland carries with it a risk of about 1 in 2000 of the individual subsequently developing thyroid cancer. Combination of such dose/risk relationships with the assessed probabilities of accidents of various degrees of seriousness allow estimates to be made of the likely health impact from



Frequency of man-made events involving fatalities.

(Data from the Rasmussen study amended to include delayed deaths from nuclear accidents).

accidents associated with an expanding nuclear power programme.

During the past decade the UKAEA's Safety and Reliability Directorate (which now works not only for the Authority but also directly for the Health and Safety Executive in appropriate areas) has pioneered techniques of systems reliability and monitoring which are respected worldwide. It has made detailed studies of the likelihood of reactor accidents, using the extensive experience on component reliability which exists in the nuclear and other industries. Similar studies have been made in the USA, the best known being that of Professor Rasmussen of the Massachusetts Institute of Technology. In the UKAEA studies, realistic criteria have been developed which our reactor engineering capability should be able to achieve. These design criteria, when combined with the known relationship between radiation dose and the risk of cancer, lead to the conclusion that when we have 100 power reactors close to towns there might, once in 1000 years, be an accident which would result in a few delayed deaths from cancer and, once in 10,000 years, an accident leading to some tens of deaths. More serious accidents would be even less likely. As in all industries, smaller accidents will happen more frequently but their consequences will be in terms of loss of generating capacity and financial penalty rather than harm to people.

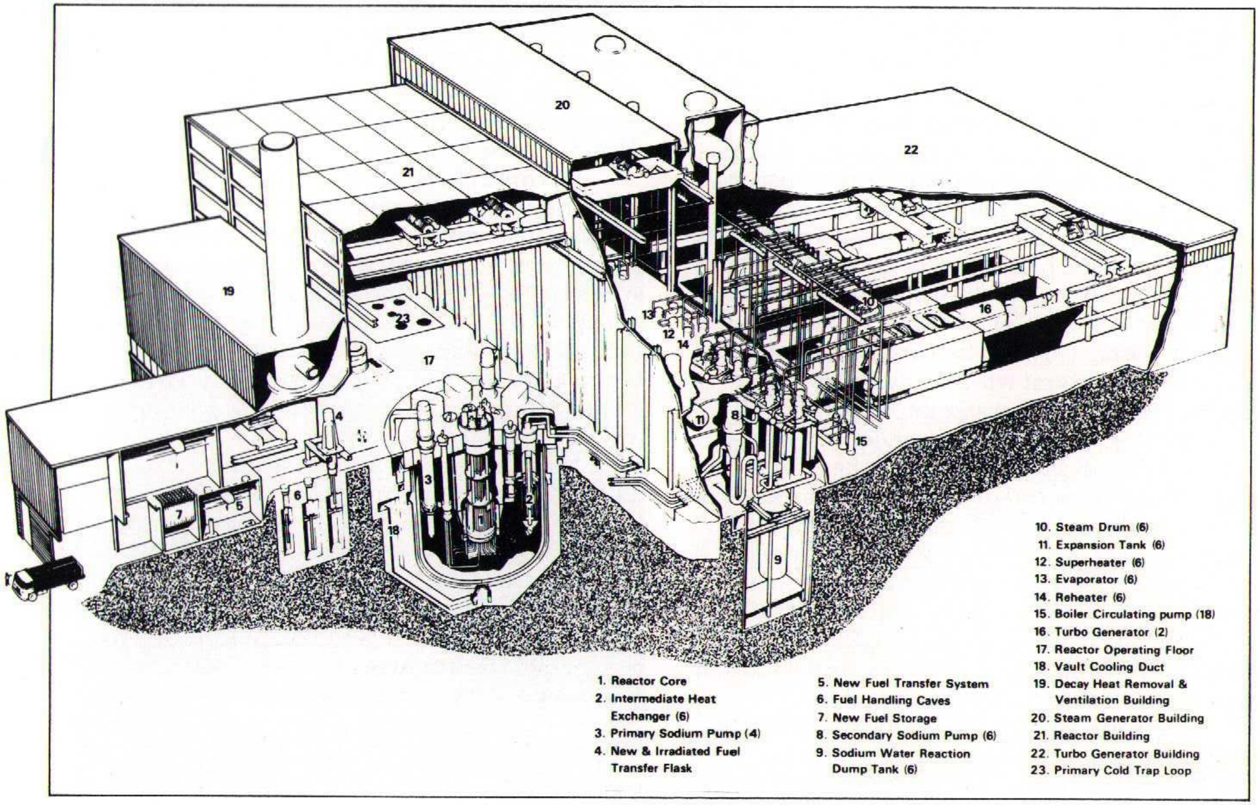
To put these figures into context, it should be remembered that about 60 coal miners in the U.K. die each year as a result of immediately fatal pit accidents. In addition many more delayed deaths and incapacitating diseases arise from their occupation. Figures taken from the Rasmussen study suggest that, in the USA, air crashes causing 100 or more deaths may be expected on average every three years; fires causing 100 or more deaths every eight years; failure of large dams causing 100 or more deaths every 20 years and releases of chlorine gas causing 100 or more deaths every 80 years. A further example of a risk imposed by society is that of our being killed by an aircraft crashing on us. Statistics indicate that in the U.K. there is likely to be such an accident killing a few people every ten years; every 10,000 years we could expect an accident of this nature to kill several hundred people. Society has the choice to reduce many of these risks to zero, for example by not building dams or by forbidding overflying by aircraft, but our experience of the benefits persuades us to accept the risks. We can do little about risks imposed by nature but merely to introduce some perspective, it is worth noting that in the U.K. about once in a million years a single falling meteorite could be expected to kill several hundred people.

