National Radiological Protection Board

Living with radiation

National Radiological Protection Board

The National Radiological Protection Board was created by the Radiological Protection Act, 1970, which came into effect on 1 October of that year and applies to the whole of the United Kingdom.

The Government's purpose in proposing the legislation was to establish a national point of authoritative reference in radiological protection. The Statute gave the Board the following functions:

> by means of research and otherwise, to advance the acquisition of knowledge about the protection of mankind from radiation hazards and
>
> to provide information and advice to persons (including Government Departments) with responsibilities in the United Kingdom in relation to the protection from radiation hazards either of the community as a whole or particular sections of it.

The Act also empowered the Board to provide technical services to persons concerned with radiation hazards and to charge for these services. It also organises training courses.

Requests for further information about the work of the Board should be addressed to the Information Officer, National Radiological Protection Board, Chilton, Nr Didcot, Oxon OX11 0RQ. Telephone Abingdon (0235) 831600.

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Foreword

The National Radiological Protection Board was established by the Radiological Protection Act of 1970 to advance knowledge and to provide information and advice about radiological protection. Apart from responding to numerous specific enquiries, the Board has fulfilled its responsibilities for the provision of information and advice in many ways. These have included the arrangement of courses at many different levels, participation in symposia, and the provision of seminars tailored to the needs and interests of particular groups including politicians, public officials, scientists, and journalists. Publications have also played an important part.

The staff of the Board are encouraged to publish the results of their work in the open literature. Wherever possible, papers are offered for publication in scientific and technical journals and in the proceedings of conferences. In addition, the Board has its own series of reports, and short topical articles appear in the Radiological Protection Bulletin, a bi-monthly Board publication.

In 1973, the Board published a booklet 'Living with Radiation', which was intended for a wide readership. The booklet is now out of date in a number of respects, but the Board was sufficiently encouraged by its reception to undertake the production of this revised version. As before, the objectives are to indicate the nature of ionising radiation, its sources and effects, and the means of protecting persons against it. It is also hoped that readers might be stimulated to study the issues in radiological protection in depth.

Fred Dainton

Andrew McLean

1 Introduction

Exposures and effects

Radiation is a fact of life. It occurs in nature and can be produced artificially. Radiation of natural origin pervades the environment, and radiation of artificial origin has been used for several decades. Natural and artificial radiations are not different in kind or effect. The term *radiation** refers here to *ionising radiation*, of which there are several types.

The use of radiation contributes to human well-being. It is important in the development of medicine, other sciences, and industry. Radiation, however, is inherently harmful to humans, and persons must be protected from unnecessary or excessive exposure to it.

On the average, radiation of natural origin causes the highest exposure of humans. Much of this is unavoidable, although some control could be effected. Exposure to radiation of artificial origin is more readily controlled. The stringency of control is a matter for judgment by society.

The radiation effects of greatest concern are malignant diseases in exposed persons and inherited defects in their descendants. The *risk* of such effects is related to the *dose* of radiation that persons receive. *Risk factors* can be estimated: these measure the *probability* of human costs, which should be balanced against the benefits of practices that cause exposure.

System of protection

Where the balance lies is a matter for representative institutions, since society must bear the costs. Radiological organisations may make recommendations, but it is for governments to decide on the acceptability of a practice and the degree of protection to be enforced.

Most countries apply the same system of *radiological protection*, which requires doses to be minimised in a rational way and certain limits to be observed. This has had the result, in the United Kingdom, that radiation work is a relatively safe occupation, and that the health of the public is not appreciably affected by adventitious exposure.

The system of radiological protection has developed over decades and continues to evolve, but it does now enable persons to live in relative safety with radiation. The question may be asked, therefore, why radiation causes so much public anxiety.

Public anxiety

Answers can only be expressions of opinion. It might be due to fear of its effects, to the growth in its use, and to its association with *nuclear weapons*. It might also be due to a keener sensibility to the costs than to the benefits of a radiation practice. It may, however, be due to lack of information or its misinterpretation.

Sources and effects of ionising radiation are therefore described in this booklet, and the principles and practice of radiological protection are explained. Some issues regarding *nuclear power* are also examined, but weapons are not considered except in the matter of *fallout*.

The information here may help persons to judge the significance of exposure to radiation for themselves and for the community. It may also foster a careful rather than fearful approach to living with radiation.

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*When first used, terms in the GLOSSARY are italicised.

2 Concepts and quantities

Makeup of matter

All matter is composed of *elements* such as hydrogen, lithium, carbon, oxygen, iron, and lead. Elements consist of characteristic *atoms*, which contain a relatively small *nucleus* and a number of *electrons*. The nucleus may be said to contain *protons*, which carry positive electric charges, and *neutrons*, which carry no charge. The electrons are negatively charged, and may be imagined encircling the nucleus, most frequently within shells with indefinite boundaries. Atoms are relatively empty structures, and symbolic diagrams, such as that of lithium, cannot fully convey this (Figure 1).

An atom contains equal numbers of protons and electrons and is electrically neutral. It is the number of protons, called the *atomic number*, that characterises an element: the atomic number of lithium, for instance, is 3, and of oxygen 8. Atoms of the same or different elements combine to form uncharged entities called *molecules*: thus 2 atoms of oxygen form a molecule of oxygen, and 2 atoms of hydrogen combine with 1 atom of oxygen to form a molecule of water.

The mass of an atom is concentrated in the nucleus, and the number of protons plus neutrons in it is called the *mass number*. Most species of atom can be characterised by the atomic number and mass number, or simply by the name of the element and the mass number: thus characterised, they are called *nuclides*. Lithium-7, as the diagram shows, is a nuclide with 3 protons, the unique atomic number of the element lithium, plus 4 neutrons. Carbon-12 is a nuclide with 6 protons plus 6 neutrons. Lead-208, another example, is a nuclide with 82 protons plus 126 neutrons.

Protons + neutrons : **Nucleus**
Nucleus + electrons : **Atom**
Combined atoms : **Molecule**
Species of atom : **Nuclide**
Equal nos. protons : **Isotope**

Nuclides of an element that have different numbers of neutrons are called *isotopes* of that element. Hydrogen, for instance, has three isotopes: hydrogen-1, hydrogen-2 called deuterium, hydrogen-3 called tritium. Iron has ten isotopes from iron-52 to iron-61. Isotope is sometimes used incorrectly as a synonym for nuclide.

Radioactivity and radiation

Some nuclides are stable, but many are not. The stability of a nucleus is determined by the numbers of neutrons and protons, their configuration, and the forces they exert on each other. An unstable nuclide transforms spontaneously into the nuclide of another element, and in doing so, emits radiation. This property is called *radioactivity*, the transformation is termed *decay*, and the nuclide is said to be a *radionuclide*. Carbon-14, for example, is a radionuclide, which decays to nitrogen-14, a stable nuclide. Barium-140 is a radionuclide, which decays to the radionuclide lanthanum-140, which decays in turn to the stable nuclide cerium-140. Lead-210 is a radionuclide, which decays through the series shown in the diagram, the last *decay product* being a stable isotope of lead. Of the 1700 or so known nuclides, about 280 are stable (Figure 2).

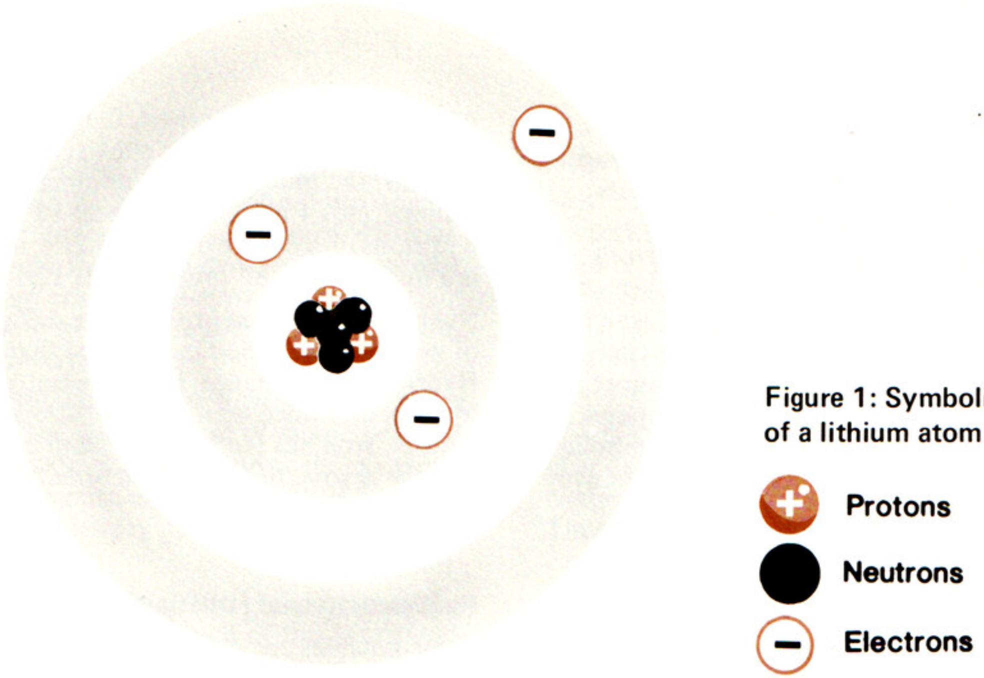

Figure 1: Symbolic diagram of a lithium atom

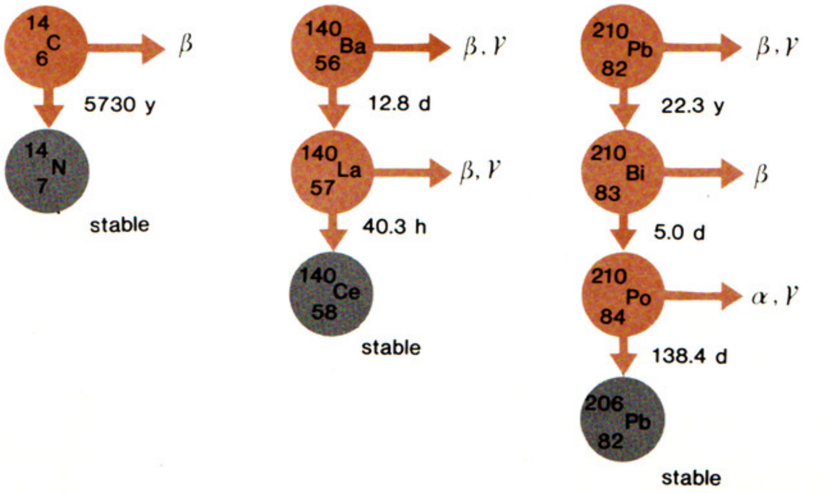

Figure 2: The decay of some radionuclides with radiations and half-lives

Radionuclides : Unstable nuclides
Radioactivity : Emitting of radiation
Radiations : α, β, γ, n, X-ray
Activity : Quantity of radionuclide
Half-life : Time to half activity

The radiations most commonly emitted by radionuclides are *alpha particles, beta particles* and *gamma rays*. An alpha particle may be said to consist of two protons and two neutrons bound together; it is therefore heavy and doubly charged. A beta particle has mass and charge equal in magnitude to an electron. A gamma ray is a discrete quantity of energy, without mass or charge, that is propagated as a wave.

It is customary to express the energy with which such radiations are produced in units of *electron volt*, symbol eV: this is equivalent to the energy gained by an electron in passing through a potential difference of 1 volt. Multiples of this unit are frequently employed, especially a million or 10^6 electron volts, symbol MeV*. The energy of alpha particles emitted by polonium-210, for instance, is about 5.3 MeV. Beta particles emitted by barium-140 and lanthanum-140 have maximum energies ranging from about 0.5 to 3.8 MeV, and gamma-ray energies from about 0.01 to 3.3 MeV.

Several *radioactive* elements exist in nature, the best known being uranium and thorium. Several other elements have naturally-occurring radioactive isotopes, the most notable being carbon-14 and potassium-40. Over the last few decades, several hundred radioactive isotopes of natural elements have been produced by artificial means, including such well-known ones as strontium-90, caesium-137, and iodine-131. Several radioactive elements have also been produced, for instance promethium and plutonium, but the latter does occur in trace quantities in uranium ores.

The quantity of a radionuclide is described by its *activity*, the rate at which spontaneous decays occur in it. Activity is expressed in a unit called the becquerel, symbol Bq, after a French scientist. A Bq corresponds to the decay of one radionuclide per second. Multiples of the becquerel are frequently used such as the megabecquerel, MBq. One gram of plutonium-239, for instance, has an activity of approximately 2000 MBq: it emits about 2000 million alpha particles each second.

Activity was formerly expressed in a unit called the curie.*

The time taken for the activity of a radionuclide to lose half its value by decay is called the *half-life*, symbol $t_{\frac{1}{2}}$. Each radionuclide has a unique and unalterable half-life: for carbon-14 it is 5730 years; for barium-140, 12.8 days; for lanthanum-140, 40.3 hours; for plutonium-239, 24,131 years; for uranium-238, 4.47×10^9 years. Values for various radionuclides range from fractions of a second to millions of years. In successive half-lives, the activity of a radionuclide is reduced by decay to $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, $\frac{1}{16}$, and so on of the initial value, so that it is possible to predict the activity remaining at any future time. A stable nuclide might be regarded as a radionuclide with an infinite half-life.

There are many other ionising radiations, but two require special mention, *X-rays* and neutrons. X-rays are usually produced by bombarding a metal target with electrons in an evacuated tube. They have similar properties to gamma rays, but generally have lower energy: an ordinary X-ray machine in a hospital

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*For scientific notation, prefixes, and symbols, see APPENDIX I.

* The relationship between some old and new radiation units is shown in APPENDIX II.

emits X-rays with energies up to 0.15 MeV. Neutrons can be liberated from various nuclides in a number of ways. If, for instance, beryllium-9 is bombarded with 5.3 MeV alpha particles from polonium-210, the nuclide carbon-12 is formed, and neutrons with an average energy of 4.2 MeV are emitted. The most powerful source of neutrons, however, is a *nuclear reactor*, which is described in Chapter 7.

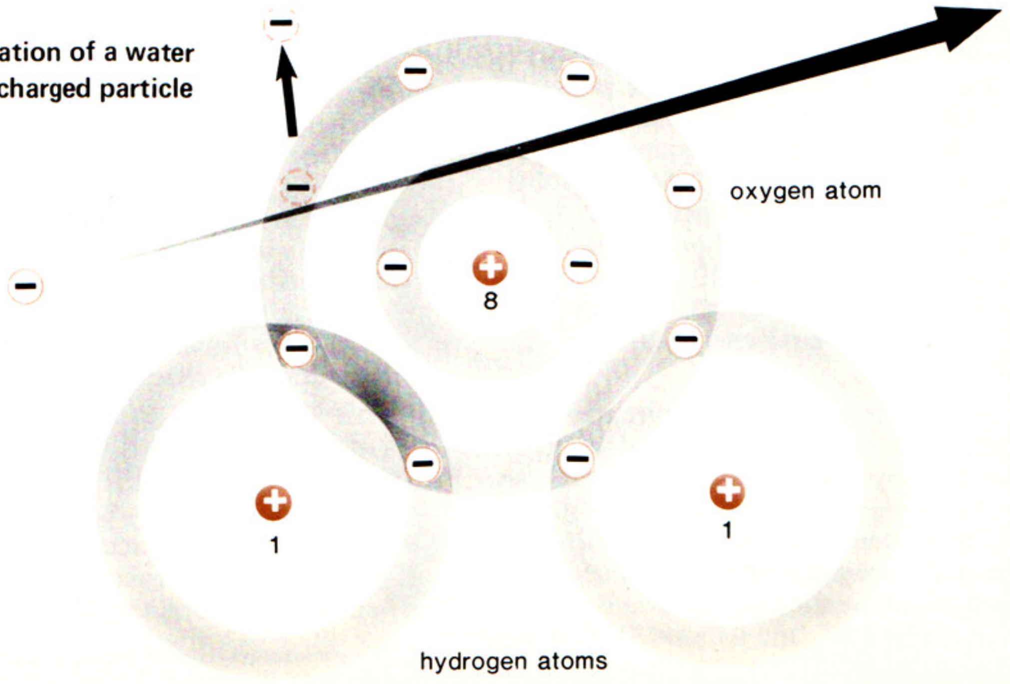
Velocity of radiations

Gamma rays and X-rays are similar in nature to visible light and so always move at the speed of light, 3×10^8 metres per second. The initial velocity of a particle, however, depends on its energy and mass, but it cannot travel faster than light.

