IAEA

International Atomic Energy Agency

Radiation, People and the Environment

RADIATION, PEOPLE AND THE ENVIRONMENT

... a broad overview of ionizing radiation,
its effects and uses,
as well as the measures in place
to use it safely

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CONTENTS

Chapter 1 Introduction

Radiation is a fact of life. We live in a world in which radiation is naturally present everywhere. Light and heat from nuclear reactions in the Sun are essential to our existence. Radioactive materials occur naturally throughout the environment, and our bodies contain radioactive materials such as carbon-14, potassium-40 and polonium-210 quite naturally. All life on Earth has evolved in the presence of this radiation.

Since the discovery of X rays and radioactivity more than 100 years ago, we have found ways of producing radiation and radioactive materials artificially. The first use of X rays was in medical diagnosis, within six months of their discovery in 1895. So a benefit from the use of radiation was established very early on, but equally some of the potential dangers of radiation became apparent in the doctors and surgeons who unwittingly overexposed themselves to X rays in the early 1900s. Since then, many different applications of radiation and radioactive materials have been developed.

We can classify radiation according to the effects it produces on matter, into ionizing and non-ionizing radiation. *Ionizing radiation* includes cosmic rays, X rays and the radiation from radioactive materials. *Non-ionizing radiation* includes ultraviolet light, radiant heat, radio waves and microwaves.

This book deals with ionizing radiation, a term, which for simplicity, is often shortened to just radiation. It has been prepared by the International Atomic Energy Agency (IAEA) in co-operation with the National Radiological Protection Board (United Kingdom) as a broad overview of the subject of ionizing radiation, its effects and uses, as well as the measures in place to use it safely.

As the United Nations agency for nuclear science and its peaceful applications, the IAEA offers a broad spectrum of expertise and programmes to foster the safe use of radiation internationally. It has a statutory responsibility for the development of safety standards that are applicable to managing the wide variety of applications that use radiation. It provides assistance to its Member States on the application of those standards through technical co-operation projects such as training courses and advisory services. It also facilitates information exchange through conferences, and publications, such as this one.

Some uses of ionizing radiation

Medical diagnosis and treatment

Nuclear power

Industrial radiography

Sterilization of medical equipment

Food irradiation

Satellite batteries

Scientific and medical research

Benefits and risks

The benefits and risks of any practice involving radiation need to be established, so that an informed judgement can be made on their use, and any risks minimized. The discovery of ionizing radiation and radioactive materials has led to dramatic advances in medical diagnosis and treatment, and they are used for a wide range of procedures in industry, agriculture, and research. Nevertheless, they can be harmful to human beings, and people must be protected from unnecessary or excessive exposures. So in circumstances that we can control, we need to make a careful balance between the benefits and the risks of the procedures that expose people to radiation.

Public anxiety

The greatest concern about ionizing radiation stems from its potential to cause malignant diseases in people exposed to it and inherited defects in later generations. The likelihood of such effects depends on the amount of radiation that a person receives, whether from a natural or an artificial source. As the effects of ionizing radiation have become better understood during recent decades, a system of radiological protection has been developed to protect people from exposure to sources of radiation. But public anxiety remains.

Radiation is one cause, among many, of the 'dread disease' cancer. Our senses cannot detect radiation, making this invisible risk seem even more insidious. Our collective anxiety is strengthened by memories — and, in some cases, ongoing effects — of accidents at nuclear power plants and other facilities, and by the common tendency to associate any form of radiation with all things 'nuclear', including nuclear weapons.

Another contributory reason for general heightened sense of concern about radiation may be the lack of reliable and accessible information and the misunderstandings that arise. The aim of this book is to help by providing information for those who are not experts. In the following chapters, we describe the sources and effects of ionizing radiation of all types and explain the principles and practices of radiological protection.

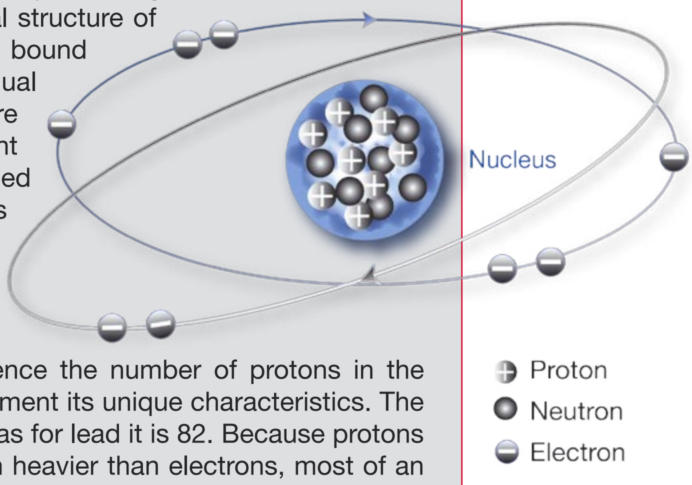
Chapter 2 Atoms and radiation

Structure of matter

All matter in the world about us consists of *atoms*. These are the basic building blocks of the *elements* such as hydrogen, carbon, oxygen, iron, and lead. Each atom contains a tiny central positively charged *nucleus* and a number of *electrons*. The electrons carry negative electric charge and move around the nucleus in clouds — or shells as they are called — with loosely defined boundaries. The nucleus is typically 10 000 times smaller than the electron clouds and the electrons themselves are even smaller. This means that the atom is mainly empty and difficult to depict except in diagrams, which are largely schematic.