12 The Fast Reactor

Fast reactors can be designed to produce more fissile material from the non-fissile uranium-238 than is used to sustain the fission chain reaction, so greatly increasing the total utilisation of the energy content of uranium. The fast reactor is therefore an important option for future conservation of our fuel resources. For over 20 years the development of fast reactors in the U.K. has followed a systematic step-by-step approach. Our experience of the 250 MW(e) prototype at Dounreay in Scotland could now be used in the building of a full scale demonstration power station of about 1300 MW(e) capacity.

The word 'fast' as applied to nuclear reactors needs some explanation. In thermal reactors a moderating material (e.g. graphite or heavy water) is used to slow down the neutrons to the energy levels required for the optimum production of new fissions. Fast reactors have no moderator and, as their name implies, utilise neutrons travelling at higher speeds. Although the fast reactor can operate by burning uranium alone, it works better with plutonium and in prototype and experimental fast reactors now operating in Britain, France, the USSR and the USA, the fuel in the core is a mixture of about

Cutaway of a typical 1300 MW(e) Commercial Fast Reactor.



1. Reactor Core
2. Intermediate Heat Exchanger (6)
3. Primary Sodium Pump (4)
4. New & Irradiated Fuel Transfer Flask
5. New Fuel Transfer System
6. Fuel Handling Caves
7. New Fuel Storage
8. Secondary Sodium Pump (6)
9. Sodium Water Reaction Dump Tank (6)
10. Steam Drum (6)
11. Expansion Tank (6)
12. Superheater (6)
13. Evaporator (6)
14. Reheater (6)
15. Boiler Circulating pump (18)
16. Turbo Generator (2)
17. Reactor Operating Floor
18. Vault Cooling Duct
19. Decay Heat Removal & Ventilation Building
20. Steam Generator Building
21. Reactor Building
22. Turbo Generator Building
23. Primary Cold Trap Loop

80% uranium and 20% plutonium. This design is followed for the larger commercial reactors now under development. Initially the plutonium will come from irradiation of uranium in thermal reactors. Around the fast reactor core is a 'blanket' of uranium depleted in the 235 isotope. In this blanket, and in the core, neutrons are captured by uranium-238 thereby yielding more plutonium which after extraction will help to fuel further reactors.