Initial velocities of radiations

Radiation	*Energy, MeV*	*Velocity, m s^{-1}*
alpha	1	7.0×10^6
	4	1.4×10^7
neutron proton	1	1.4×10^7
beta	0.1	1.6×10^8
	1	2.8×10^8
X-ray γ ray	any	3×10^8

Figure 3: Ionisation of a water molecule by a charged particle



Of particular interest in relation to the operation of some nuclear reactors are *thermal neutrons*. These are neutrons that have been slowed to the degree that they have the same average thermal energy as the atoms or molecules through which they are passing. The average energy of neutrons at ordinary temperatures is about 0.025 eV, corresponding to an average velocity of 2200 metres per second (2.2×10^3 m s^{-1}).

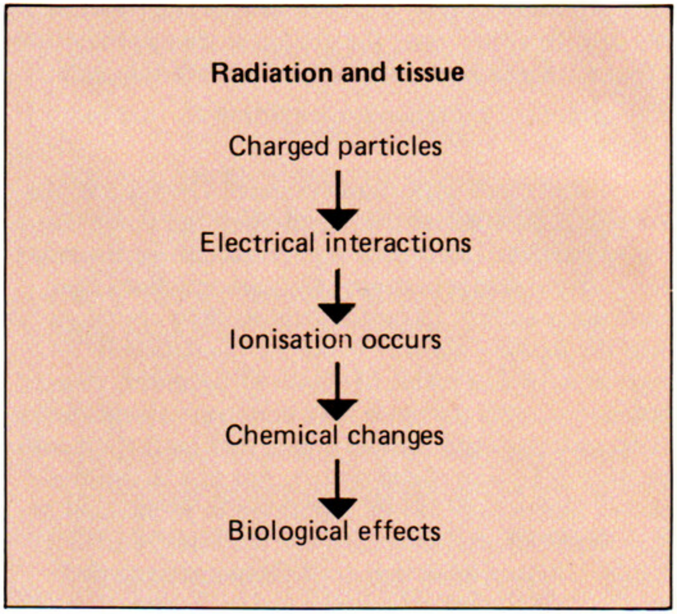
Radiation and tissue

When radiation enters tissue, it loses energy. Alpha and beta particles, being charged, lose energy in *electrical interactions* with the atomic electrons near which they pass. Gamma rays and X-rays transfer energy in a variety of ways, but each involves the liberation of electrons, which then lose energy in electrical interactions. Neutrons also transfer energy in various ways, the most important being collisions with hydrogen nuclei, which are single protons; these protons are set in motion, and being charged, again lose energy in electrical interactions.

In such electrical interactions, an electron may be ejected from an atom in a molecule, thus leaving the molecule positively charged. This is shown in symbolic fashion for a molecule of water, which has 10 protons: only 9 atomic electrons remain after the passage of a charged particle, and the molecule as a whole has one excess positive charge (Figure 3).

The process by which a neutral atom or molecule becomes charged is called *ionisation* and the resulting entity an *ion*. An ejected electron may, in turn, ionise other atoms or molecules.

The passage of a charged particle through atoms may also impart energy to the atomic electrons without actually ejecting them. This process is called *excitation*, which is dissipated as heat in tissue.



Charged water molecules change to entities called *free radicals*, which are highly reactive in a chemical sense, and could, for instance, alter important molecules in tissue. The grouping of an oxygen and a hydrogen atom, OH, is such an entity.

The basic unit of tissue is the cell. Each cell has a nucleus, which may be regarded as its control centre. The *nucleus of a cell* differs from the nucleus of an atom. Water constitutes about 80% of the cell, the other 20% being complex compounds.

Of particular importance is the compound deoxyribonucleic acid, *DNA*, found mainly in the nucleus. DNA controls the structure and function of the cell and passes on copies of itself. Although the ways in which radiation damages cells are not fully understood, many involve changes to DNA. There are two modes of action. A DNA molecule may become ionised, resulting directly in chemical change, or it may be changed indirectly by a free radical in the water of the cell. In either case, the chemical change may find expression as a harmful biological effect.

The effects of radiation are explored further in Chapter 5.

One of the most important properties of the various ionising radiations is how deeply they can enter tissue. Alpha particles can scarcely penetrate the dead outer layer of the skin; consequently, radionuclides that emit them are not hazardous unless they are taken into the body. This may occur by inhalation or ingestion, or as a result of a wound becoming contaminated. Beta particles may penetrate a centimetre or so of tissue, and radionuclides that emit them are hazardous to superficial tissues, but not to internal organs unless they are incorporated in them. Gamma rays, however, can pass through the body, and as a result, radionuclides that emit them are hazardous whether on the outside or the inside. X-rays and neutrons can also pass through the body.

Dose quantities

Ionising radiations cannot be directly detected by the human senses, but they can be detected and measured by a variety of means including *photographic films, geiger tubes,* and *scintillation counters.* Measurements made with such detectors can be interpreted in terms of the radiation dose absorbed by the body or by a particular part of the body. When measurements are not possible, as, for instance, when a radionuclide is deposited in an internal organ, it is possible to calculate the dose absorbed by that organ if the activity in it is known.

Absorbed dose is expressed in a unit called the gray, symbol Gy, after a British scientist. It is a measure of the energy imparted by ionising radiation to a unit mass of matter such as tissue. A Gy corresponds to a joule per kilogram. Sub-multiples of the gray are frequently used such as the microgray, μGy.

Absorbed dose was formerly expressed in a unit called the rad. See Appendix II.

Equal absorbed doses do not necessarily have equal biological effects: one Gy of alpha radiation to tissue, for instance, is more harmful than one Gy of beta radiation, because an alpha particle, being slower and more heavily charged, loses its energy much more densely along its path in tissue. To put all ionising radiations on an equal basis with regard to potential for causing harm, another quantity is needed. This is the *dose equivalent*. It is expressed in a unit named the sievert after a Swedish scientist, and its symbol is Sv. Dose equivalent is equal to the absorbed dose multiplied by a factor that takes account of the way a particular radiation distributes energy in tissue, thus influencing its effectiveness in causing harm. For gamma rays, X-rays, and beta particles, the factor is set at 1, and the gray and sievert are numerically equal. For alpha particles, the factor is 20, so that 1 Gy of alpha radiation corresponds to a dose equivalent of 20 Sv. Sub-multiples of the Sv are commonly used such as the millisievert, mSv.

Dose equivalent was formerly expressed in a unit called the rem. See Appendix II.

The dose equivalent thus provides an index of the risk of harm from exposure of a particular tissue to various radiations: one Sv of alpha radiation to the lung, for example, is deemed to create the same risk of inducing fatal lung cancer as one Sv of beta radiation. However, the risk of fatal malignancy per Sv is not the same for the various tissues of the body: it is lower for the thyroid than for lung, for instance. There is another important type of harm: the risk of serious hereditary damage, through irradiating the testes and ovaries, is different in kind and magnitude, and must also be taken into account. If the risk per Sv for the various tissues of the body are added, a value is obtained for the overall risk per Sv of irradiating the whole body and for the fractional contribution that each tissue makes to it. The fractional risk contributed by the lung, for example, is 0.12 and by the thyroid 0.03.

The concept of fractional risk enables one to construct a common index of risk for non-uniform irradiation of the body, a circumstance which frequently occurs when radionuclides are taken into the body. If a single tissue receives a certain dose equivalent, this can, in effect, be converted to a dose equivalent to the whole body by applying the appropriate fractional risk as a weighting factor to it. If several tissues receive various dose equivalents, and if the appropriate weighting factors are applied to each, the sum of the products is the dose equivalent to the whole body that would yield the same overall risk. The sum of the weighted dose equivalents is called the *effective dose equivalent*. It is also expressed in sieverts.

Risk weighting factors

Tissue or organ	*Factor*
Testes and ovaries	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder	0.30
Whole body total	1.00

In the table of risk weighting factors here, the remainder entry refers to the five tissues or organs, other than those listed, that receive the highest dose equivalent in a given circumstance. They include such organs as the stomach and the liver, to each of which is assigned a weighting factor of 0.06.

Calculation of effective dose equivalent

Consider a circumstance in which a radionuclide causes irradiation of the lung, the liver, and the surfaces of the bones. Suppose that the dose equivalents to each tissue are respectively 100, 70, and 300 mSv. The effective dose equivalent is calculated thus:

$100 \times 0.12 + 70 \times 0.05 + 300 \times 0.03 =$
24.5 mSv.

The calculation indicates that the risk of fatal cancer associated with this pattern of irradiation corresponds to the risk of fatal malignancy and serious hereditary harm from a dose equivalent of 24.5 mSv received uniformly throughout the whole body.

It is seen in the next chapter that the effective dose equivalent from radiation of natural origin is, on the average, 1860 μSv in a year to inhabitants of the United Kingdom. Since the population of the United Kingdom is about 56 million, the effective dose equivalent to the whole community is the product of these two numbers, about 100,000 *man-sieverts*, symbol man-Sv. The quantity obtained by multiplying the average effective dose equivalent by the numbers of persons exposed to a given source of radiation is called the *collective effective dose equivalent*. It is

Hierarchy of dose quantities

Absorbed dose
energy imparted by radiation to
unit mass of tissue

↓

Dose equivalent
absorbed dose weighted for harmfulness
of different radiations

↓

Effective dose equivalent
dose equivalent weighted for susceptibility
to harm of different tissues

↓

Collective effective dose equivalent
effective dose equivalent to a group
from a source of radiation

an important quantity when assessing the risk of communal harm from exposure to ionising radiation, as emerges later.

Effective dose equivalent is frequently abbreviated to dose, and collective effective dose equivalent to *collective dose.* **This usage is adopted in subsequent chapters, except when exactness of expression is essential.**

3 Radiation of natural origin

As indicated in Chapter 1, radiation of natural origin pervades the whole environment. Radiation reaches the earth from outer space, the earth itself is radioactive, and natural radioactivity is present in diet and in air. Everybody is exposed to natural radiation to a greater or lesser extent, and most persons receive the highest dose of all from it.

Cosmic radiation

The origin of *cosmic rays* is a matter of debate. One view is that they come mainly from our galaxy, the other that they come from outside it. The sun also gives rise to some. Those of undetermined origin are fairly constant in number, but those from the sun are given off in bursts during solar flares. The numbers of cosmic rays entering the earth's atmosphere are also affected by the earth's magnetic field: more enter near the poles than the equator. As they penetrate the atmosphere, they undergo complex reactions and are gradually absorbed by it, so that the dose decreases as altitude decreases. In the United Kingdom, the annual effective dose equivalent from cosmic rays is about 310 μSv on the average.

Because most persons live at low altitudes, there is little variation in annual dose on that account, but it changes from 290 μSv a year in the south of England to 320 μSv a year in the north of Scotland because of the increase in latitude. There is little that can be done to affect exposure to cosmic radiation, since it readily penetrates ordinary buildings.

Terrestrial gamma rays

All materials in the earth's crust are radioactive. Indeed it is believed that energy from the decay of natural radioactivity deep in the earth may contribute to the shaping of the crust. Uranium, thorium, and potassium-40 contribute to that energy.

Uranium is dispersed throughout soil and rock at various low concentrations. Where it reaches about 1500 parts per million in an ore, it may be economic to mine it for use in nuclear reactors. Uranium-238 is the parent of a long series of radionuclides of several elements, which change successively until the stable nuclide lead-206 is reached: the last three changes are shown in the diagram in Chapter 2. Among the earlier decay products is an isotope of the radioactive gas radon, namely radon-222, some of which diffuses into the atmosphere, where it continues to decay. Thorium is similarly dispersed in the earth, and thorium-232 is the parent of another radioactive series. Potassium-40 constitutes 120 parts per million of the stable element, which in turn makes up about 2.4% by weight of the earth's crust.

The gamma rays emitted by the radionuclides in the earth irradiate the whole body more or less uniformly. Since building materials are extracted from the earth, they too are radioactive, and persons are irradiated indoors as well as outdoors. Doses are affected by the surface geology of the area and the structure of the buildings, but the average effective dose equivalent from terrestrial gamma rays in the United Kingdom is about 380 μSv in a year. There are considerable variations about this value and some individuals receive doses several times higher than the average.

Short of choosing an area to live on the basis of gamma-ray background and of selecting ordinary building materials on the basis of radioactive content, little can be done to affect this dose. However, unusual building sites and materials with elevated levels of radioactivity might well be avoided.

Radon decay products

When radon gas enters the atmosphere from the ground, it is dispersed in the air, and concentrations out of doors are low. However, when radon enters a dwelling, either from the walls or through the floor, the concentration builds up because of the restriction in the supply of outdoor air. The immediate decay products of radon-222 are solid radionuclides with short half-lives, often called radon daughters, which attach themselves to dust particles in the air. When these are inhaled, they irradiate the lung.

The annual effective dose equivalent in the United Kingdom from radon decay products is estimated to be 800 μSv, on the average. There are pronounced variations about this mean, and individual dwellings have been discovered in which the dose to the occupants was more than an *order of magnitude* higher.

It is possible to affect the dose received indoors from radon decay products. Apart from the radioactivity in the ground and in the building materials, the main factor affecting dose is the state of ventilation. Increasing the ventilation rate in a dwelling decreases the dose, but the tendency nowadays is to save energy by reducing ventilation, which increases dose. The conflicting requirements of energy saving and dose saving are being studied in several countries, including the United Kingdom.

Radioactivity in diet

Other radionuclides from the uranium and thorium series are present in air, food, and water, in particular lead-210 and polonium-210: these irradiate the body tissues internally. Potassium-40 is taken into the body in diet and is the major source of internal irradiation apart from radon decay products. A number of radionuclides such as carbon-14 are created in the atmosphere by cosmic rays, and these also contribute to internal irradiation.

The effective dose equivalent from these sources of internal radiation is estimated to be 370 μSv in a year, on the average, in the United Kingdom, of which potassium-40 contributes 170 μSv. Information is not available on individual variations, but the potassium-40 content of the body is biologically controlled and varies with age and sex, being about twice as high in boys as in old women.

There is little possibility of affecting internal exposure from these inhaled and ingested radionuclides except by avoiding any food and water with high radioactive content. It is possible, for instance, to check that water supplies do not have unusually high concentrations of radionuclides.