The oxygen atom planetary presentation with a nucleus of 8 protons and 8 neutrons within 8 orbital electrons

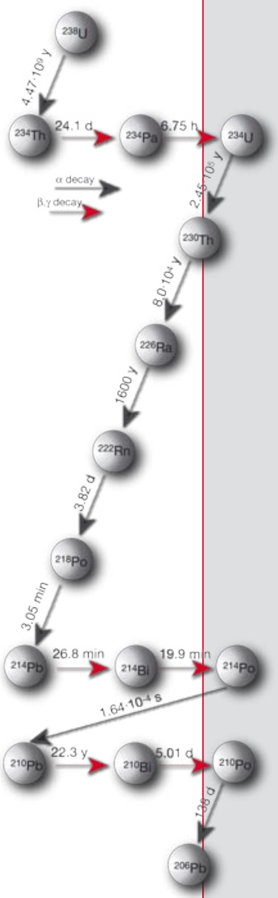
The nucleus of the atom contains *protons*, which carry a positive charge equal to the electron's negative charge, and *neutrons*, which carry no charge at all. It is not necessary here to consider the more fundamental structure of protons and neutrons, or how in detail they are bound together in the nucleus. Each atom contains equal numbers of protons and electrons and is therefore electrically neutral. Atoms of the same or different elements can, combine to form larger, uncharged entities called *molecules*. For example, two atoms of oxygen form one molecule of oxygen, and two atoms of hydrogen combine with one atom of oxygen to form one molecule of water.



Nucleus = Protons + neutrons

The number of electrons in the atom — and hence the number of protons in the nucleus, called the *atomic number* — gives an element its unique characteristics. The atomic number of carbon is 6, for instance, whereas for lead it is 82. Because protons and neutrons have the same mass, and are much heavier than electrons, most of an atom's mass is concentrated in the nucleus, and the total number of protons plus neutrons is called the *mass number*.

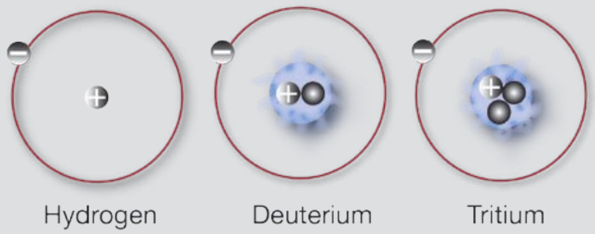
Since the number of electrons equals the number of protons in an electrically neutral atom, we can specify an atomic species by the number of protons and neutrons it contains. Moreover, since the number of protons is unique to each element, we can simply use



Decay of radionuclides: different types of radiation and half-lives for uranium-238 series

the name of the element together with the mass number to specify each species or *nuclide*. So carbon-12 is a nuclide with six protons plus six neutrons. Lead-208, for comparison, is a nuclide with 82 protons and 126 neutrons.

Nuclides of an element that have the same number of protons, but different numbers of neutrons, are called *isotopes* of that element. Hydrogen, for instance, has three isotopes: hydrogen-1 (common hydrogen with a nucleus of only one proton), hydrogen-2 called deuterium (one proton and one neutron), and hydrogen-3 called tritium (one proton and two neutrons). Iron has ten isotopes from iron-52 to iron-61, all with the 26 protons that characterize the element, but with 26 to 35 neutrons.



Isotopes of hydrogen

Nucleus = Protons + neutrons

Radioactivity and radiation

Although many nuclides are stable, most are not. Stability is determined mainly by the balance between the number of neutrons and protons a nuclide contains. Smaller stable nuclei have about equal numbers: larger stable nuclei have slightly more neutrons than protons. Nuclei with too many neutrons tend to transform themselves to a more stable structure by converting a neutron to a proton: this process, known as beta decay, results in the emission of a negatively charged electron called a *beta particle*. Nuclei with too many protons convert the excess protons to neutrons in a different form of beta decay: they lose positive charge through the emission of a *positron*, which is a positively charged electron.

These transformations often leave the nucleus with excess energy that it loses as *gamma rays* — high energy *photons*, which are discrete parcels of energy without mass or charge. The spontaneous transformation of a nucleus is called *radioactivity,* and the excess energy emitted is a form of (ionizing) radiation. The act of transformation is termed *decay* and the nuclide that changes and emits radiation is called a *radionuclide*.

Some heavy nuclei decay by producing an *alpha particle* consisting of two protons and two neutrons. Identical with a nucleus of helium, the alpha particle is much heavier than the beta particle and carries two units of positive charge.

Natural Radionuclides

Many radionuclides occur in nature. Carbon, for instance, is mostly in the form of carbon-12 with six protons and six neutrons and is completely stable. Interactions with cosmic rays in the atmosphere can produce carbon-14, a radionuclide consisting of six protons and eight neutrons. Carbon-14, with its extra neutrons, decays by changing a neutron to a proton and emitting a beta particle: in this way, the nuclide transforms to stable nitrogen-14, which consists of seven protons and seven neutrons. Measuring these decays in carbon-bearing materials is the basis of the technique of carbon dating.