The fast reactor is often referred to as a 'massive producer of dangerous plutonium'. In fact, although it can produce more fissile material than it consumes, the net amount of plutonium produced per unit of power output would be less than in the present thermal reactors. Indeed, it will finally be operated to produce as much plutonium as we need for fuel and no more. It does contain a large amount of plutonium (4 tonnes in a commercial reactor), but this is only between two and three times as much as the amount which accumulates in a thermal reactor of corresponding power.

Because of the high power density in the relatively small fast reactor core there must be very efficient removal of heat both in normal and abnormal situations. The material used to transfer heat from the core of present fast reactors to the steam raising circuits is liquid sodium, and in a commercial reactor there would be about 4000 tonnes in the coolant circuits. Technology for handling liquid sodium on a large scale is highly developed.

There are features which make liquid-sodium cooled fast reactors different from thermal reactors on safety grounds – some make them more attractive, some less attractive. The use of sodium as a coolant is generally favourable to safe operation. The low operating pressure ensures that the sodium would not be lost rapidly through leaks or breaks of the coolant circuit – there is no likelihood of rapid depressurisation such as could conceivably occur in some current thermal reactor systems. Furthermore, the excellent heat-transfer properties of sodium and its high heat storage capacity allow the fast reactor, when it has been shut down, to remain independent of any further power requirements for heat removal for several hours.

The high chemical reactivity of the liquid sodium coolant is a major factor in selecting compatible construction materials but the well known need to prevent contact between sodium and cooling water affects the non-radioactive circuits only. Water to sodium leaks in the heat exchangers that have occurred during the commissioning of the Dounreay Prototype Fast Reactor have been rectified without risk to people or plant.

A blockage of the flow of sodium in the channels of the core could cause overheating and extensive melting if the reactor were not immediately shut down. If such an event were also to cause a compaction of the reactor core then the power output could rise so rapidly as to damage the reactor. It is highly improbable but conceivable that the reactor vessel could be penetrated and substantial quantities of radioactive material could be released (although a high proportion of fission products, particularly radio-iodine, combine chemically with the sodium and are so prevented from leaving the reactor containment). Design features are incorporated to make the likelihood of blockage very small, with instrumentation to detect any change in flow and shut down the reactor if a blockage did occur. Finally, a secondary containment is provided which is capable of containing the maximum predicted energy release.

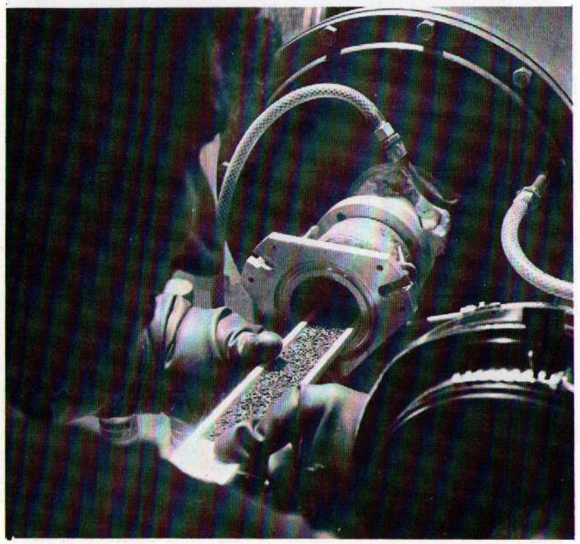
Experience in the operation of sodium-cooled fast reactors, since 1959 in the U.K., has shown these reactors to be stable and easy to control in normal use. Future fast reactors built in this country, like any other nuclear power stations, would have to satisfy the stringent safety standards laid down by the Nuclear Installations Inspectorate before a licence could be granted.

13 Plutonium

As we have already seen, plutonium is a very valuable nuclear fuel. But it is also a difficult material. It is both highly radio-toxic and a material used in the manufacture of nuclear weapons. The dangers of its continued production and use has been high on the list of arguments against the further development of nuclear power. Its safe use has always been a major concern of the nuclear industry.