Total doses

The total effective dose equivalent from radiation of natural origin is, on the average, about 1860 μSv in a year in the United Kingdom. Differences in individual doses may exceed 5000 μSv in a year, and differences in average doses from one locality to another may exceed 1000 μSv. The collective effective dose equivalent is about 100,000 man-Sv in a year.

Average annual effective dose equivalents in the UK from radiation of natural origin

Source	*μSv*
Cosmic radiation	310
Terrestrial gamma rays	380
Radon decay products	800
Other internal radiation	370
Total	1860

4 Radiation of artificial origin

Medical procedures

The X-ray sets used in hospitals and clinics are probably the best-known source of artificial radiation. They are employed for a wide variety of diagnostic procedures from simple chest radiography to complicated dynamic studies of the heart. A chest X-ray, for instance, would involve a dose equivalent to the lung of about 1 mSv. Radionuclides are also administered to patients for investigative purposes, one of the most common being technetium-99m, which has a short half-life, and is used for a wide variety of examinations such as brain and bone scans.

Radiation is also used therapeutically. One of the main methods of treating cancers is, paradoxically, to irradiate the malignant tissues heavily and so prevent the tumour cells from functioning. Beams of high-energy X-rays, or gamma rays from cobalt-60 sources, are frequently used in external therapy. Very high absorbed doses are required, and several tens of grays might be prescribed. Beams of neutrons and other ionising radiations are also used. Radionuclides are administered for therapeutic purposes, such as iodine-131 for the treatment of thyroid cancer.

Although the use of radiation in medicine offers enormous direct benefit to patients, it does, through them, contribute to the dose that the population as a whole experiences. The average effective dose equivalent is estimated to be 500 μSv in a year, almost entirely from diagnostic X-ray procedures. For a population of 56 million, this represents a collective dose of about 28,000 man-Sv. It would be possible to affect this overall dose by reducing the dose to individual patients or the frequency of radiological procedures.

Medical procedures might cause harm indirectly to future descendants of patients. Considerable interest therefore centres on a quantity called the *genetically*

Annual doses from medical procedures in the UK

Average effective dose equivalent	500 μSv
Collective effective dose equivalent	28,000 man-Sv
Genetically significant dose	120 μSv

significant dose, particularly in relation to the diagnostic use of X-rays. This quantity may be described as the dose that, if given to every member of the population, would produce the same hereditary harm as the doses actually received by individuals. For diagnostic radiology, the genetically significant dose is determined by the doses to the *gonads* of patients and the numbers of children expected to be conceived subsequently; it is therefore an indicator of the care with which reproductive organs are protected in medical procedures and the amount of radiography of pregnant women and children that is done in the country.

The value of the genetically significant dose in the United Kingdom was about 120 μSv in 1977 compared with 140 μSv in 1957, but there would appear to be scope for further reduction. As a comparison, the annual genetically significant dose from natural radiation is about 1000 μSv. Account is taken of the risk of hereditary harm in the concept of effective dose equivalent.

Fallout from weapons tests

Artificial radioactivity is spread throughout the world as a result of nuclear weapons tests in the atmosphere. About 3 tonnes of plutonium-239, for instance, has been deposited on land. A wide variety of radionuclides is involved, but those of principal interest from the point of view of dose are carbon-14, strontium-90, and caesium-137.

Much of the radioactivity is initially injected into the upper atmosphere, from which it is transferred slowly to the lower atmosphere and then more quickly to earth. The process and the material is called fallout. Since the test ban treaty in 1963, the activity in the upper atmosphere has declined markedly, although the decline is occasionally arrested by further tests carried out by non-signatory states.

The radionuclides occurring in fallout are inhaled directly or ingested in diet, and both processes cause internal exposure of the body. Radionuclides that emit gamma rays, when deposited in the soil, cause external irradiation. The average effective dose equivalent from fallout in the United Kingdom is about 10 μSv in a year at present, down from a peak of 80 μSv in the early sixties; a further decline will occur if testing is not resumed on a significant scale. The corresponding annual collective dose is 560 man-Sv. There is nothing that can be done about the doses to which humans are committed from tests that have already taken place.

Annual doses from weapons fallout in the UK

Average effective dose equivalent	10 μSv
Collective effective dose equivalent	560 man-Sv

Discharges to the environment

Artificial radioactivity is discharged to the environment by the *nuclear power industry*. Some aspects of nuclear power are discussed in Chapters 7 and 8, but it is appropriate to consider here the doses that arise from routine discharges.

The uranium required for nuclear reactors is imported. In the United Kingdom, it is first prepared as a fuel, then used in the reactors, and then reprocessed. Radioactivity is discharged in a controlled manner to air and to surface water at each of the three stages. Discharges are subject to legal restriction. The dose received by members of the public depends on the nature and activity of the radionuclides released and how they are dispersed in the environment, and on the location, living, and dietary habits of the persons involved. The information here refers to conditions during the late nineteen seventies. Since conditions change from year to year, however, values are rounded to avoid any suggestion of undue accuracy.

Doses arising from discharges to the environment by the nuclear power industry during the late nineteen seventies

Stage	*To*	*Maximum, μSv in year*	*Collective, man-Sv in year*
Fuel preparation	Air	5	0.1
	Water	50	0.1
Reactor operation	Air	200	10
	Water	100	0.1
Fuel reprocessing	Air	200	10
	Water	1300	130

Radioactivity discharged to air during fuel preparation gives rise to a collective effective dose equivalent of about 0.1 man-Sv in a year to the population of the United Kingdom, and the annual effective dose equivalent to individuals living near the preparation plants is judged to be less than 5 μSv. Discharges to water also result in an annual collective effective dose equivalent of about 0.1 man-Sv, and a maximum effective dose equivalent to local individuals that does not exceed 50 μSv in a year.

Radioactive gases and particulate matter discharged to air by reactors give rise to a collective effective dose equivalent to the United Kingdom population of about 10 man-Sv in a year, and the annual effective dose equivalent to the most exposed local individuals is estimated to be under 200 μSv in a year. Discharges of water from the special ponds for holding used fuel at reactor sites cause a maximum effective dose equivalent to local individuals of less than 100 μSv in a year, and a collective effective dose equivalent in the United Kingdom of about 0.1 man-Sv in a year through eating fish containing caesium radionuclides.

The collective effective dose equivalent to the population of the United Kingdom due to discharges to air during fuel reprocessing is estimated to be less than 10 man-Sv in a year, and the maximum annual effective dose equivalent to individuals less than 200 μSv. The discharge of low-activity liquid wastes leads to a collective effective dose equivalent of 130 man-Sv in a year and an annual effective dose equivalent to the most exposed local individuals of 1300 μSv, once again through eating fish containing caesium radionuclides.

The collective dose to the population of the United Kingdom from all controlled waste discharges by the

Annual doses from discharges of artificial radioactivity in the UK

Average effective dose equivalent	3 μSv
Collective effective dose equivalent	150 man-Sv
Representative value, most exposed individuals	1000 μSv

nuclear power industry is therefore about 150 man-Sv in a year, which would imply an average dose of about 3 μSv a year to all individuals if the dose were evenly distributed throughout the whole population. A representative value for the most exposed individuals in the country is about 1000 μSv.

Since these discharges are controlled, they could, by definition, be reduced. Reduction would, however, require expenditure, and it is one of the functions of the regulating authorities to decide whether further reductions are warranted. The bases for such decisions are discussed in Chapter 6.

There are controlled discharges of a minor nature to air and surface water from various research, defence, industrial, and medical establishments. Even though individual and collective doses from these are negligible, they are subject to the same legal constraints as discharges from the nuclear power programme.

Some solid low-activity waste from all establishments is buried in local and selected tips or dumped at sea; individual and collective doses from this practice are also negligible.

Occupational exposure

Radiation of artificial origin is widely used in general industry, primarily for process and quality control, for diagnostic purposes in dentistry and veterinary medicine, and is an essential research tool in colleges, universities, and elsewhere. There are, consequently, considerable numbers of persons exposed to ionising radiation as a result of their work, in addition to those in medicine and in the nuclear power industry. The total number of persons classified as radiation workers in the United Kingdom is about 110,000.

The effective dose equivalent that a radiation worker may receive is limited by law: essentially, it may not exceed 50 mSv in a year. Few workers receive doses above this limit, and the majority receive a relatively small fraction of it. The average dose to medical workers, for instance, is about 2 mSv in a year, to workers in the nuclear power industry about 5.5 mSv in a year, and to radiographers working in factories about 9 mSv. Industrial radiographers working on pipelines and other sites, of whom there are about 2000 in the United Kingdom, receive high doses, the average being about 27 mSv in a year.

The overall average of the effective dose equivalent to radiation workers is about 4 mSv in a year. It

Annual doses from occupational exposure in the UK

Average effective dose equivalent	
to the radiation workers	4 mSv
over the whole population	9 μSv
Collective effective dose equivalent	500 man-Sv

might be technically possible to reduce doses to workers even further, but the cost of doing so might not be warranted in the particular circumstances. This topic is explored in Chapter 6.

The collective effective dose equivalent from all occupational exposure to ionising radiation is about 500 man-Sv in a year, to which the nuclear power industry contributes almost 20%, and the annual effective dose equivalent, averaged over the whole population of the United Kingdom, is about 9 μSv.

Miscellaneous sources of radiation

Most members of the public are exposed to ionising radiation from a variety of artificial sources or from natural sources in artificial circumstances. These miscellaneous sources include watches luminised with radioactive material, television receivers, and air travel, which are appurtenances of modern life. The doses to wearers of watches are declining as less hazardous radionuclides are used, and the doses from television receivers are low because the tubes are well shielded, but the extra doses that persons receive from cosmic rays, in flight, will increase with increasing travel by United Kingdom citizens. It is possible to control the doses from some, at least, of these sources.

Annual doses from miscellaneous sources in the UK

Average effective dose equivalent	8 μSv
Collective effective dose equivalent	450 man-Sv

Average annual effective dose equivalents in the UK from radiation of artificial origin

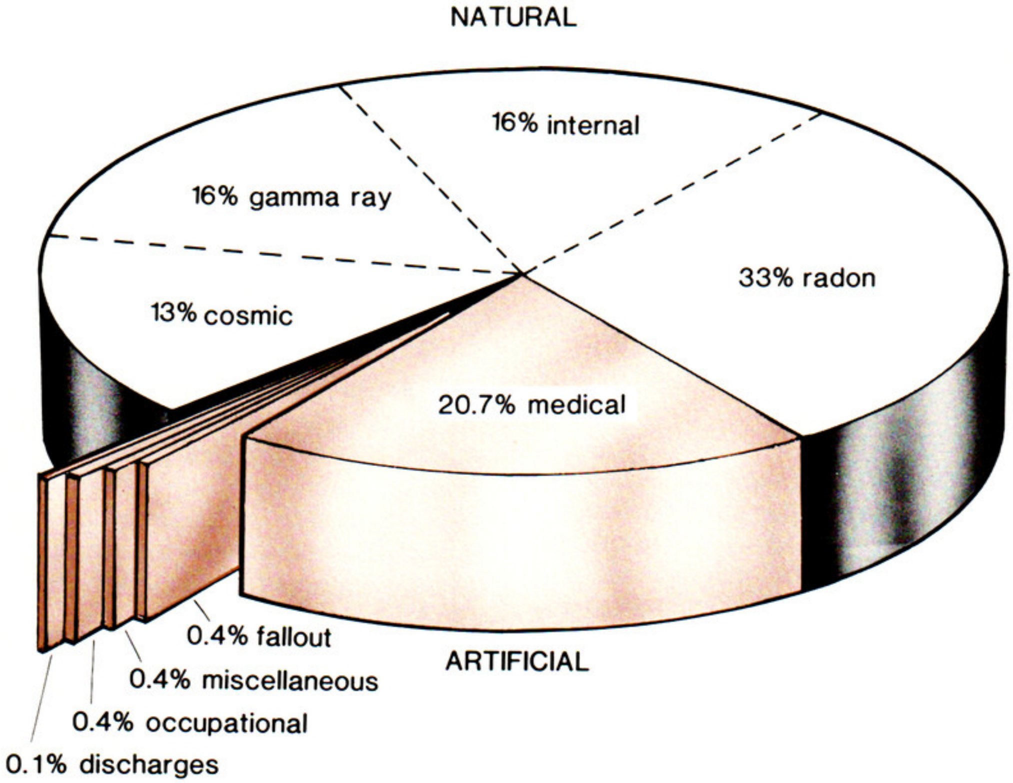
Source	*μSv*
Medical procedures	500
Weapons fallout	10
Discharges to environment	3
Occupational exposure	9
Miscellaneous sources	8
Total	530

The average dose to members of the public from such miscellaneous sources is about 8 μSv in a year, so that the collective dose to the whole population is about 450 man-Sv.

Overall doses

The total dose from radiation of artificial origin is, on the average, about 530 μSv in a year in the United Kingdom. Medical procedures are by far the greatest source of exposure of the population as a whole.

Figure 4: Average annual dose to the population of the UK



Data on doses from all sources of radiation are given in Chapters 3 and 4. The overall effective dose equivalent from radiation of natural and artificial origin is about 2400 μSv a year, on the average, for members of the population of the United Kingdom. The percentage contribution of each source to the overall value is shown here.

Natural radiation contributes almost 80% and dominates all other sources. Doses from it vary considerably, but neither this nor its size justifies doses from the other sources. A central tenet of radiological protection is that every source must be considered on its merits. Nevertheless, such a diagram may help to promote a sense of proportion.

5 Radiation effects

Early injuries

If the whole body is exposed to a very high dose of radiation, death may occur within a matter of weeks: an instantaneous absorbed dose of 5 Gy or more would probably be lethal. If a small area of the body is briefly exposed to a very high dose, death may not occur, but there may be other early effects: an instantaneous absorbed dose of 5 Gy or more to the skin would probably cause reddening in a week or so, and a similar dose to the testes or ovaries might cause sterility. But if the same total doses are received in a protracted fashion, there may be no early signs of injury. Damage may have occurred, however, and it may be manifested later in the irradiated individual or perhaps in the individual's descendants.

Malignant diseases

The most important late effect of radiation is cancer, particularly fatal cancer. The fundamental processes by which cancer is induced by radiation are not fully understood, but a greater *incidence* of various malignant diseases, cancers for short, has been observed in groups of humans who had been exposed to various high doses of radiation years previously. Few persons so exposed contract cancer, but each person has a probability of contracting it that depends largely on the dose received. Probability is used here to express mathematical chance: it is not used in the vernacular sense. The situation is analogous to smoking, where those who smoke most run the highest risk of lung cancer, but by no means all of them will contract it.

If the number of persons in an irradiated group and the doses that they have received are known, and if the number of cancers eventually observed in the group exceeds the number that would be expected in an otherwise similar non-irradiated group, the excess number of cancers may be attributed to the radiation, and the risk of cancer per unit dose equivalent may be calculated. It is called a risk factor.

Not all cancers are fatal. Mortality for radiation-induced thyroid cancer is about 3%, for example; for breast cancer, mortality is about 30%. The total risk of inducing cancer by uniformly irradiating the whole body is about 3 times the risk of inducing a fatal cancer. Because of its overwhelming significance, however, the risk of fatal cancer is of most concern in radiological protection. It facilitates comparison with the other fatal risks of life, whereas comparisons of non-fatal risks are fraught with difficulty.