Other naturally occurring radionuclides are formed in sequences or series of decays that originate from the elements uranium and thorium. Each of these series ends with a stable nuclide of lead, but they also pass through radionuclides of other familiar elements. The diagram shows the decay series from uranium-238 ending in the stable nuclide lead-206: it passes through the radionuclide radon-222, which is of special significance in radiological protection.

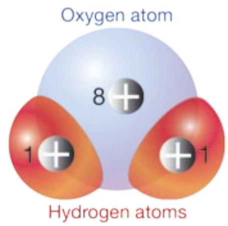
Radionuclides	*Unstable nuclides*
Radioactivity	*Emission of radiation*
Radiation types	*Alpha, beta, gamma, neutron, and X ray*
Activity	*Decay rate of radionuclide*
Half-life	*Time to half activity*

Radiation Energy

The energy of the various types of radiation — alpha and beta particles and gamma rays — is usually expressed in the unit of electron volt, symbol eV. Multiples of this unit are often used, such as a million or 10^6 electron volts, symbol MeV. For instance, the energy of alpha particles emitted by polonium-214 is about 7.7 MeV. Beta particles from lead-214, also formed in the uranium-238 decay series, have a maximum energy of 1.0 MeV, and gamma rays produced by it have energies up to 0.35 MeV.

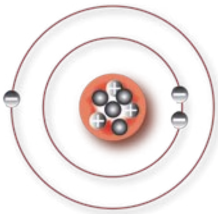
During the past few decades, several hundred radioactive isotopes (radioisotopes) of natural elements have been produced artificially including, for example, strontium-90, caesium-137 and iodine-131. Several new radioactive elements have also been produced in quantity, for instance promethium and plutonium, although the latter does occur naturally in trace amounts in uranium ores.

Molecule =
Combined atoms



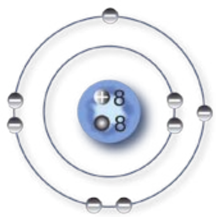
Water molecule

Atom =
Nucleus + electrons



Lithium-7
(radioactive)

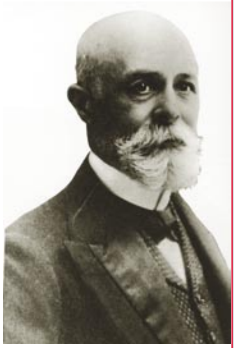
Nuclide =
Species of atom



Oxygen atom

Proton
Neutron
Electron

Marie Curie
(1867–1934)

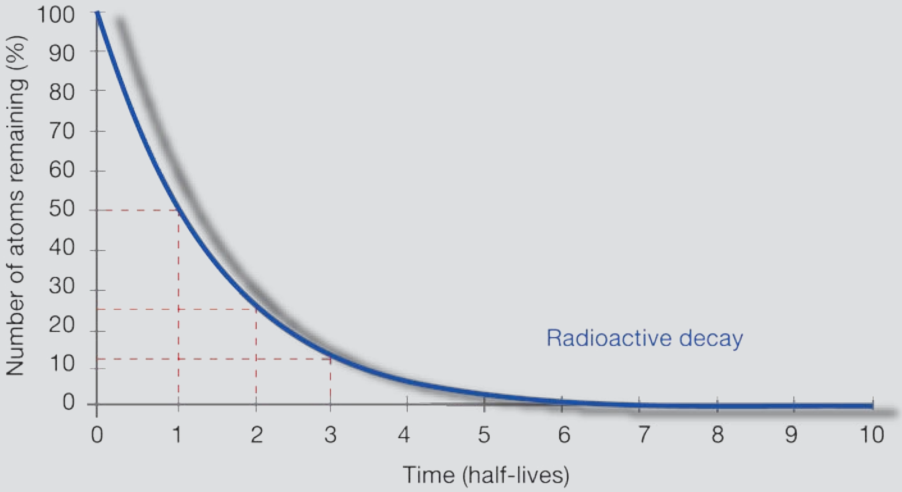


Henri Becquerel
(1852–1908)

The rate at which spontaneous transformations occur in a given amount of a radioactive material is known as its *activity*. Activity is expressed in a unit called the *becquerel*, symbol Bq, where 1 Bq equals one transformation per second. The becquerel is named after the French physicist Henri Becquerel. As the unit is so small, multiples of the becquerel are frequently used, such as the megabecquerel, MBq, which is 1 million becquerels. One gram of radium-226, for instance, has an activity of approximately 37 000 MBq: it emits about 37 000 million alpha particles each second (an old unit of activity, the curie — named after the Polish-born French scientist Marie Curie — was originally defined as the activity of one gram of radium).