Plutonium-239, the most important isotope of plutonium, has a half life of 24,000 years and emits predominantly alpha radiation which can penetrate only up to 0.04 mm in biological tissue. Outside the body, therefore, plutonium is not a serious risk, but once taken into the body and deposited in sufficient amount in bone or soft tissue it can be very dangerous. This has been recognised in the ICRP recommendations since 1951; the maximum permissible annual intake by inhalation (in practice the most dangerous route) is now calculated as less than one millionth of a gramme. Although this is a very small amount in terms of weight, the ease of detection of plutonium using radiation measuring instruments makes it possible to control intake far below the levels of concern. Sensitive techniques have been developed which enable us to measure plutonium present in the lung at well below the maximum permissible level. Not all forms of plutonium and not all modes of intake are equally dangerous. The current maximum permissible intake by ingestion, for example, is many thousands of times greater than for inhalation. To what extent plutonium, apart from its radioactivity, is also hazardous as a heavy metal poison is irrelevant; its radiotoxicity is far more

Uranium-plutonium granular fuel being unloaded in a glove box from a high temperature sintering furnace.



Critical organs for plutonium and total 'nominal' cancer risk from ICRP current values of the maximum permissible annual intake (MPAI).

Medical Research Council, 1975.

Material Form	Critical Organ	MPAI (μCi)	Cancer Risk (per 10,000)
Ingestion			
Soluble	**Bone**	**40** **(0.6mg)**	**3**
Insoluble	**Gut**	**220** **(3 mg)**	**4**
Inhalation			
Soluble	**Bone**	**0.005** **(0.08μg)**	**2**
Insoluble	**Lung**	**0.08** **(1μg)**	**15**

important than any possible chemical toxicity.

Following considerable discussion in the USA about the validity of internationally recommended safety standards for plutonium, the British Medical Research Council has made a comprehensive review of its potential hazards to man; its report was published in 1975. From a study of all the available information the report concludes that 'the existing derived safety standards . . . fulfil the intention of the ICRP although adjustment by small factors may be needed'. Present values of the maximum permissible annual intake for radiation workers are considered to be 'of about the right order consistent with good practice except that the value for inhaled insoluble plutonium-239 in relation to other values seems on the high side by a factor of five'. In considering the total risk to the general public from plutonium-239 the risk of genetic damage is assessed as 'only a minor part of the total (risk)'. The ICRP continues to keep its recommended levels under careful review.

From experiments with animals there is no doubt that plutonium is carcinogenic. But these experiments have involved relatively large doses. Hundreds of people have been exposed to plutonium in the course of their work both in this country and abroad; some, mainly overseas and during the 1940's, were exposed at levels considerably higher than present limits. In spite of this no cancers have been reported that are clearly attributable to plutonium.

As a result of weapons tests in the atmosphere some 5 tonnes of plutonium have been well distributed over the earth. If this amount had been shared equally among the world's 4000 million inhabitants each person would now contain about one milligram. In fact, the amount of plutonium in people today, although measurable, is tens of millions of times lower. This is due partly to the unwillingness of the human body to absorb ingested plutonium and partly to the impossibility of distributing it so that it is all available to people. This, of course, shows the falseness of some of the more extreme calculations which have been made to illustrate the dangers of wider use of plutonium. The often repeated conclusion that a piece of plutonium the size of an orange (or grapefruit or cricket ball) could kill millions of people, while factually correct, omits to add 'if the impossible could be accomplished of dividing it into that many million equal parts and fixing each part in a separate pair of human lungs'.

Fast Reactor fuel pellets.

But having said that, it is undeniable that plutonium is one of our most toxic industrial materials, although certainly not, as sometimes claimed, the most toxic material known to man. That distinction belongs to some natural products such as anthrax spores, botulism toxin or venom of some species of reptiles; weight for weight these can cause death more quickly and more certainly than plutonium. Experience over many years confirms that plutonium can be handled safely in large quantities and that present technology can do much to reduce the consequences of accidents. Nevertheless, research aimed at even better understanding of the behaviour of plutonium in man and in the environment continues and will undoubtedly lead to further improvements.