United Nations reviews

Risk factors have been determined in studies of various groups, pre-eminently the survivors of the *atomic bombs* in Japan. Broadly corroborative data have been obtained from studies on patients who had been exposed to radiation for the treatment of non-malignant conditions or for diagnostic purposes, on persons exposed to intense nuclear fallout in the

Calculation of a risk factor

If a group of 50,000 persons had each received a dose of about 2 Sv to a particular organ, and if 100 more cancers of the organ appeared in this group than in a similar but unexposed group, the risk factor would be $\frac{100}{50{,}000 \times 2}$, which is 1 in 1000 per Sv, or 10^{-3} Sv^{-1} in scientific notation.

Marshall Islands, on uranium miners, and on workers in the luminising industry.

Information of this nature is reviewed periodically by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) which was established in 1955 and which publishes its reports to the General Assembly. In its 1977 report, UNSCEAR provides estimates of the risk factors for fatal cancers as a result of the irradiation of certain tissues. It indicates, for instance, that the risk factor for leukaemia, a cancer-like disease of the white blood cells, is about 1 in 500 per Sv (2×10^{-3} Sv^{-1}). This means that, if a person receives a dose equivalent of 1 Sv to the red bone marrow, the most important blood-forming tissue, there is a 1 in 500 chance that he will eventually die of leukaemia as a result of that dose. On the average, death would occur about a decade after the dose was incurred.

Hereditary defects

Another important late effect of radiation is hereditary damage, the probability but not severity of which depends on dose. The damage arises through irradia-

Principal harmful radiation effects: Conditions for occurrence and sources of information

	Effect	*Condition*	*Information*
Early	Death	Very high dose and dose rate: to much of body	Human data from various sources.
	Erythema	to area of skin	
	Sterility	to testes and ovaries	
Late	Malignant diseases	Any dose or dose rate. Probability depends on dose. Manifested years later.	Risk data for humans by linear extrapolation from high doses and dose rates. Various sensitivities of organs.
	Hereditary defects	Any dose or dose rate. Probability depends on dose. Manifested in descendants.	Risk data for humans by inference from mouse data. Upper limit from human data.
	Non-malignant changes	Very high dose. Various times to manifestation.	Human data from various sources.
	Developmental changes	Irradiation of embryo. Manifested after birth.	Limited human data.

tion of the gonads, which produce the sperm cells in males and the egg cells in females. Ionising radiation induces *mutations*, which are usually harmful, in these cells or their precursors. The exact processes by which mutations occur are not known, but they involve chemical change to the DNA. The hereditary defects that mutations may cause range from the serious, such as severe mental retardation, to the trivial, such as skin blemishes.

Mutations occur in human populations in a seemingly spontaneous manner, that is, without any apparent cause, but radiation of natural origin may make a contribution to the number. However, no direct evidence for hereditary defects, attributable to exposure either from natural or artificial radiation, has been found in human offspring. Extensive studies of the offspring of the Japanese bombing survivors, in particular, have failed to show statistically signifi-

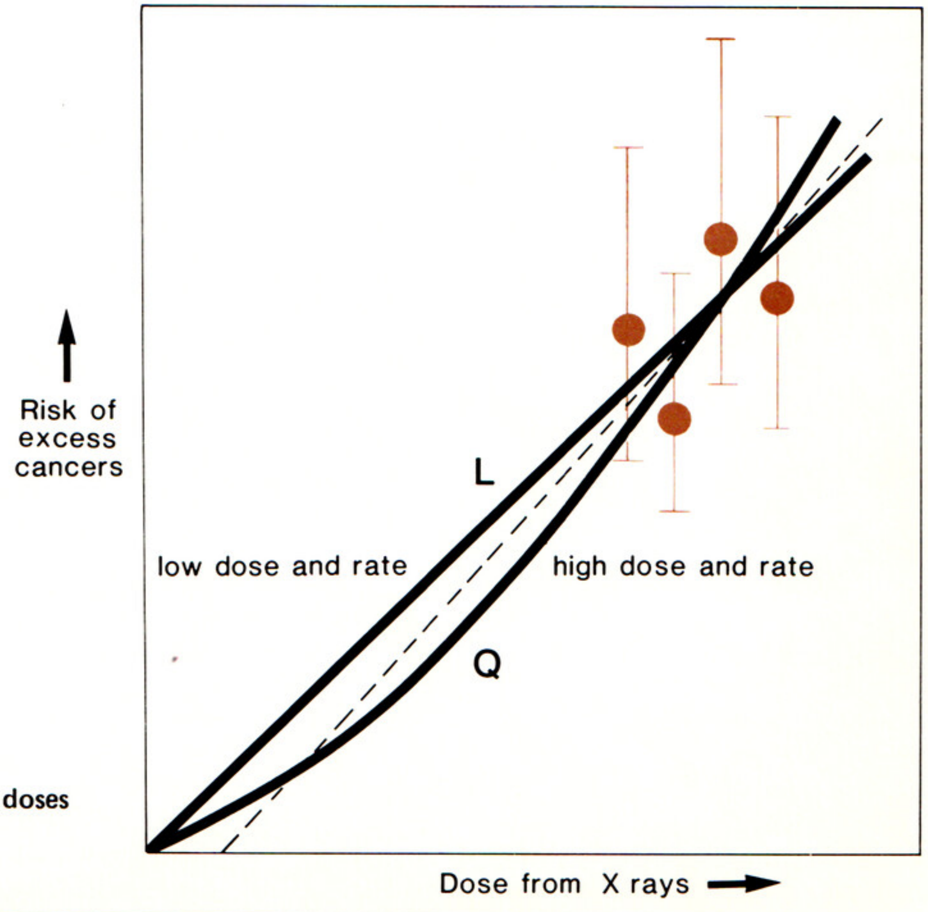


Figure 5: Estimating risk at low doses from data at high doses

cant increases in hereditary defects, but these negative findings help to provide an upper estimate of the risk factor for such effects.

For several decades, extensive studies have however been made of the hereditary damage induced in experimental animals, mainly mice, by exposing them to ionising radiation. These studies have covered a wide range of both dose and dose rate. They provide information on the frequency with which hereditary defects are induced by known doses, and this information, with the negative Japanese findings, enabled UNSCEAR to estimate a risk factor for serious hereditary damage to humans: its value is about 1 in 50 per Sv (2×10^{-2} Sv^{-1}) when all generations subsequent to the irradiation are taken into account. About half of this damage would be expressed in the children and grandchildren of the irradiated persons, which implies a risk factor of 1 in 100 per Sv (10^{-2} Sv^{-1}) for the first two generations.

Irradiation of the gonads is potentially harmful only if it occurs before or during the reproductive period of life. For those who will not subsequently have children, there is, by definition, no hereditary risk. The fraction of a group of persons for whom irradiation of the gonads has hereditary significance depends on the ages of the persons and therefore the numbers of children that they are likely to have, but a value of 0.4 would appear to be appropriate for general populations. Thus, the average risk of serious hereditary defects in the first two generations would be 1 in 250 per Sv (4×10^{-3} Sv^{-1}).

Dose-risk relationships

The risk factors determined by UNSCEAR derive, as far as cancers are concerned, from relatively high doses delivered in short periods. Such situations are not encountered in the normal course of events: persons are usually exposed to relatively low doses delivered over long periods. The problem therefore is to decide what risk factors are appropriate in the normal situations.

The difficulty is illustrated, in idealised form, in the diagram. Results of a hypothetical study on four groups of persons who had been exposed to high doses of X-rays at high dose rates are shown. The groups had received different average doses, and excess cancers of a particular organ had appeared in each group. The four points represent estimates of the mean risk at each dose, and the vertical bars represent confidence intervals for them (Figure 5).

To obtain the risk at low doses, it is necessary to extend a curve downwards from the points at high doses. In doing so, it must be decided whether it should go through the origin of the graph. If there is no dose, there can be no excess, so the curve cannot cut the vertical axis. If it were to cut the horizontal axis, as shown by the dotted line, it would imply that there was some threshold dose below which there was no risk, an implication which is unacceptable without proof of its validity. The curve is therefore constrained to go through the origin. What remains to be decided is its shape.

Two solid curves are shown which fit the points satisfactorily. The general shape of the curve Q is developed from experimental and theoretical *radiobiology:* it represents a quadratic equation linking risk to dose. The drawback is that its exact shape cannot be predicted for cancers in humans, so that it is impossible to use it to estimate risk at low doses.

Curve L is a straight line. The justification for this shape is the practical need to estimate risk at low doses and dose rates. It may lead to overestimation, the degree of which depends on the type of radiation, but it provides a cautious means of overcoming the lack of human data for the situations that normally prevail. The risk factor is given by the slope of the line: it is equal to the risk at any point on it, divided by the corresponding dose.

In radiological protection, therefore, it is assumed that the risk factors for cancers do not decrease with decreasing dose or dose rate. The same assumption is made in relation to the risk factor for hereditary damage given earlier. This means, for instance, that the risk associated with 1 mSv is deemed to be one thousandth of the risk associated with 1 Sv, and that it is considered immaterial whether 1 Sv is delivered in a burst or spread over several years. It also implies that any dose, no matter how small, creates a finite risk of cancer or hereditary defects.

International recommendations

These cautious assumptions underpin the approach to protecting persons against ionising radiation advocated by the International Commission on Radiological Protection (ICRP). The risk factors put forward by the Commission, which are consistent with those determined by the United Nations committee, are shown here. Each tissue or organ contributes a certain fraction of the total risk factor of 1.65×10^{-2} Sv^{-1} for irradiation of the whole body, and this is the basis of the risk weighting factor discussed earlier in relation to effective dose equivalent.

The risk factor for serious hereditary defects in children and grandchildren is included, because such injury might well be considered by individuals as being as important as fatal injury to themselves.

The values are intended for application to an average individual regardless of age or sex, but values for actual individuals depend on both age and sex: if a person receives a radiation dose late in life, a cancer may not have time to express itself before the person dies of another cause, and the risk factor for breast

Risk factors for serious hereditary defects in the first two generations and for fatal cancers from irradiation of various tissues and organs

Tissue or organ	*Risk factor* *per Sv*	*Risk factor* *(Sv^{-1})*	*Fractional contribution*
Gonads (hereditary)	1 in 250	(4×10^{-3})	0.25
Breast	1 in 400	(2.5×10^{-3})	0.15
Red bone marrow	1 in 500	(2×10^{-3})	0.12
Lung	1 in 500	(2×10^{-3})	0.12
Thyroid	1 in 2000	(5×10^{-4})	0.03
Bone surfaces	1 in 2000	(5×10^{-4})	0.03
Remainder	1 in 200	(5×10^{-3})	0.30
Whole Body	1 in 60	(1.65×10^{-2})	1.00

cancer is virtually zero for men and twice the tabulated value, or 1 in 200 per Sv (5×10^{-3} Sv^{-1}) for women. On the average, however, the overall risk factor for cancer is about 1 in 80 per Sv (1.25×10^{-2} Sv^{-1}). It dominates over the hereditary risk in the first two generations.

Communal risk

An important consequence of the assumption of a linear relationship between dose and risk without the existence of a threshold is that the collective effective dose equivalent becomes an indicator of communal risk. It makes no difference, in communal terms, whether, in a community of 40,000 persons, each receives an effective dose equivalent of 2 mSv, or in a community of 20,000 persons, each receives 4 mSv: the collective dose in each community is 80 man-Sv, and the communal cost in each community may be one cancer death. In personal terms, however, members of the smaller community run a greater risk.

The utility of collective dose in radiological protection is discussed further in Chapter 6.

Other late effects

There is a category of late effect that does not involve an element of probability: such an effect will appear in an individual if a large enough dose equivalent is received, and the severity will increase with increasing dose. These effects are not ordinarily fatal, but they can be disabling or distressing. The function of some organs may be impaired or other non-malignant changes may be induced in them: the best-known examples are cataract and skin damage. High cumulative dose equivalents of the order of 10 Sv are normally required to bring them about.

Irradiation during pregnancy

Special mention must be made of the risks to children irradiated in the womb. If an embryo is exposed to radiation, developmental defects such as a reduction in the diameter of the head may be induced. Developmental defects arise because the organs are being formed during the early weeks of pregnancy. There are insufficient human data, however, for risk factors to be estimated.

If, later in pregnancy, a foetus is exposed to radiation, there will be an enhanced risk of malignancies in childhood: the risk factor is estimated to be about 1 in 40 per Sv (2.3×10^{-2} Sv^{-1}), which is about twice the overall risk of cancer for the average individual. These are the reasons why pregnant women. do not have X-rays taken of the abdomen unless there is an adequate clinical case for doing so, and why there are special restrictions on the doses that fertile and pregnant women may receive if they are employed as radiation workers.

Register of radiation workers

Because of the way in which they are derived, risk factors used in radiological protection must be regarded as approximations. It is essential therefore to make use of every opportunity to test the validity of the present estimates. One way of doing this is to study the incidence of fatal malignant diseases among persons who were occupationally exposed to radiation under supervised conditions. The doses that radiation workers receive are routinely monitored in the United Kingdom, and cumulative doses can be determined. A National Registry for Radiation Workers has therefore been established by the Board, in which the lifetime dose and cause of death of individual workers are recorded.

This information will be analysed as it builds up to discover whether there are any differences between the general patterns of mortality of radiation workers and other groups, and among groups of radiation workers with different lifetime doses. It will be analysed in particular for evidence of excess cancers, and estimates will be made of the bounds within which risk factors lie.

The major technical difficulty in such a project is caused by the high incidence of many cancers in the community: about 20% of the population of the United Kingdom dies of cancer. Since cancers induced by radiation are indistinguishable from those that otherwise occur, the difficulty lies in detecting a slight difference in incidence and appraising it in a statistical sense. Nevertheless, it should be possible to demonstrate, within a decade, whether the present risk factors are correct within an order of magnitude.

6 The system of radiological protection

Central principles

Approaches to radiation protection are remarkably consistent throughout the world. This is due in large measure to the International Commission on Radiological Protection, an autonomous scientific organisation which has published recommendations for protection against ionising radiation for over half a century. Its authority derives from the scientific standing of its members and the merit of its recommendations. Governments evaluate the recommendations and put them into practice in a manner appropriate to the countries concerned.

The present system of radiological protection is based on three central requirements. Each of these requirements involves social considerations, the first two explicitly, the last implicitly; there is therefore considerable need for the exercise of judgment.

Scope of application

In principle, the requirements apply to all sources of radiation, but there are obvious constraints in practice. Nothing can sensibly be done about the normal levels of dose from radiation of natural origin, but abnormally high doses can be avoided. Nothing can be done about the fallout from previous weapons tests, but future tests need not be conducted in the atmosphere. The use of radiation in medicine is a matter of clinical judgement, and it would be inappropriate to specify limits on individual dose, but the collective dose from medical procedures is high, and clinicians must have regard to the other ICRP requirements. Essentially, however, the requirements apply in full only to the exposure of radiation workers, to the exposure of the public from industrial and other practices involving radiation, and to the exposure of the public to miscellaneous artificial sources. It is

The central requirements of radiological protection as expressed by the International Commission on Radiological Protection

1 No practice shall be adopted unless its introduction produces a positive net benefit.

2 All exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account.

3 The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission.

in this restricted sense that the three requirements of radiological protection are discussed here.

Acceptability of practices

The first requirement emphasises the obvious need to consider harmful effects when deciding whether a proposed practice or operation involving exposure to ionising radiation is acceptable. Radiation effects would be regarded as one of the costs of the proposal, and the costs would be set against the benefits. It would also be necessary to analyse the costs and benefits of alternative ways of achieving the same end without involving radiation.