Half lives

The time taken for the activity of a radionuclide to fall to half its original value is called the *half-life*, symbol $t_{1/2}$. Put another way, this is the time for half the nuclei in a sample to decay. Each radionuclide has a unique half-life, which can range from fractions of a second to billions of years. For iodine-131, it is 8 days; caesium-137, 30 years; carbon-14, 5730 years; plutonium-239, 24 000 years; and uranium-238, 4470 million years. In successive half-lives, the activity of a radionuclide is reduced by decay to ½, ¼, 1/8 and so on, of its initial value. This means that we can predict the activity remaining at any future time. As the amount of a radionuclide decreases, the radiation emitted decreases proportionately.

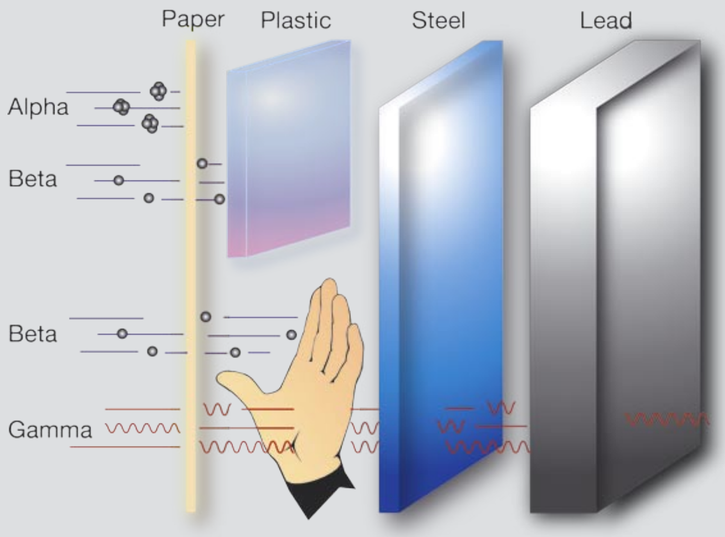


Types of radiation

Most of the common types of radiation come from radioactive materials, but some types of radiation are produced in other ways. The most important example is that of X rays that are normally produced by firing a beam of electrons at a metal target (usually tungsten). The electrons in the metal atoms absorb energy from the electron beam — in scientific terms, the metal atoms become 'excited' — and then release the energy in the form of X rays as they 'relax'. The radiation, therefore, comes from the metal atoms but, unlike radioactivity, it is not from the nucleus. Because of how they are produced, there is no half-life for an X ray. Once the beam is switched off, the X rays disappear.

Alpha radiation (α) is a positively charged helium nucleus emitted by a larger unstable nucleus. It is a relatively massive particle, but it only has a short range in air (1–2 cm) and can be absorbed completely by paper or skin. Alpha radiation can, however, be hazardous if it enters the body by inhalation or ingestion, because large exposures can result in nearby tissues, such as the lining of the lung or stomach.

Beta radiation (β) is an electron emitted by an unstable nucleus. Beta particles are much smaller than alpha particles and can penetrate further into materials or tissue. Beta radiation can be absorbed completely by sheets of plastic, glass, or metal. It does not normally penetrate beyond the top layer of skin. However large exposures to high-energy beta emitters can cause skin burns. Such emitters can also be hazardous if inhaled or ingested.



Gamma radiation (γ) is a very high energy photon (a form of electromagnetic radiation like light) emitted from an unstable nucleus that is often emitting a beta particle at the same time. Gamma radiation causes ionization in atoms when it passes through matter, primarily due to interactions with electrons. It can be very penetrating and only a substantial thickness of dense materials such steel or lead can provide good shielding. Gamma radiation can therefore deliver significant doses to internal organs without inhalation or ingestion.

X rays are high-energy photons, like gamma radiation, and are produced artificially by the rapid slowing down of an electron beam. X rays are similarly penetrating and, in the absence of shielding by dense materials, can deliver significant doses to internal organs.

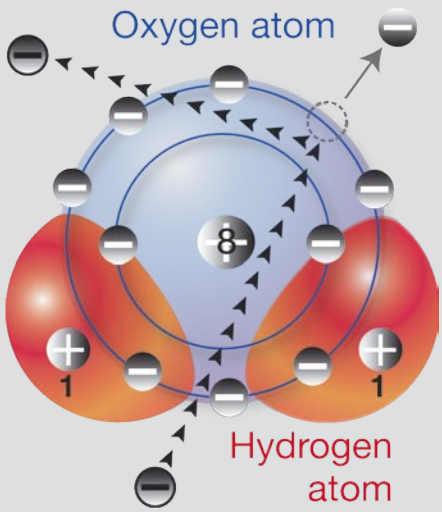
Neutron radiation (n) is a neutron emitted by an unstable nucleus, in particular during atomic fission and nuclear fusion. Apart from a component in cosmic rays, neutrons are usually produced artificially. Because they are electrically neutral particles, neutrons can be very penetrating and when they interact with matter or tissue, they cause the emission of beta and gamma radiation. Neutron radiation therefore requires heavy shielding to reduce exposures.

Cosmic radiation comes from deep space. It is a mixture of many different types of radiation, including protons, alpha particles, electrons and other various exotic (high energy) particles. All these energetic particles interact strongly with the atmosphere and, as a result, cosmic radiation at ground level becomes primarily muons, neutrons, electrons, positrons and photons. Most of the dose at ground level comes from muons and electrons.