14 Security and Safeguards

In today's increasingly violent society there is understandable concern that nuclear materials should not get into the wrong hands, so as to pose a threat to sections of the public or even nations. The need to prevent this is well recognised and both the Government and the nuclear industry have consistently given the greatest attention to security in the light of the circumstances of the time. However, it is not true that an increase in nuclear power production, and in particular the use of fast reactors, will necessarily require a major increase in national security. There is no reason to expect the impact on society to be significantly different or greater than exists today.

Given the continuing existence of national and international terrorism, nuclear materials and plants must be considered among the potential targets. However, the terrorist would have to make a judgment as to whether the attractiveness of materials used in the nuclear industry (in particular plutonium) outweighs the difficulties and risks of acquiring them. There are, indeed, easier and more attractive targets, with potentially terrifying implications. If plutonium is unique, it is rather in respect of the care with which it is protected.

The problems facing would-be hijackers are immense, purely on account of the size and weight of the transport containers. They would need specialised equipment and handling facilities unless their efforts were to be rewarded by rapidly lethal doses from many of the materials being transported. Theft of a succession of relatively small amounts of material from a nuclear establishment is countered by a range of security measures.

The special property of plutonium which could be of interest to terrorists is that it is the material of nuclear weapons. But many of the statements made about the terrorists' use of plutonium have seriously underestimated the difficulties they would face, especially in the fabrication of an improvised nuclear device. To construct an efficient weapon, pure plutonium-239 is needed; the material which comes from reactors and fuel reprocessing plants contains relatively high amounts of other plutonium isotopes. With this material, even given enough time, expertise and facilities, only a crude device of relatively low explosive power could be made. Stocking and transporting plutonium as a mixture with uranium, in the form it is required in fast reactor fuel, further reduces its attractiveness to the potential terrorist because in this form it is useless for nuclear weapons; very elaborate chemical plant is needed to separate the two elements. A threat of dispersion of plutonium as a toxic rather than an explosive weapon could undoubtedly also be a severe one but other toxic materials, far less well protected, could pose an equal or greater threat.

Because of the possible dangers if fissile materials got into the wrong hands, stringent security measures are taken at every point in their processing, storage and transportation. The public has no wish to see security endangered by detailed discussion of these measures, but they are no less stringent than the standards for physical protection published by the International Atomic Energy Agency.

International safeguards are undertaken by the IAEA and under agreements with individual countries the IAEA carries out inspections to verify the reports it receives of the amounts and location of nuclear materials in the country concerned. Inspections, similar to but more extensive than those of the IAEA, are also made in the U.K. by Euratom in accordance with the Treaty of Rome. The amount of IAEA inspection will increase greatly with the implementation of the U.K. offer under the Treaty on the Non-Proliferation of Nuclear Weapons to place under IAEA safeguards all its civil nuclear activities subject only to exclusion for national security reasons.

15 Conclusions

It is now more than 20 years since the first electricity from nuclear energy was fed into the National Grid. From that time until now, late 1976, when some 12% of our electricity comes from nuclear reactors, the technical development of nuclear power in the U.K. has proceeded in a careful and logical manner. Its course has been and will continue to be determined by progress in technology, including that of safety assurance, and assessed energy demand.

As with every industrial undertaking, including all methods of producing energy, nuclear power brings with it some risk. Zero risk is never attainable and it makes no sense to demand it. The safety record of the nuclear industry in this country, both as regards its employees and the public, has been exemplary – the facts speak for themselves. The techniques of reliability assessment and risk prediction are more highly developed than in any other industry. These techniques and responsible examination of other safety and security issues lead to the conclusion that a growing programme of nuclear power can be achieved with minimal risk to man and his environment, both in the short and long term future.

When the misconceptions, exaggerations and areas of emotion and irrationality have been identified and put to one side, the nuclear debate resolves itself into a question of perspective and judgment. Can the small risks which remain be accepted, bearing in mind both the undoubted benefits of clean production of power from assured fuel resources and the growing demands for energy which other power sources (new or old) will be unable to satisfy in the foreseeable future?

It is hoped that by presenting information and introducing some necessary perspective this booklet will have helped the reader towards his answer to this question.

The Prototype Fast Reactor, Dounreay, at night.

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