The question of acceptability can therefore be a profound one, extending beyond radiological protection, and requiring resolution ultimately by Parliament. Although it has been sanctioned by statute for a few decades, the nuclear power programme might be used to illustrate this point.

Some of the radiological consequences of the nuclear power programme have been described in Chapter 4, namely the discharge of radioactivity to the environment and the doses received by the workers in the industry. To this must be added the potential for reactor accidents of varying frequency and severity and the creation of highly active wastes, topics which are discussed in Chapters 7 and 8. Account should also be taken of doses and accidents to the overseas uranium miners.

A comparison would need to be made with the consequences of alternative methods of producing power, using coal for instance. Large volumes of waste are produced in this power industry, noxious substances including natural radioactivity from the coal are discharged at the power stations, miners suffer occupational disease, and there is potential for mine accidents of varying frequency and severity.

Strategic and economic factors would also need to be considered, for instance: the diversity, security, availability, and reserves of various fuels; the construction and operating costs of various types of power station; the expected demand for electricity; and, not least, the willingness of persons to work in a particular industry.

Radiation effects are therefore only one element in such a complicated question of acceptability, but it is essential that they be fully recognised and given due weight at the decision-making stage.

Few would question that the use of X-rays is generally acceptable in medicine: the benefits are undoubted, even though individual and collective doses are high. Nevertheless, the acceptability of any particular procedure needs to be established: a mass X-ray programme for cancer in a particular organ that might cause more cancers than it was likely to reveal would be unacceptable. For the reasons given in Chapter 5, medical irradiation during pregnancy requires strong justification and careful techniques.

Some practices that, by common consent, fail to satisfy the first requirement are proposed from time to time. These include quack remedies, toys, and items of jewellery that contain radioactive material. They are not accepted.

Minimising doses

The second requirement of radiological protection underlines the necessity to minimise exposures from accepted practices, but not to an absurd degree. It implies that mere compliance with a dose limit is not sufficient: the doses actually received must be as low as social and economic circumstances warrant.

This precept has been developing in radiological protection over two decades, with the result that average annual doses to radiation workers are about an order of magnitude below the legal limit of 50 mSv that has prevailed throughout the period, although doses vary from one group of workers to another. Annual doses to individual members of the public, for whom the dose limit has been 5 mSv, have been considerably below this value, even for the most exposed persons.

These low doses arise from a combination of factors. Since compliance with definite limits is required, average doses will naturally be lower. Protection schemes in places of work are usually designed so that the doses to most staff are well below the limit. Practices that cause irradiation of members of the public are controlled on the basis of cautious estimates of the dose to the most highly exposed group of individuals and an assessment of the reductions below the limit that might be appropriate. In some situations, the views of trades unions and of representatives of the public may be sought. Such procedures are qualitative but judicious ways of fulfilling the requirement to keep all doses as low as reasonably achievable.

Cost-benefit analysis

A more quantitative approach to the second requirement is through cost-benefit analysis, which is of use in deciding the allocation of resources and an aid to informed judgement. This technique is undergoing rapid development in radiological protection at the time of writing, and it is difficult to forecast the effect it may have on future levels of dose. It requires harmful radiation effects to be valued in monetary terms for direct comparison with expenditure to reduce them. Collective dose is used to represent the risk of harmful effects.

Although collective dose is used in the analysis, the ethical difficulty cannot be avoided of placing a monetary value on human harm or on changes in the risk of harm, such as death, that different levels of

The use of cost-benefit analysis in radiological protection

Suppose that a number of methods, or variants of one method, are being considered in turn for reducing collective dose from a certain radiation practice. They bring about progressively greater reductions in collective dose and require progressively greater expenditure, but each increase in expenditure brings about a smaller reduction in collective dose. Eventually a point is reached where the extra expenditure to bring about any more reduction balances the monetary value of that reduction. At that point, the collective dose is as low as reasonably achievable, further expenditure would not be warranted, and protection is said to be optimised.

expenditure bring about. The difficulty is compounded by the fact that the harm may occur in future generations. Quantitative analysis of this nature may clarify the consequences of alternative actions, but there will still be a need for sensitive judgement. Ethical difficulties are not peculiar to radiological protection, however, and another advantage of such an analysis is that it may indicate whether resources could be used elsewhere to greater advantage.

Dose limits

The third requirement of radiological protection expresses the obligation not to expose individuals and their descendants to an unacceptable degree of risk. This is brought about by imposing a strict limit on the effective dose equivalent that a person may receive: for a radiation worker, the limit is 50 mSv in a year, and for a member of the public, 5 mSv in a year. These limits are, in effect, arbitrary constraints on the method of fulfilling the second requirement and are values to be observed without regard to cost. They are designed to control the incidence of effects such as cancer and hereditary damage that involve an element of probability.

There are two common misconceptions about dose limits. The first is that they mark an abrupt change in biological risk. That this is not so will be clear from the discussion in Chapter 5 on the relationship between dose and risk for these effects and indeed from the fact that there are two limits: the limits are chosen on social grounds. The second is that compliance with the dose limits is the only important requirement in the system of radiological protection: on the contrary, the requirement to keep doses as low as reasonably achievable is even more important, and it is their joint impact on an accepted practice that determines the effectiveness of the system of radiological protection. A situation in which all the workers were unquestioningly allowed to receive 50 mSv, year in year out, would not be acceptable.

Effectiveness of protection

It was seen in Chapter 4 that the average effective dose equivalent to radiation workers in the United Kingdom is about 4 mSv in a year. It was seen in Chapter 5 that the overall risk factor for fatal cancers is about 1 in 80 per Sv (1.25×10^{-2} Sv^{-1}). The average risk of fatal cancer that a radiation worker runs in the United Kingdom is therefore about 1 in 20,000 per year (5×10^{-5} y^{-1}), which results from fulfilling the central requirements described above.

One way of judging the effectiveness of the system of radiological protection is to compare this average annual risk of fatal cancer with the average annual risk of fatal accidents in other occupations. Although crude, such a criterion is clear and on the whole cautious, since radiation effects of this nature occur late, and fatal diseases in other occupations are ignored. The comparison is made here, using fatality rates typical of the last two decades. Radiation workers are seen to be ranked with furniture and food workers in what might be regarded as relatively safe industries, and indeed to suffer a risk roughly equal to that for all employment. Even if the average radiation risk were superimposed on the conventional risk for employment as a whole, the overall risk might still be regarded as unexceptional. In fact, the fatal accident rate in the nuclear power industry is about 1 in 70,000 per year (1.4×10^{-5} y^{-1}).

The data illustrate why prolonged exposure at 50 mSv a year for a group of radiation workers might prove unacceptable: it implies an annual risk of 1 in 1600

(6.3×10^{-4} y^{-1}) which would rank them with workers in relatively hazardous occupations. Considerable effort is expended therefore in reducing high exposures among workers.

Average annual risk of death in the UK from accidents in various industries and from cancers potentially induced among radiation workers

Industries	*Risk of death*	
	per year	*(y^{-1})*
Deap sea fishing	1 in 400	(2.5×10^{-3})
Coal mining	1 in 4000	(2.5×10^{-4})
Construction	1 in 5000	(2.0×10^{-4})
Metal manufacture	1 in 7000	(1.4×10^{-4})
Timber, furniture, etc.	1 in 17,000	(5.9×10^{-5})
All employment	1 in 20,000	(5.0×10^{-5})
Radiation workers (4 mSv per year average)	1 in 20,000	(5.0×10^{-5})
Food, drink, and tobacco	1 in 30,000	(3.3×10^{-5})
Textiles	1 in 40,000	(2.5×10^{-5})
Clothing and footwear	1 in 300,000	(3.3×10^{-6})

Protection of the public

With regard to members of the public, it was seen in Chapter 4 that a representative annual dose to the most exposed individuals in the country from the discharge of radioactivity to the environment is about 1 mSv. This implies an average risk of cancer of 1 in 80,000 in a year (1.25×10^{-5} y^{-1}) as a result of the application of the system of radiological protection.

This level of risk, which is experienced by relatively few persons in the country, may be judged by comparison with the fatal risks, self-imposed or otherwise, that are part of everyday life. Some such risks, calculated for recent years, are shown here in rounded form, but the risk of death from natural causes for a 40-year old person is included merely to give an

Average annual risk of death in the UK from some common causes and from cancers potentially induced among highly-exposed individuals

Cause	*Risk of death*	
	per year	*(y^{-1})*
Smoking 20 cigarettes a day	1 in 200	(5×10^{-3})
Natural causes, 40 years old	1 in 500	(2×10^{-3})
Accidents on the road	1 in 5000	(2×10^{-4})
Accidents in the home	1 in 10,000	(1×10^{-4})
Accidents at work	1 in 20,000	(5×10^{-5})
Radiation exposure (1 mSv per year)	1 in 80,000	(1×10^{-5})

added sense of perspective. The radiation risk applies to a relatively few highly-exposed individuals.

Prolonged exposure at the limit of 5 mSv in a year specified for members of the public from all sources might prove unacceptable, because of the magnitude of the attendant risk. Indeed, it would exceed that experienced by radiation workers in general.

National risk

The collective dose to the whole population of the United Kingdom from those practices to which the radiological protection system applies in full is about 1000 man-Sv in a year. Such a collective dose might imply about 10 deaths a year from cancer and about 10 serious hereditary defects in all subsequent generations. This potential harm has to be judged against the national benefit of using radiation in industry and other practices, apart from medicine, for a year.

It may be recalled that the collective dose from natural radiation is about 100,000 man-Sv in a year, that is, one hundred times greater.

Limits for single organs

To prevent harmful effects in an exposed person that do not involve an element of probability, strict limits are also imposed on the dose equivalent that any single tissue or organ may receive in a year. For radiation workers, this limit is 500 mSv in a year, and for members of the public, 50 mSv. To avoid cataract, however, a radiation worker may not receive a dose equivalent of more than 300 mSv in a year to the eye, nor a member of the public 30 mSv in a year.

These limits do not attract as much attention as the limits of 50 mSv and 5 mSv in a year designed to control harmful effects with an element of probability, that is, cancer and hereditary damage. Nevertheless, both sets of limits must be applied, and in circumstances where the body is unevenly irradiated, the single-organ limits may be the most restrictive. It is easy to imagine this occurring in the case of a narrow beam of X-rays that might irradiate the eye, but it can also occur with radionuclides that concentrate in a particular organ.

Set of dose limits for radiation workers and members of the public, mSv in a year

Quantity	*Worker*	*Public*
Effective dose equivalent or Uniform dose equivalent to body	50	5
Dose equivalent to single organ or tissue	500	50
Dose equivalent to eye	300	30

Legal controls

The system of radiological protection described above applies therefore to practices involving exposure to ionising radiation that must be acceptable to society and capable of being modified. Its primary purpose is to reduce the risk of harmful effects as far as social and economic conditions allow; to judge by comparisons with other practices and circumstances, it would appear to be achieving this purpose in the United Kingdom, as elsewhere. The system depends heavily on numerical estimates of risk, but even more heavily on judgement of the residual risk that might be tolerated by individuals and society. Exposure to ionising radiation is therefore a fit matter for parliamentary control, and it is comprehensively regulated by statute.

A substantial body of legislation has built up since the end of the Second World War. Various acts, regulations, and orders are supported by codes of good practice and advisory literature. Virtually every practice is dealt with from the use of nuclear power stations to the use of X-ray sets for examining animals.

This system of controls has been reinforced by obligations incurred through membership of the European Communities. These obligations are expressed in basic safety standards for workers and the general public with which Member States must comply. The basic standards do not differ in essence from the controls that evolved nationally: both are derived from the recommendations of ICRP.

The National Radiological Protection Board advises the Government on the acceptability of ICRP recommendations for application in the United Kingdom. It has done so in regard to the system of radiological protection outlined here. The Board's function is advisory in this matter: the responsibility for formulating and implementing legal controls rests elsewhere.

In general, governmental responsibility for radiological protection falls to Ministers and their staffs operating within the scientific and administrative structure and policy of the various Departments. This has the advantage that radiological hazards are considered in the context of other hazards with which a Department is concerned, and specialist advice may be obtained from the Board.

The same approach is evident in the control of hazards caused by the use of radiation at places of work and by nuclear installations such as reactors. This responsibility falls to the Health and Safety Commission supported by its Executive, which employs inspectors to enforce the relevant statutory provisions. Radiation is, however, but one of many occupational and industrial hazards that are subject to regulation and inspection, and the enforcement of radiological safety fits into the general pattern. The Commission consults the Board.

Since its formation, the Board has advised manufacturers and suppliers of consumer goods containing radioactive material on the acceptability or otherwise of the products. They were not legally obliged, however, to follow the advice. At the time of writing, there is a proposal to make regulations under an appropriate statute requiring goods containing radioactive substances to be approved by the Board.

7 Nuclear reactors

Figure 6: Sites of nuclear power stations and nuclear fuel factories

The doses to the public from routine discharges of radioactivity to the environment as a result of the nuclear power programme are given in Chapter 4, and the doses to workers in the industry are also discussed there. In this chapter, consideration is given to another aspect of nuclear power, namely, the safety of nuclear reactors.

The power programme

Nuclear reactors have been used to produce electricity since the nineteen fifties. The Electricity Boards now operate eleven reactor stations at various sites in the United Kingdom, each containing two reactors, and five more stations are under construction, bringing the total number of sites to twelve. When these stations are operating, about 20% of the electric power generated in the United Kingdom will be of nuclear origin. In 1980, the Government announced a further expansion of the industry that would raise the proportion to 30% or so.

British Nuclear Fuels Limited and the United Kingdom Atomic Energy Authority also operate a number of nuclear reactors, which supply some electricity to the national grid (Figure 6).

Types of reactor

Nuclear reactors are so called because they depend for their operation on a reaction between neutrons and the atomic nuclei of the fuel. There are two types, *thermal reactors* and *fast reactors*. With one exception, all the power reactors operating and planned in the United Kingdom are thermal.