Chapter 3 Radiation and matter

When radiation passes through matter, it deposits energy in the material concerned. Alpha and beta particles, being electrically charged, deposit energy through *electrical interactions* with electrons in the material. Gamma rays and X rays lose energy in a variety of ways, but each involves liberating atomic (orbiting) electrons, which then deposit energy in interactions with other electrons. Neutrons also lose energy in various ways, the most important being through collisions with nuclei that contain protons. The protons are then set in motion and, being charged, they again deposit energy through electrical interactions. So in all cases, the radiation ultimately produces electrical interactions in the material.

In some cases, an electron in the material may receive enough energy to escape from an atom leaving the atom or molecule thus formed positively charged. The figure illustrates this process for a molecule of water. The molecule has ten protons and ten electrons altogether, but only nine atomic electrons remain after a charged particle passes by; the molecule as a whole is left with one excess positive charge.



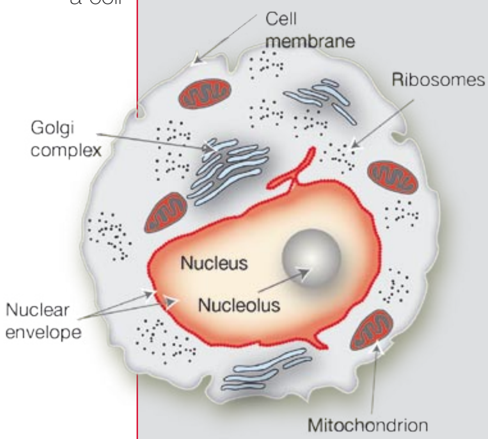
Ionization of a water molecule by a charged particle

The process by which a neutral atom or molecule becomes charged is called *ionization* and the resulting entity an *ion*. Once removed from an atom, an electron may in turn ionize other atoms or molecules. Any radiation that causes *ionization* — either directly, as with alpha and beta particles or indirectly as with gamma rays, X rays, and neutrons — is known as ionizing radiation. Charged particles passing through atoms may also give energy to the atomic electrons without actually removing them; this process is called *excitation.*

Ionization in tissue

Each time a charged particle ionizes or excites an atom, it loses energy until it no longer has enough energy to interact; the final result of these energy losses is a minute rise in the temperature of the material of which the atom is a part. In this way, all the energy deposited in biological tissues by ionizing radiation is eventually dissipated as heat through increased vibrations of the atomic and molecular structures. It is the initial ionization and the resulting chemical changes that cause harmful biological effects.

Diagram of a cell



The basic unit of biological tissue is the cell, which has a control centre called the nucleus. The *nucleus of a cell* is an intricate structure and not to be confused with the nucleus of an atom. About 80 per cent of the cell consists of water, the other 20 per cent being complex biological compounds. When ionizing radiation passes though cellular tissue, it produces charged water molecules. These break up into entities called *free radicals*, such as the free hydroxyl radical (OH), which is composed of an oxygen atom and a hydrogen atom. Free radicals are highly reactive chemically and can alter important molecules in the cell.

One particularly important molecule is deoxyribonucleic acid, *DNA*, found mainly in the nucleus of the cell. DNA controls the structure and function of the cell and passes on copies of itself: its molecules are large and the structures that carry them, *chromosomes*, are visible through the microscope. We still do not fully understand all the ways in which radiation damages cells, but many involve changes to the DNA. There are two ways in which this can happen. Radiation may ionize a DNA molecule leading directly to a chemical change, or the DNA may be changed indirectly when it interacts with a free hydroxyl radical produced in the water of the cell by the radiation. In either case, the chemical change can cause a harmful biological effect leading to the development of cancers or inherited genetic defects. Chapter 5 has more detail on radiation effects.

Diagram of DNA

Ionizing radiation and tissue

Charged particles
↓
Electrical interactions
↓
Ionization occurs
↓
Chemical changes
↓
Biological effects

A most important property of the various types of ionizing radiation is their ability to penetrate matter. The depth of penetration for a particular type of radiation increases with its energy, but varies from one type of radiation to another for the same amount of energy. With charged particles such as alpha and beta particles, the depth of penetration also depends on the mass of the particle and its charge. For equal energies, a beta particle will penetrate to a much greater depth than an alpha particle. Alpha particles can scarcely penetrate the dead, outer layer of human skin; consequently, radionuclides that emit them are not hazardous unless they are taken into the body through breathing or eating or through a skin wound. Beta particles penetrate about a centimetre of tissue, so radionuclides that emit them are hazardous to superficial tissues, but not to internal organs unless they too are taken into the body. For indirectly ionizing radiation, such as gamma rays and neutrons, the degree of penetration depends on the nature of their interactions with tissue. Gamma rays can pass through the body, so radionuclides that emit them may be hazardous whether on the outside or the inside. X rays and neutrons can also pass through the body.

Dose quantities

We cannot detect ionizing radiation directly through our senses, but we can detect and measure it by other means: these include established methods based on *photographic films, geiger–müller tubes*, and *scintillation counters*, as well as newer techniques using *thermoluminescent materials* and *silicon diodes*. We can interpret the measurements we make in terms of the energy that the radiation concerned would have deposited throughout the human body or in a particular part of the body. When direct measurements are not possible — when, for instance, a radionuclide is deposited in an internal organ — we can calculate the dose absorbed by that organ provided that we know the amount of activity retained in the organ.