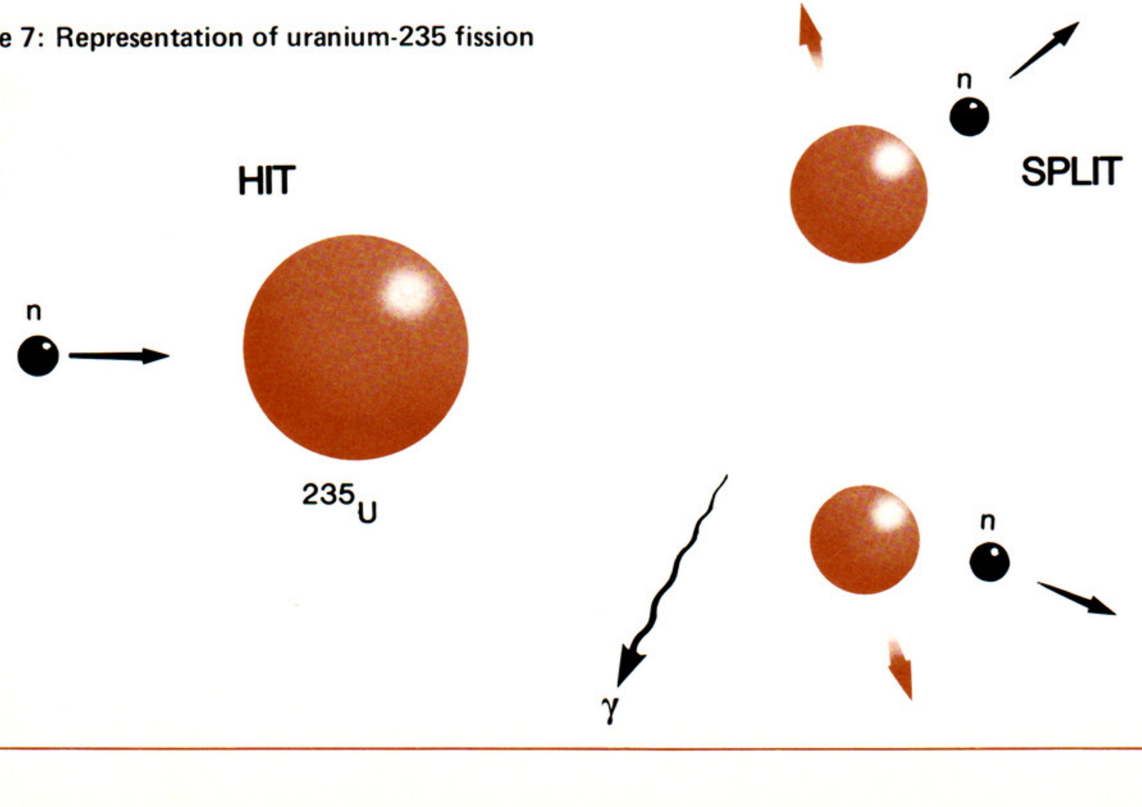
The fuel for thermal reactors is uranium. Neutrons react most effectively with uranium when they have been deliberately slowed until their thermal energy reflects that of their surroundings. The processes that occur in thermal reactors are described below.

The fuel for fast reactors is plutonium mixed with uranium. *Fast neutrons* are used to greatest effect with this fuel. The neutrons also interact with the uranium to create plutonium. If the fuel is surrounded by uranium, more plutonium can be created than is consumed. Such reactors may become important in the future for the nuclear power programme, since they offer a means of utilising uranium to a much greater extent than thermal reactors. A prototype fast reactor has been developed and operated at Dounreay in Scotland.

Reactor processes

Despite variations in design, all thermal reactors operate on the same principle, the *fission* of uranium-235. Natural uranium contains about 99.3% by weight of uranium-238, about 0.7% by weight of uranium-235, and a negligible amount by weight of another uranium isotope. Some thermal reactors are fuelled by uranium with natural composition. In the interests of efficiency, other thermal reactors use fuel in which the uranium-235 content has been increased to 2 or 3%; such material is called *enriched uranium*. Uranium in which the content of uranium-235 is below the desired level for reactor operation is called *depleted uranium*.

Figure 7: Representation of uranium-235 fission



When the nucleus of an atom of uranium-235 is hit by a neutron, energy is liberated: the nucleus splits into two or more fragments, which fly apart, gamma rays are emitted, and some fast or energetic neutrons are released. If these extra neutrons are slowed so as to improve the chance of reacting, they split other uranium-235 nuclei, liberate more energy, and release more neutrons. Thus, a chain reaction can be set up. The splitting process is called fission, the fragments are known as *fission products*, and the liberated energy appears mainly as heat in the fuel (Figure 7).

Neutrons may also be captured by an atom of uranium-238 to form uranium-239. This radionuclide decays through a short-lived intermediary to plutonium-239, which may be used with depleted uranium in fast reactors. Other radioactive elements such as americium and curium are also formed in reactors. Such elements and uranium belong to a group called the *actinides*.

Reactor layout

Reactor fuel is assembled in an array called the core. This also contains the material that reduces or moderates the speed of the neutrons and is called the *moderator*. Heat is conducted away from the core by a coolant. The reactor is regulated mainly by the movement of control rods in the core, which act by absorbing neutrons: they enable the reactor to be brought up to power, held there, and shut down when required. The temperature of the core also has a regulating effect. When a reactor is at power, the chain reaction is just self-sustaining: one of the neutrons released in a fission causes, on the average, another fission (Figure 8).

In thermal reactors designed in the United Kingdom, the moderator is graphite and the coolant pressurised carbon dioxide gas. In most other countries, pressurised water is used as both moderator and coolant in thermal reactors; these are the so-called *Pressurised Water Reactors (PWR)*. Coolants are passed through heat exchangers to make steam to drive the turbine generators which make electricity.

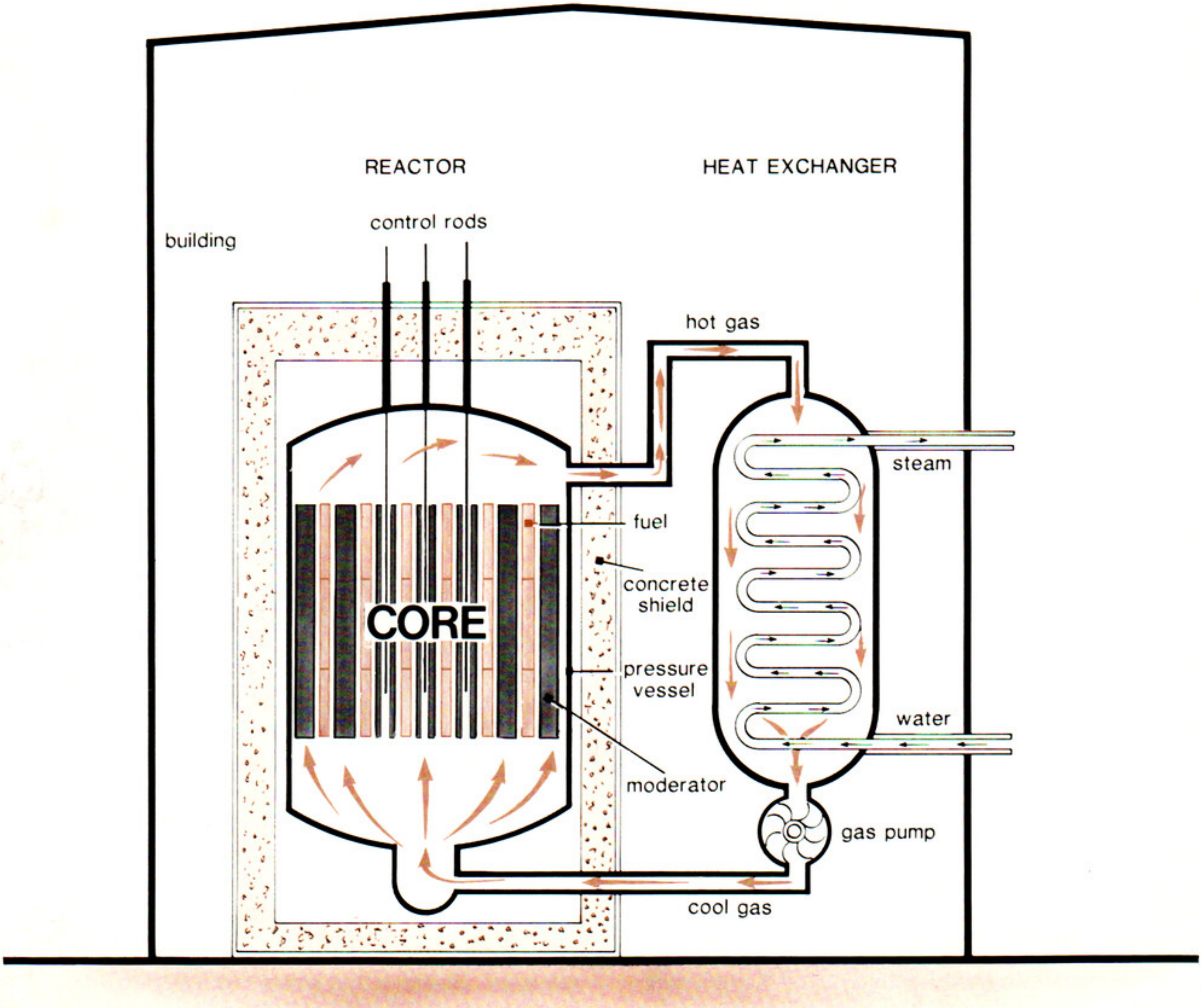
The core of a commercial reactor may contain from one hundred to several hundred tonnes of fuel. In the United Kingdom, the newer *Advanced Gas-cooled Reactors (AGR)* contain, on the average, over 100 tonnes of enriched uranium oxide. The older *Magnox reactors* contain, on the average, over 300 tonnes of uranium metal of natural composition. The fuel is sealed in metal containers, and the core is contained in a pressure vessel. The Magnox reactors are named after the magnesium alloy fuel containers used in them. The immediate fuel containment is frequently called the cladding. Massive concrete shielding is also provided, because of the intense radiation eventually emitted by the core. The reactors, and in virtually all cases the heat exchangers, are further contained in the reactor building.

Radioactivity and power output

Fresh fuel is only mildly radioactive and can be handled without shielding. The initial activity in the core of a reactor is about 10^{13} Bq. When the reactor has been operating for some while, however, the activity will have increased about ten million times to approximately 10^{20} Bq. These enormous increases of activity are due mainly to the creation of fission products in the fuel. It explains why so much shielding is required around the core and why it is vital that the various containments should not be breached.

An enormous quantity of power is produced in reactors. The thermal power of a typical AGR, for instance, is 1500 MW (1500 million watts), which is equivalent to the power dissipated by 1.5 million

Figure 8: Schematic diagram of gas-cooled nuclear reactor of the Magnox type



single-bar electric fires. Since the volume of the core of an AGR is about 550 cubic metres, it is vital that the method of removing heat be effective and continuous, otherwise the fuel container and the fuel itself may melt and release activity. It is also vital that the reactor be controlled so that the rate of production of heat does not exceed the capacity of the cooling arrangements, and that the reactor can be shut down rapidly and reliably in the event of an incipient accident.

Even when a reactor has been shut down, the fission products in the fuel continue to generate heat merely by radioactive decay. Immediately after shutdown, the power produced is about 7% of operating power, although this further reduces with time; some cooling must therefore be continued to prevent melting.

Characteristics of thermal reactors

Fuel	: uranium of natural composition or enriched in uranium-235 isotope
Process	: fission of uranium-235 by slow neutrons
Moderator	: graphite (UK), water elsewhere
Coolant	: carbon dioxide gas (UK), water elsewhere
By-products	: plutonium, depleted uranium, radioactive wastes

Safety record

The key mechanisms for reactor safety are therefore control, cooling, and containment. Reactors must be designed, constructed, and operated so that the probability of failure of these mechanisms, with consequent release of radioactivity to the environment, is extremely low.

This objective is pursued in the United Kingdom against the background of almost 300 reactor-years of experience by the Electricity Boards in the operation of Magnox and AGR reactors, and almost 200 reactor-years of experience with nine similar reactors by the United Kingdom Atomic Energy Authority and British Nuclear Fuels Limited. Thus some 30 thermal power reactors have been designed and constructed in Great Britain and have operated for almost 500 reactor-years without an accident involving serious exposure of staff or members of the public. Five hundred reactor-years is the sum of all the years of operation of all the reactors up to 1980.

This record, although encouraging, is not a guarantee of future safety, nor indeed proof of an acceptably low probability of accidents. To illustrate this point, it is only necessary to recall that a forerunner of the United Kingdom gas-cooled reactors suffered a severe accident at Windscale, Cumbria, in 1957, in which the fuel over-heated and substantial activities of fission products were released to the atmosphere, the most important being iodine-131. In 1979, furthermore, a pressurised water reactor at Three Mile Island, Pennsylvania, suffered severe core damage, which resulted in the release of moderate quantities of gaseous radioactivity to the environment. Nobody was acutely injured in either case, but it must be assumed that each accident created a finite risk of harmful late effects in the population.

Hypothetical major accident

Although the same fission process occurs in a reactor as in a nuclear weapon, the conditions for an explosive nuclear reaction of comparable energy cannot exist. If, however, high enough temperatures were accidentally reached to melt the fuel, there would be some danger that thermal or chemical forces might breach or over-pressurise the other containments, thus causing the release to the atmosphere of substantial activities of gaseous and volatile fission products. Of particular concern would be the radioactive isotopes of the gases krypton and xenon, the radioactive isotopes of iodine, an element which is highly volatile, and the radioactive isotopes of the element caesium. Virtually all of these radionuclides emit beta particles and gamma rays.

Following an accidental release, the radioactivity would be dispersed from the power station in a spreading plume or cloud and in a manner determined by the characteristics of the release and the prevailing weather conditions. The potential consequences for public health of an accidental release would also depend on the distribution of population downwind from the station, and on the effectiveness of countermeasures such as evacuation. Since virtually all United Kingdom nuclear stations are on the coast, an off-shore wind could greatly reduce the consequences of an accident.

Direct exposure to a passing plume would cause external irradiation of the whole body and internal irradiation from inhaling radioactivity. Such exposure, if it occurred before the plume from a major accidental release had spread and been diluted sufficiently, might cause early deaths.

The gaseous radioactivity would continue to disperse and be diluted in the atmosphere, but some activity would be deposited on the ground. Fields, crops, roads and dwellings could become contaminated, and persons could be exposed in a multiplicity of ways.

The late health consequences of exposure could, in particularly adverse and serious circumstances, be large. The dominant effect would probably be non-fatal cancer of the thyroid. Iodine has a particular affinity for this gland, and the doses to it from the inhalation of iodine-131, in particular, and its ingestion in milk from cows on contaminated pasture, could lead to a high incidence of thyroid cancers. As noted in Chapter 5, mortality for thyroid cancer induced by radiation is low.

Contamination of land and property, particularly with caesium-137, might require a considerable amount of remedial action such as deep ploughing and decontamination of the surfaces of buildings. Considerable time might need to elapse before doses became sufficiently low for evacuees to return. The extent and cost of this disruption of social and economic life would depend on the magnitude of the release.

Designing against accidents

The foregoing description of a hypothetical major release of radioactivity underlines the necessity for the designers of nuclear reactors to analyse stringently

Factors to consider when judging risks from nuclear reactors

Safety record of nuclear power industry and manner of operation

Quality of engineering design and execution

Stringency of regulatory requirements and supervision

Adequacy of emergency plans and choice of site the faults that might arise during operation, and for the licensing authority, the Health and Safety Executive, to assess these analyses. Potential faults will range from those that might not cause any release of radioactivity to those that might cause releases ranging from the trivial to the major. Faults of varying severity will have various mathematical probabilities of occurring, and the designers must estimate these probabilities using theoretical and experimental data, and ensure that they are below the required levels.

The present approach of the Executive in licensing reactors is to require that they be designed and operated so that the probability of accidents is as remote as reasonably practicable. This requirement is in keeping with the second requirement of radiological protection. In assessing compliance, the Executive looks for design and operational features that progressively reduce the probability of increasingly severe accidents. Safety assessment principles for new reactors have been published by the Executive. They include numerical guidelines for accidents of lower severity, but for major accidents, the basic requirement is to be applied on a case-by-case basis. The assessed probability of a major accident clearly has to be extremely low to satisfy the expectations of society in this matter.

Emergency planning

Even if the probability of an accident is low, prudence demands that emergency plans be established for nuclear power stations.

Emergency plans are required by law and exist for each station in the United Kingdom. They depend on cooperative action between the licensee's staff and local authorities and emergency services. The administration of such plans is facilitated by organisations called Local Liaison Committees, with membership reflecting the local and county organisations that would be involved in protecting the population in the event of a serious accident. There would inevitably be involvement by central authorities in a serious emergency.