The amount of energy that ionizing radiation deposits in a unit mass of matter, such as human tissue, is called the *absorbed dose*. It is expressed in a unit called the *gray,* symbol Gy, where 1 gray is equal to 1 joule per kilogram. Submultiples of the gray are often used, such as the milligray, mGy, which is one-thousandth of a gray. The gray is named after the English physicist Harold Gray (*pictured on page 13*).

Types of ionizing radiation differ in the way in which they interact with biological materials, so that equal absorbed doses (meaning equal amounts of energy deposited) do not necessarily have equal biological effects. For instance, 1 Gy to tissue from alpha radiation is more harmful than 1 Gy from beta radiation because an alpha particle, being slower and more heavily charged, loses its energy much more densely along its path. So in order to put all the different types of ionizing radiation on an equal basis with respect to their potential for causing harm, we need another quantity. This is the *equivalent dose*. It is expressed in a unit called the *sievert*, symbol Sv. Submultiples of the sievert are commonly used, such as the millisievert, mSv, which is one-thousandth of a sievert. The sievert is named after the Swedish physicist Rolf Sievert (*pictured on page 13*).

Equivalent dose is equal to the absorbed dose multiplied by a factor that takes into account the way in which a particular type of radiation distributes energy in tissue so that we can allow for its relative effectiveness to cause biological harm. For gamma rays, X rays, and beta particles, this radiation-weighting factor is set at 1, so the absorbed dose and equivalent dose are numerically equal. For alpha particles, the factor is set at 20, so that the equivalent dose is deemed to be 20 times the absorbed dose. Values of the radiation weighting factor for neutrons of various energies range from 5 to 20.

Hierarchy of dose quantities

Absorbed dose
Energy imparted by radiation to unit mass of tissue

↓

Equivalent dose
Absorbed dose weighted for the harm of different types of radiation

↓

Effective dose
Equivalent dose weighted for the harm to different tissues

↓

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

Calculation of effective dose

Consider a circumstance in which a radionuclide causes exposure of the lung, the liver, and the surfaces of the bones.

Suppose that the equivalent doses to the tissues are, respectively, 100, 70, and 300 mSv.

The effective dose is calculated as (100 × 0.12) + (70 × 0.05) + (300 × 0.01) = 18.5 mSv

The calculation shows that the risk of harmful effects from this particular pattern of radiation exposure will be the same as the risk from 18.5 mSv received uniformly throughout the whole body.

Defined in this way, the equivalent dose provides an index of the likelihood of harm to a particular tissue or organ from exposure to various types of radiation regardless of their type or energy. So 1 Sv of alpha radiation to the lung, for example, would create the same risk of inducing fatal lung cancer as 1 Sv of beta radiation. The risk to the various parts of the human body varies from organ to organ. For example, the risk of fatal malignancy per unit equivalent dose is lower for the thyroid than for the lung. Moreover, there are other important types of harm such as non-fatal cancers or the risk of serious hereditary damage caused by irradiation of the testes or ovaries. These effects are different both in kind and in magnitude and we must take them into account when assessing the overall detriment to the health of human beings arising from exposure to radiation.

Tissue or organ	*Tissue weighting factor*
Gonads	*0.20*
Bone marrow (red)	*0.12*
Colon	*0.12*
Lung	*0.12*
Stomach	*0.12*
Bladder	*0.05*
Breast	*0.05*
Liver	*0.05*
Oesophagus	*0.05*
Thyroid	*0.05*
Skin	*0.01*
Bone surface	*0.01*
Remainder	*0.05*
Whole body total	***1.00***

We can deal with all these complexities by taking the equivalent dose in each of the major tissues and organs of the body and multiplying it by a weighting factor related to the risk associated with that tissue or organ. The sum of these weighted equivalent doses is a quantity called the *effective dose*: it allows us to represent the various dose equivalents in the body as a single number. The effective dose also takes account of the energy and type of radiation, and therefore gives a broad indication of the detriment to health. Moreover, it applies equally to external and internal exposure and to uniform or non-uniform irradiation.

It is sometimes useful to have a measure of the total radiation dose to groups of people or a whole population. The quantity used to express this total is the *collective effective dose.* It is obtained by adding, for all exposed people, the effective dose that each person in that group or population has received from the radiation source of interest. For example, the effective dose from all sources of radiation is, on average, 2.8 mSv in a year. Since the world population is about 6000 million, the annual collective effective dose to the whole population is the product of these two numbers — about 17 000 000 *man sievert*, symbol man Sv.

It is common for effective dose to be abbreviated to *dose* and collective effective dose to *collective* dose. This will be the case in the following chapters except where exactness is essential.