The essentials of such plans require an early assessment of the magnitude and nature of the release, its dispersion in the environment, and the doses that might arise. At various levels of dose, countermeasures might be employed such as requiring persons to stay indoors, issuing stable iodine tablets to protect the thyroid, the banning of local foodstuffs such as milk, and the evacuation of some areas.

Choosing a site

There are many social and technical factors affecting the choice of sites for reactor stations, one of the most important being safety. Prime considerations are the density of population in the neighbourhood and the ease with which evacuation could be effected in the event of an emergency.

Early reactors in the United Kingdom were located on remote sites, and there is still a cautious policy of locating new types of reactor remotely. Later thermal reactors have, however, been built on semi-urban sites that satisfy certain criteria employed by the Health and Safety Executive. Such criteria evolve continually, and at the time of writing, siting policy and its relationship to emergency planning is being reviewed.

Safety prospects

It is essential to the acceptability of the nuclear power programme that the probability of accidents involving a risk to public health be extremely low in absolute terms and in relation to the risks created by other industrial plant. There cannot, however, be absolute assurance of the safety of reactors, but risk can be reduced by ingenuity in design, thoroughness in prior fault analysis, caution in siting, care in construction, vigilance in operation, comprehensiveness in emergency planning, and rigour in licensing. In short, there must be a proper pursuit of engineering excellence and keen sensitivity to society's expectations on safety. On the part of society, it is a matter of deciding whether to depend on engineering skill and safeguards to achieve an acceptably low level of risk. Such dependence is not unique to nuclear engineering.

8 Radioactive wastes

Routine discharges of radioactivity to air and water as a result of the nuclear power programme are discussed in Chapter 4, and dose estimates are given. In this chapter, the management and disposal of other wastes that arise in the nuclear fuel cycle are discussed.

Nuclear fuel cycle

A chemical compound of uranium is imported from which fuel for thermal reactors is prepared. After a period in the reactor, the fuel is removed for reprocessing. At each of these stages, radioactive wastes are produced (Figure 9).

Plutonium and depleted uranium are recovered during reprocessing. Depleted uranium from the AGR programme may be recycled, and depleted uranium from Magnox reactors, with the plutonium, may be used in fast reactors. At the time of writing, all these materials are stored.

Waste categories

Low-level wastes
Contain various radionuclides with short half-lives and trace quantities of radionuclides with long half-lives.

Intermediate-level wastes
Contain larger quantities of fission products and actinides with long half-lives. Low heat content, high bulk.

High-level wastes
Contain most of the fission products and actinides from the fuel cycle. High heat content, low bulk.

Categories of waste

Radioactive wastes can be placed in three broad categories according to their activity content: low-level wastes, intermediate-level wastes, and high-level wastes.

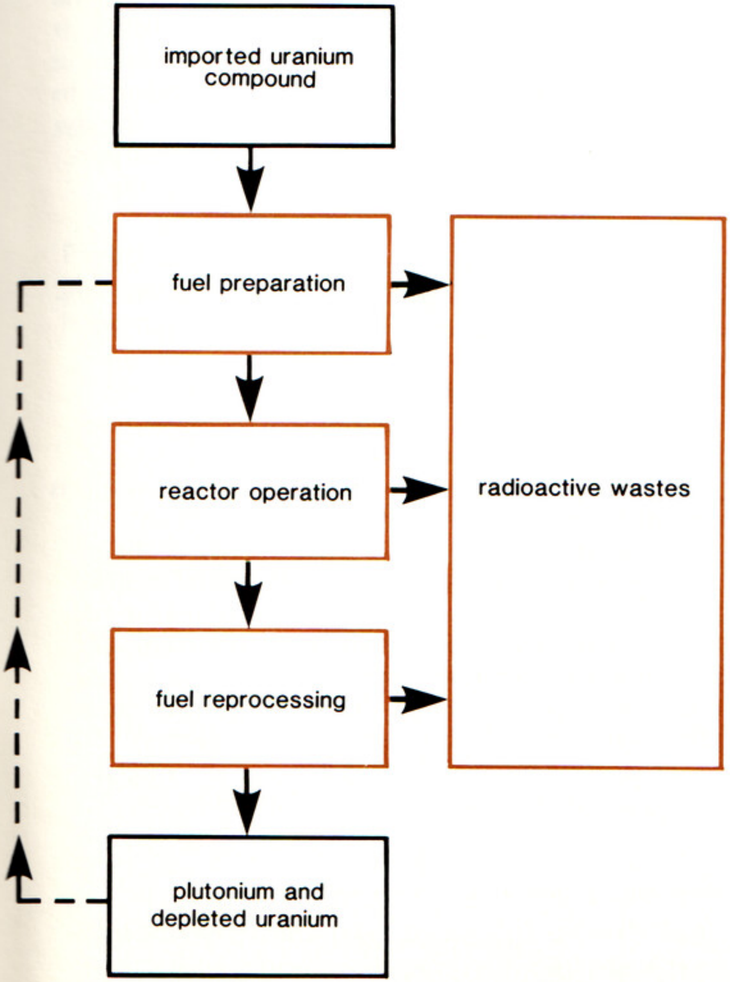


Figure 9: Simplified diagram of nuclear fuel cycle

Waste management

The objectives of *waste management* are to process the wastes in such a way that they are in a suitable form for storage and *disposal*, and to dispose of them so that there are no unacceptable risks to present and future generations. Disposal implies an absence of intent ever to retrieve the waste.

Different options are available for the *conditioning* and disposal of the various categories of waste. Low-level wastes do not generally need conditioning: they can be packaged and disposed of directly either by shallow land burial at certain locations in the United Kingdom or by dumping in a controlled manner at sea. As indicated in Chapter 4, the doses to the public from these procedures are negligible.

Most intermediate-level wastes and all high-level wastes are stored, at the time of writing, at the various nuclear sites. A large research programme is in progress to determine the best options for conditioning and disposal.

Intermediate-level wastes

Intermediate-level wastes could be conditioned by incorporation in such materials as concrete, bitumen, or plastic resins. Disposal options under consideration are sea-dumping and deep burial on land, the latter being called *geological disposal*. The volume of these wastes is large by comparison with that of high-level wastes, but their overall activity content is lower and their heat output is small. The technical problems of conditioning and disposal are therefore likely to be less than for high-level wastes, but their prospective volume may make it desirable to select an earlier management option for them. There could be over 60,000 m^3 of such wastes by the end of the century.

High-level liquid waste

The remainder of this chapter, however, deals with high-level waste, because it is the disposal of this category of waste which causes most general concern. The view is also held by many that if the feasibility and acceptability of disposing of these wastes can be established, the management options for intermediate-level wastes will become easier to select. The high-level liquid wastes that arise at the fuel reprocessing factory at Windscale, Cumbria, are used as an illustrative example.

Fuel from the reactor is initially very radioactive and consequently very hot. Many of the 300 or so radioactive fission products that are created have short half-lives, so the fuel is stored and cooled for a period at the power station to allow a substantial degree of decay to occur. It is then transported to the Windscale factory, where the cladding is removed by mechanical means, the fuel itself is dissolved in acid, and the solution is separated chemically into three main streams: uranium, plutonium, and liquid waste. The liquid waste contains virtually all the low-volatility fission products, most of the other actinides, and some unextracted uranium and plutonium. It is concentrated by partial evaporation and stored in tanks fitted with cooling coils.

This liquid is the most active waste in the nuclear fuel cycle, containing, as it does, over 95% of the activity. In 1976, there were about 700 m^3 in store in the United Kingdom with a total activity of about 1.5×10^{19} Bq, arising mainly from the reprocessing of fuel from Magnox reactors. By the year 2000, there may well be 5000 m^3 of such liquid containing 4×10^{20} Bq.

Solidification and storage

Although it is possible to store this liquid in relative safety, there is, as with all liquids, a danger of leakage. Solidification of the waste would make storage safer and would, in any case, be required for disposal. The method of solidifying waste that is at present being considered in the United Kingdom is vitrification, a process in which the waste is mixed with the ingredients to make Pyrex-like glass, which is then sealed in metal containers. The liquid waste that may arise by the year 2000 could eventually be incorporated in less than 2000 m^3 of glass, because of the reduction in volume that occurs in processing.

Such solid waste could be stored for centuries with appropriate cooling, supervision, and periodic renovation, but this imposition might be unacceptable to future generations. There would also be a risk, no matter how remote, that some natural or human event might disperse the activity. Furthermore, the half-lives of some of the radionuclides are so long that perpetual supervision would be required, and this cannot be assured. For example, in the century following reprocessing, the overall activity in the waste would decay merely by two orders of magnitude, in a thousand years by four orders of magnitude, and in ten thousand years by five orders of magnitude. Cooled storage for some tens of years would, in any event, be required to allow the heat output of the glass to decay to an acceptable level for disposal: 50 years after manufacture, for instance, 1 m^3 of glass would still be as powerful as a 3 kilowatt heater.

Disposal options

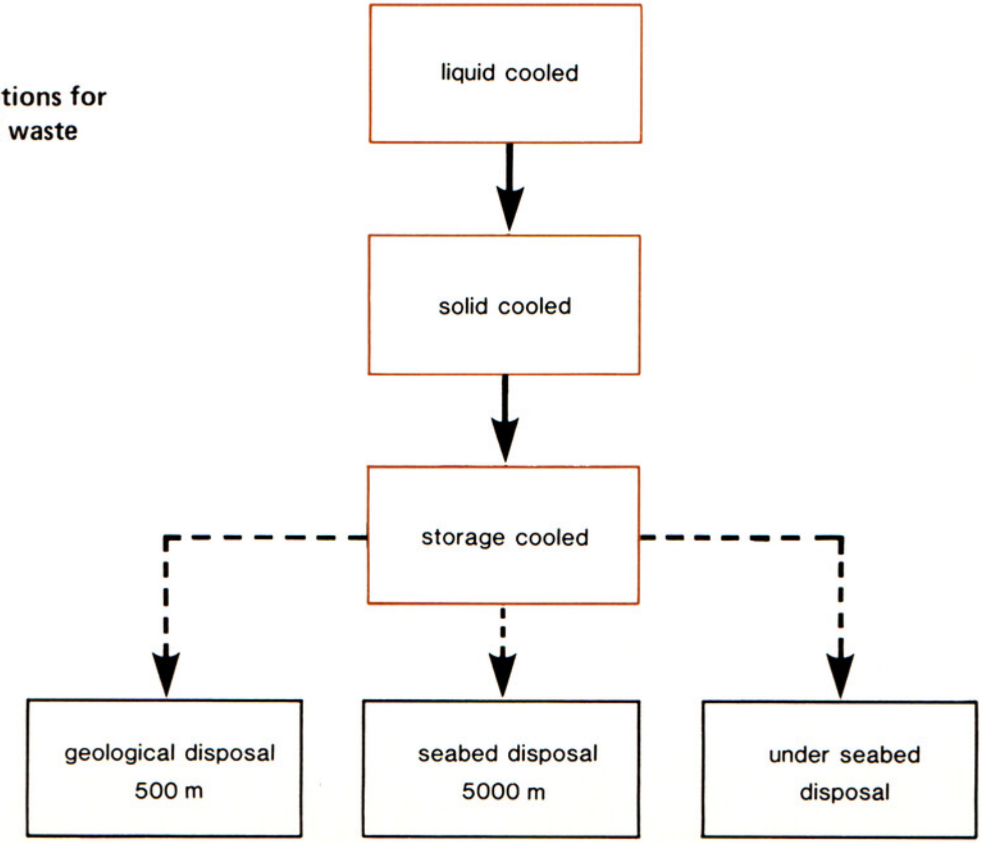
Three disposal options are being considered for high-level waste: geological disposal, disposal under the seabed, and disposal on the seabed. None of the research studies on these options has advanced to the stage where a choice can be made, and a decade or so may be necessary to determine the optimum solution. It would seem imprudent, however, to rule out any of these options at this stage (Figure 10).

A common characteristic of the studies is that they are based on predictive *modelling* of the probability that waste may return to man, and the consequences, in terms of dose, if it should. It is not possible, because of the nature of the problem, to demonstrate the adequacy of a disposal option in an experimental sense. The acceptability of a disposal option will therefore depend, among other things, on the adequacy of the modelling.

Geological disposal

As presently envisaged, an underground waste repository would be mined at a depth of about 500 m in rock. The containers would be placed in an array of holes so as to limit heating of the rock. The excava-

Figure 10: Management options for high-level liquid waste



tion would eventually be back-filled with selected materials.

Cataclysmic events, such as volcanic eruptions, that might return all the radioactivity to the surface of the earth at once, can be imagined, but they are extremely improbable. The main concern is about gradual dispersion that might extend over many years and later still cause human exposure. It would be necessary, also, to take into account the probability of geological and climatic changes and human actions that might hasten the dispersal.

If groundwater were never to reach the waste, containment would persist indefinitely. It must be assumed that water will, however, and the consequences need to be considered. Water would gradually corrode the container, leach the radioactive material out of the glass, and transport it away from the disposal site, where it would mix with uncontaminated water. However, various physical processes, collectively called *sorption,* would act to retard the transport of most radionuclides in geological media, that is, cause them to move more slowly than the groundwater.

Predictions are based on mathematical models of the release of the various radionuclides by the water, their transport through the groundwater system to the surface of the earth or the point of abstraction, their retardation by geochemical processes, and the radioactive decay that occurs meanwhile. The situation is complicated by the fact that some of the actinides, including the uranium isotopes, decay through series of radionuclides.

Geological disposal of vitrified waste: factors affecting return to man

Corrosion of container by groundwater
Leaching of radionuclides from glass
Gradual transport by water
Retardation and radioactive decay
Emergence or abstraction

The complexity of the problem is compounded by the lack of firm data on some of the physical processes that have to be described mathematically. A further complication is that some of the data are likely to be specific to a repository site. Nevertheless, early studies of a general nature, with reasonable assumptions in lieu of precise information, have shown that disposal deep underground may be feasible and need not be ruled out for reasons of radiological protection. What the early studies show most clearly, however, is that considerable research is still needed on many aspects of this disposal option.

Undersea disposal

Disposal under the deep seabed would involve the burial of containers in sediments on the floor of the Atlantic basin, where the average depth of water is about 5000 m. Shallow burial under tens of metres of sediment could be achieved by allowing the container to fall freely to the bottom: deep burial under several hundreds of metres would require drilling and back-filling.

Corrosion and leaching by the water in the sediments would gradually occur, and the activity would be transported through the sediments to the bottom water. The radionuclides are expected to be strongly sorbed by the sediments, thus delaying their movement, but considerable research is still needed on the properties of these sediments.

Disposal on the deep seabed in the same ocean area is the easiest option. It would obviate the need for

Undersea disposal of vitrified waste: factors affecting return to man

- Corrosion of container by seawater
- Leaching of radionuclides from glass
- Gradual dispersion in ocean
- Losses and radioactive decay
- Uptake by marine life

prior cooled storage. In this case, there would be a premium on prolonged integrity of the container, so as to delay the onset of leaching directly into the bottom water.

For both sea-disposal options, it is necessary to predict the radiological consequences of the gradual contamination of the seawater. Mathematical models are required to describe the dispersal of radioactivity from the disposal site, any losses that might occur apart from radioactive decay, and the uptake of radioactivity by marine organisms that might be harvested for human consumption. Considerable research is also needed on all these processes. Early studies on sea-disposal options suggest that they may be feasible and that neither need be ruled out for reasons of radiological protection.

Time scales and criteria

Over the next decade or so, the concentrated research effort should clarify and strengthen the analyses of the radiological implications of the various options for the disposal of high-level waste, which may extend beyond those mentioned above. Only when the uncertainties in the predictive models have been reduced to acceptable levels will it be possible to consider which particular option should be recommended.

The gradual nature of the return of radioactive material to man's immediate environment has also been mentioned. With underground disposal, for instance, a waste container might be designed to resist complete corrosion for a hundred years or more, complete leaching of the glass might take a thousand years or more, and radionuclides might variously take a hundred to several hundred thousand years to reach maximum concentrations in usable waters, depending on how weakly or strongly sorbed each was. Consequently, humans might receive doses from the repository over a period extending from a hundred to a million years later.

It is therefore necessary to develop criteria of acceptability that take account of these time scales. Such criteria will involve sociological as well as radiological considerations.

Social considerations

It is difficult to predict social conditions even in a hundred years' time. If history is a guide, there may well be advances in the control of malignant diseases in that period, so that the potential harmfulness of radiation would be reduced. There may, on the other hand, be more stringent standards for contamination, so that practices that are permitted today may not be acceptable then. Shifts in population may occur, diets may change, and living styles may alter, so that present estimates of dose become invalid. There may indeed be more uncertainty in modelling social conditions than in modelling the physical phenomena mentioned earlier.

The question for society is what weight to give now to a mathematical probability of harmful effects in the distant future. This problem is not peculiar to waste disposal, nor to radiological protection, although it is particularly pointed here. The most ethical answer may be to assume that present conditions persist and that harm to future generations is of equal importance as harm to this generation, but such a solution may not be sound for potential effects centuries and millenia from now.

Prospects for success

A considerable amount of research remains to be done before the long-term radiological consequences of waste disposal can be predicted with sufficient confidence for the best disposal option to be suggested. Society will also need to develop a moral view of the significance of potential harm at a distant time under unpredictable social circumstances. In the meantime, storage is not unacceptable, and haste is unnecessary. There is no reason to suppose, however, that an acceptable solution to the problem of waste disposal cannot be agreed before the end of the century.

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10 Glossary

Absorbed dose Quantity of *ionising radiation.* The amount of energy imparted to unit mass of matter such as tissue. Unit gray, symbol Gy. 1 Gy = 1 joule per kilogram.

Actinides A group of fifteen *elements* with *atomic number* from that of actinium (89) to lawrencium (103) inclusive. All are *radioactive.* Group includes uranium, plutonium, americium, curium.

Activity Quantity of a *radionuclide.* Describes the rate at which *decays* occur in an amount of a radionuclide. Unit becquerel, symbol Bq. One Bq corresponds to the decay of one radionuclide per second.

Advanced Gas-cooled Reactor (AGR) A development of the *Magnox reactor,* using *enriched uranium* oxide fuel in stainless steel containers.

AGR *Advanced gas-cooled reactor.*

Alpha particle A particle consisting of two *protons* plus two *neutrons.* Emitted by a *radionuclide.*

Atom The smallest portion of an *element* that can combine chemically with other atoms.

Atom bomb See *nuclear weapon.*

Atomic number The number of *protons* in the *nucleus* of an *atom.* Symbol Z.

Becquerel See *activity*

Beta particle A particle, emitted by a *radionuclide,* with mass and charge equal in magnitude to an *electron.* The electric charge may be positive, in which case, the beta particle is called a positron.

Collective dose Frequently used for *collective effective dose equivalent.*

Collective effective dose equivalent The quantity obtained by multiplying the average *effective dose equivalent* by the numbers of persons exposed to a given source of radiation. Expressed in man-sievert, symbol man-Sv. Frequently abbreviated to collective dose.

Conditioning In relation to *radioactive waste,* to bring into a proper and fit condition for storage or *disposal.*

Cosmic rays High-energy *ionising radiations* from outer space. Complex composition at the surface of the earth.

Decay The spontaneous transformation of a *radionuclide.* The decrease in the *activity* of a radioactive substance.

Decay product A *nuclide* or *radionuclide* produced by *decay.* It may be formed directly from a radionuclide or as a result of a series of successive decays through several radionuclides.

Depleted uranium Uranium in which the content of the isotope uranium-235 has been decreased. Refers to a decrease below the natural value of 0.7% by weight or to a decrease below the desired content in *enriched uranium.*

Disposal In relation to *radioactive waste,* dispersal or emplacement in any medium without the intention of retrieval.

DNA Deoxyribonucleic acid. The compound that controls the structure and function of cells and is the material of inheritance.

Dose General term for quantity of *radiation.* See *absorbed dose, dose equivalent, effective dose equivalent, collective effective dose equivalent.* Frequently used for effective dose equivalent.

Dose equivalent The quantity obtained by multiplying the *absorbed dose* by a factor to allow for the different effectiveness of the various ionising radiations in causing harm to tissue. Unit sievert, symbol Sv. The factor for gamma rays, X-rays, and beta particles is 1, for neutrons 10, and for alpha particles 20.

Effective dose equivalent The quantity obtained by multiplying the *dose equivalents* to various tissues and organs by the risk weighting factor appropriate to each and summing the products. Expressed in sieverts, symbol Sv. Risk weighting factors are tabulated in Chapter 2. Frequently abbreviated to dose.

Electrical interaction A force of repulsion acting between electric charges of like sign and a force of attraction acting between electric charges of unlike sign.

Electron An elementary particle with low mass, 1/1836 that of a *proton,* and unit negative electric charge. Positively-charged electrons, called positrons, also exist. See *beta particle.*

Electron volt Unit of energy employed in radiation physics. Equivalent to the energy gained by an electron in passing through a potential difference of 1 volt. Symbol eV. 1 eV = 1.6×10^{-19} joule approximately.

Element A substance with *atoms* all of the same *atomic number.*

Enriched uranium Uranium in which the content of the isotope uranium-235 has been increased above its natural value of 0.7% by weight.

Excitation A process by which *radiation* imparts energy to an *atom* or *molecule* without causing *ionisation.* Dissipated as heat in tissue.

Fallout The transfer of *radionuclides* produced by *nuclear weapons* from the atmosphere to earth. The material transferred.

Fast neutrons Conventionally, *neutrons* with energies in excess of 0.1 MeV. Corresponding velocity about 4×10^6 m s^{-1}.

Fast reactors See *nuclear reactor.*

Fission Nuclear fission. A process in which a *nucleus* splits into two or more nuclei and energy is released. Frequently refers to the splitting of a nucleus of uranium-235 into two approximately equal parts by a *thermal neutron* with emission of other *neutrons.*

Fission products *Nuclides* or *radionuclides* produced as a result of *fission.*

Free radical A grouping of *atoms* that normally exists in combination with other atoms, but can sometimes exist independently. Generally very reactive in a chemical sense.

Fusion Thermonuclear fusion. A process in which two or more light *nuclei* are formed into a heavier nucleus and energy is released.

Gamma ray A discrete quantity of energy, without mass or charge, that is propagated as a wave. Emitted by a *radionuclide.* See *X-ray.*

Geiger tube A glass or metal envelope containing a gas at low pressure and two electrodes. *Ionising radiation* causes discharges, which are registered as electric pulses in a counter. The number of pulses is related to *dose.*

Genetically significant dose The dose that, if given to every member of a population, would produce the same genetic (hereditary) harm as the actual doses received by the various individuals. Expressed in sievert, symbol Sv, the unit of *dose equivalent.*

Geological disposal In relation to *radioactive waste,* disposal deep underground.

Gonads Ovaries and testes.

Gray See *absorbed dose.*

Half-life The time taken for the *activity* of a *radionuclide* to lose half its value by *decay.* Symbol $t_{1/2}$.

Incidence The degree of occurrence of an effect or an event.

Ion Electrically charged *atom* or grouping of atoms.

Ionisation The process by which a neutral *atom* or *molecule* acquires an electric charge. The production of *ions.*

Ionising radiation *Radiation* that produces *ionisation* in matter. Examples are *alpha particles, beta particles, gamma rays, X-rays,* and *neutrons.*

Isotope *Nuclides* with the same number of *protons* but different numbers of *neutrons.* Not a synonym for nuclide.

Magnox reactor A *thermal reactor* named after the magnesium alloy in which the uranium metal fuel is contained. The *moderator* is graphite and the coolant carbon dioxide gas.

Man-sievert See *collective effective dose equivalent.*

Mass number The number of *protons* plus *neutrons* in the *nucleus* of an *atom.* Symbol A.

Modelling In relation to the *disposal* of *radioactive waste,* describing in quantitative terms the physical processes that influence the movement of *radionuclides* through a medium.

Moderator A material used in *nuclear reactors* to reduce the energy and speed of the *neutrons* produced as a result of *fission.*

Molecule The smallest portion of a substance that can exist by itself and retain the properties of the substance.

Mutation A chemical change in the *DNA* in the *nucleus of a cell.* Mutations in sperm or egg cells or their precursors may lead to inherited effects in children. Mutations in body cells may lead to effects in the individual.

Neutron An elementary particle with unit atomic mass approximately and no electric charge.

Nuclear power Power obtained from the operation of a *nuclear reactor.* Refers in the text to electric power.

Nuclear power industry The industry associated with the production of *nuclear power.* In the United Kingdom, the preparation of fuel for *nuclear reactors,* the operation of reactors, the subsequent reprocessing of the fuel, and the disposal of *radioactive wastes.*

Nuclear reactor A device in which nuclear *fission* may be sustained in a self-supporting chain reaction involving *neutrons.* In thermal reactors, fission is brought about by *thermal neutrons,* in fast reactors by *fast neutrons.*

Nuclear weapon Explosive device deriving its power from the *fission* or *fusion* of *nuclei* or from both.

Nucleus The core of an *atom,* occupying little of the volume, containing most of the mass, and bearing positive electric charge.

Nucleus of cell The kernel of the basic unit of tissue. Contains the important material *DNA.*

Nuclide A species of *atom* characterised by the number of *protons* and *neutrons* and, in some cases, by the energy state of the *nucleus.*

Order of magnitude Quantity given to the nearest power of ten.

Photographic film Film with emulsion sensitive to *ionising radiation.* The degree of blackening is related to *dose.*

Pressurised Water Reactor (PWR) A *thermal reactor* using water both as a *moderator* and coolant. Uses *enriched uranium* oxide fuel.

Probability The mathematical chance that a given event will occur.

Proton An elementary particle with unit atomic mass approximately and unit positive electric charge.

PWR *Pressurised water reactor.*

Radiation The process of emitting energy as waves or particles. The energy thus radiated. Frequently used for *ionising radiation* in the text.

Radioactive Possessing *radioactivity.*

Radioactive waste Useless material containing *radionuclides.* Frequently categorised, in the *nuclear power industry,* according to *activity* content and other criteria given in Chapter 8, as low-level, intermediate-level, and high-level waste.

Radioactivity The property of *radionuclides* of spontaneously emitting *ionising radiation.* By extension, materials containing radionuclides.

Radiobiology The study of the effects of *ionising radiation* on living things.

Radiological protection The science and practice of limiting the harm to humans from *radiation.*

Radionuclide An unstable *nuclide* that emits *ionising radiation.*

Risk The *probability* of injury, harm, or damage.

Risk factor The *probability* of cancer and leukaemia or hereditary damage per unit *dose equivalent.* Usually refers to fatal malignant diseases and serious hereditary damage. Symbol Sv^{-1}.

Scintillation counter A device containing material that emits light flashes when exposed to *ionising radiation.* The flashes are converted to electric pulses and counted. The number of pulses is related to *dose.*

Sievert See *effective dose equivalent.*

Sorption In relation to the transport of *radionuclides* by groundwater through rock and soil, processes such as adsorption, ion exchange, precipitation, colloidal filtration, and mineralisation.

Thermal neutrons *Neutrons* that have been slowed to the degree that they have the same average thermal energy as the *atoms* or *molecules* through which they are passing. The average energy of neutrons at ordinary temperatures is about 0.025 eV, corresponding to an average velocity of 2.2×10^3 m s^{-1}.

Thermal reactors See *nuclear reactor.*

Waste management The control of *radioactive waste* from creation to *disposal.*

X-ray A discrete quantity of energy, without mass or charge, that is propagated as a wave. Emitted by an X-ray machine. See *gamma ray.*

11 Appendix I

Scientific notation

Because of the magnitude of the numbers encountered in radiological protection, it is often more convenient to express them in scientific rather than decimal notation. This involves the use of significant figures within desired limits and multiplication by the appropriate power to 10. Examples follow.

Converting decimal to scientific notation

Decimal	*Scientific*
1,230,000	1.23×10^6
100,000	10^5
3531	3.53×10^3 *
15.6	1.56×10^1
0.239	2.4×10^{-1} **
0.001	10^{-3}
0.000 087	8.7×10^{-5}

*To 3 significant figures **To 2 significant figures

Prefixes

Some powers of 10 have special names and symbols. These may be prefixed to units of measurement: thus *kilo*gram, symbol *k*g, for 10^3 gram; *milli*metre, symbol *m*m, for 10^{-3} metre. A table of prefixes follows.

Table of prefixes

Multiplier	*Prefix*	*Symbol*	*Multiplier*	*Prefix*	*Symbol*
10^1	deca	da	10^{-1}	deci	d
10^2	hecto	h	10^{-2}	centi	c
10^3	kilo	k	10^{-3}	milli	m
10^6	mega	M	10^{-6}	micro	μ
10^9	giga	G	10^{-9}	nano	n
10^{12}	tera	T	10^{-12}	pico	p
10^{15}	peta	P	10^{-15}	femto	f
10^{18}	exa	E	10^{-18}	atto	a

Symbols

Symbols are used extensively in radiological protection. The elements are usually represented by symbols, for example, C for carbon, Ba for barium, and Pb for lead. It is customary to indicate the mass number and atomic number of a particular nuclide by a superscript and subscript thus: carbon-14 by $^{14}_{6}\mathrm{C}$, barium-140 by $^{140}_{56}\mathrm{Ba}$, lead-210 by $^{210}_{82}\mathrm{Pb}$. The atomic number is frequently omitted.

A table of common symbols follows. When the symbol for a unit is shown with a superscript of −1 on its right, it signifies that the quantity is being used in a fractional context or to represent rate. Thus Sv^{-1} means per sievert, and $\mathrm{Sv\ h}^{-1}$ means sievert per hour.

Table of common symbols in radiological protection

Symbol	*Term*	*Symbol*	*Term*
α	alpha particle	A	mass number
β	beta particle	eV	electron volt
γ	gamma ray	Bq	becquerel
e	electron	Gy	gray
p	proton	Sv	sievert
n	neutron	man-Sv	man-sievert
Z	atomic number	$t_{1/2}$	half-life

See the GLOSSARY for radiological terms and APPENDIX II for the symbols for old radiation units.

12 Appendix II

Relationship between old and new radiation units

Quantity	*Old unit*	*Symbol*	*New unit*	*Symbol*	*Relationship*
Activity	curie	Ci	becquerel	Bq	1 Ci = 3.7×10^{10} Bq
Absorbed dose	rad	rad	gray	Gy	1 rad = 0.01 Gy
Dose equivalent	rem	rem	sievert	Sv	1 rem = 0.01 Sv

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