Chapter 4 Sources of ionizing radiation

Ionizing radiation enters our lives in a variety of ways. It arises from natural processes, such as the decay of uranium in the Earth, and from artificial procedures like the use of X rays in medicine. So we can classify radiation as natural or artificial according to its origin. Natural sources include cosmic rays, gamma rays from the Earth, radon *decay products* in the air, and various radionuclides found naturally in food and drink. Artificial sources include medical X rays, *fallout* from the testing of nuclear weapons in the atmosphere, discharges of radioactive waste from the nuclear industry, industrial gamma rays, and miscellaneous items such as *consumer products*. Later chapters have more information on both classes of source.

Each source of radiation has two important characteristics, the dose that it delivers to human beings and the ease with which we can do something to affect such doses. Until recently, radiation from natural sources seemed both unremarkable and unalterable — a background phenomenon. We now know, however, that doses from the decay products of radon gas (itself a product of uranium decay) in the home can be remarkably high in some areas, although it is fairly easy to reduce them in existing homes and to avoid high concentrations of the gas when building new homes. In contrast, we cannot do much to change our exposure to the other natural sources of radiation. This basic background of cosmic rays, gamma rays, and natural radioactivity within the body gives rise to an annual dose of about 1 mSv or more to an average citizen of the world. A comparable dose (at least) from radon decay products is also unavoidable in practice for most people.

It is easier, in most cases, to control artificial sources of radiation because we can alter or terminate the procedure producing the radiation, but there is always a balance to be made. It is important, for instance, to pay attention to the doses from medical X ray examinations, but it would be unwise to reduce them where this would lead to a loss of essential diagnostic information.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) was established in 1955 to estimate the potential health risks from radioactive fallout from atmospheric nuclear weapons tests. Today, UNSCEAR regularly publishes data on doses from all sources. The results of the latest review, published in 2000, are reflected in the pie chart on the next page. The annual dose, averaged over the population of the world, is about 2.8 mSv in total. Over 85 per cent of this total is

Absorbed dose is expressed in a unit called the gray, named after the English physicist

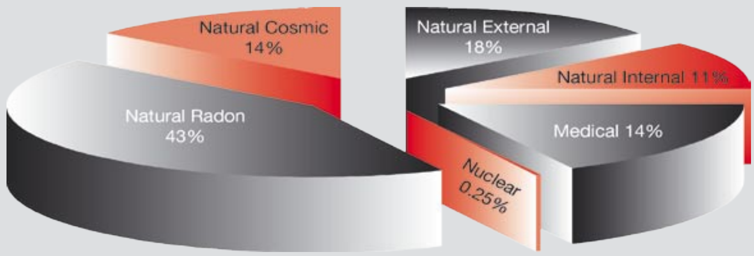
Harold Gray (1905–1965)

Rolf Sievert (1896–1966)

Equivalent dose is expressed in a unit called the sievert, named after the Swedish physicist from natural sources with about half coming from radon decay products in the home. Medical exposure of patients accounts for 14 per cent of the total, whereas all other artificial sources — fallout, consumer products, occupational exposure, and discharges from the nuclear industry — account for less than 1 per cent of the total value.

Compiled from data in Tables 1 and 2 of UNSCEAR 2000 Report to the UN General Assembly

Average radiation exposure from all sources = 2.8 mSv/a



The greatest variations in dose arise from radon decay products in the home, which can give annual doses of 10 mSv or more. Annual doses for those exposed to radiation at work are, at present, limited by law in most countries to 50 mSv or less, but only a small fraction of the workforce exceeds 20 mSv. It is unlikely that many members of the public receive more than a fraction of 1 mSv in a year from incidental exposure to artificial sources. Doses to patients in some diagnostic procedures may be around 10 mSv. For consumer products that contain radioactive material, such as smoke alarms and luminous watches, annual doses are at most 1 µSv (1 millionth of a sievert), although less common items, such as gas mantles containing thorium, may cause as much as 0.1 mSv in a year in certain circumstances.

Average annual doses to the world population from all sources of radiation

Source	***Dose (mSv)***
Natural	
Cosmic	*0.4*
Gamma rays	*0.5*
Internal	*0.3*
Radon	*1.2*
Artificial	
Medical	*0.4*
Atmospheric nuclear testing	*0.005*
Chernobyl	*0.002*
Nuclear Power	*0.0002*
Total (rounded) mSv	***2.8***

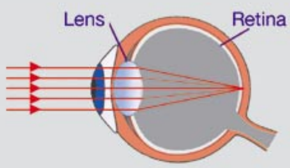
Chapter 5 Radiation effects

Radiation doses of different sizes, delivered at different rates to different parts of the body, can cause different types of health effect at different times.

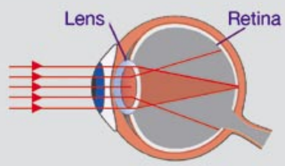
A very high dose to the whole body can cause death within weeks. For example, an absorbed dose of 5 gray or more received instantaneously would probably be lethal, unless treatment were given, because of damage to the bone marrow and the gastro-intestinal tract. Appropriate medical treatment may save the life of a person exposed to 5 gray, but a whole body dose of, say, 50 gray would almost certainly be fatal even with medical attention. A very high dose to a limited area of the body might not prove fatal, but other early effects could occur. For example, an instantaneous absorbed dose of 5 gray to the skin would probably cause erythema — painful reddening of the skin — within a week or so, whereas a similar dose to the reproductive organs might cause sterility. These types of effect are called *deterministic effects*: they occur only if the dose or dose rate is greater than some threshold value, and the effect occurs earlier and is more severe as the dose and dose rate increase. Deterministic effects in an individual can be identified clinically to be the result of radiation exposure (although on the few occasions when they have occurred as a result of accidents — see Chapter 14 — they have not always been immediately recognized as such).

One type of deterministic effects occurs a longer time after exposure. Such effects are not usually fatal, but can be disabling or distressing because the function of some parts of the body may be impaired or other non-malignant changes may arise. The best-known examples are cataracts (opacity in the lens of the eye) and skin damage (thinning and ulceration). High absorbed doses of several gray are normally required to induce these conditions.

Deterministic effects on vision



Normal lens — light is focussed normally on the retina



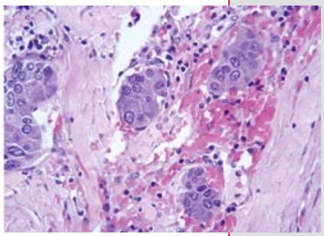
Lens with cataract — opacity of the lens blocks or distorts light from being focussed on the retina, resulting in reduced vision

If the dose is lower, or is delivered over a longer period of time, there is a greater opportunity for the body cells to repair, and there may be no early signs of injury. Even so, tissues may still have been damaged in such a way that the effects appear only later in life (perhaps decades later), or even in the descendants of the irradiated person. These types of effect are called *stochastic effects*: they are not certain to occur, but the likelihood that they will occur increases as the dose increases, whereas the timing and severity of any effect does not depend on the dose. Because radiation is not the only known cause of most of these effects, it is normally impossible to determine clinically whether an individual case is the result of radiation exposure or not.

Induction of cancers

The most important of these stochastic effects is cancer, which is always serious and often fatal. Although the exact cause of most cancers remains unknown or poorly understood, exposure to agents such as tobacco smoke, asbestos and ultraviolet radiation, as well as ionizing radiation, are known to play a role in inducing certain types of cancer. The development of cancer is a complex, multistage process that usually takes many years. Radiation appears to act principally at the initiation stage, by introducing certain mutations in the DNA of normal cells in tissues. These mutations allow a cell to enter a pathway of abnormal growth that can sometimes lead to the development of a malignancy.

Follicular Carcinoma of Thyroid
A.K. Padhy/IAEA



Given that we cannot distinguish between those cancer cases resulting from radiation exposure and those with other causes, how can we calculate the risk of cancer from radiation? In practice, we have to use epidemiology — the statistical study of the incidence (the number of cases and their distribution) of specific disorders in specific population groups. Suppose that we know the number of people in an irradiated group and the doses they have received. Then by observing the occurrence of cancer in the group and comparing with the doses and the number of cancers expected in an otherwise similar but unirradiated group, we can estimate the raised risk of cancer per unit dose. This is commonly called a *risk factor*. It is most important to include data for large groups of people in these calculations so as to minimize the statistical uncertainties in the estimates and take account of factors, such as age and gender, that affect the spontaneous development of cancer.

Not all cancers are fatal. Average mortality from radiation-induced thyroid cancer is about 10 per cent (although it is much lower — less than 1 per cent — for the cases caused in children and teenagers by the Chernobyl accident), from breast cancer about 50 per cent, and from skin cancer about 1 per cent. Overall, the total risk of inducing cancer by uniformly irradiating the whole body is about half as great again as the risk of inducing a fatal cancer. In radiological protection the risk of fatal cancer is of more concern because of its extreme significance. The use of fatal cancer risks also makes it easier to compare them with the other fatal risks encountered in life. In contrast, comparisons of non-fatal risks are fraught with difficulty.

Risk assessments

The main sources of information on the additional risk of cancer following exposure of the whole body to gamma radiation are studies of the survivors of the atomic bombs dropped on Hiroshima and Nagasaki in 1945. Because a substantial number of the people who survived the bombings are still alive today, it is necessary to predict how many extra cancers will eventually be found to have occurred in the exposed population. Various mathematical methods are used for this purpose, but this is inevitably another source of uncertainty in the risk estimates. Yet another source of uncertainty is that the doses received by the survivors can only be estimated from whatever information is available, and different assessments have reached somewhat different conclusions.

Other risk estimates for the exposure of various tissues and organs to X rays and gamma rays come from people exposed to external radiation for the treatment of non-malignant or malignant conditions and for diagnostic purposes, and also from people in the Marshall Islands exposed to severe fallout from atmospheric nuclear weapons tests. Information on the effects of alpha-emitting radionuclides comes from miners exposed to radon and its decay products, from workers exposed to radium-226 in luminous paint, from some patients treated with radium-224 for bone disease, and from other patients given an X ray contrast medium containing thorium oxide.

Information of this nature is assessed periodically by UNSCEAR and by the International Commission on Radiological Protection (ICRP) in order to determine the most appropriate risk estimates; in the case of ICRP, these risk estimates are developed for the purpose of developing recommendations for protection. The IAEA develops its radiation safety standards taking account of the advice of UNSCEAR and ICRP.

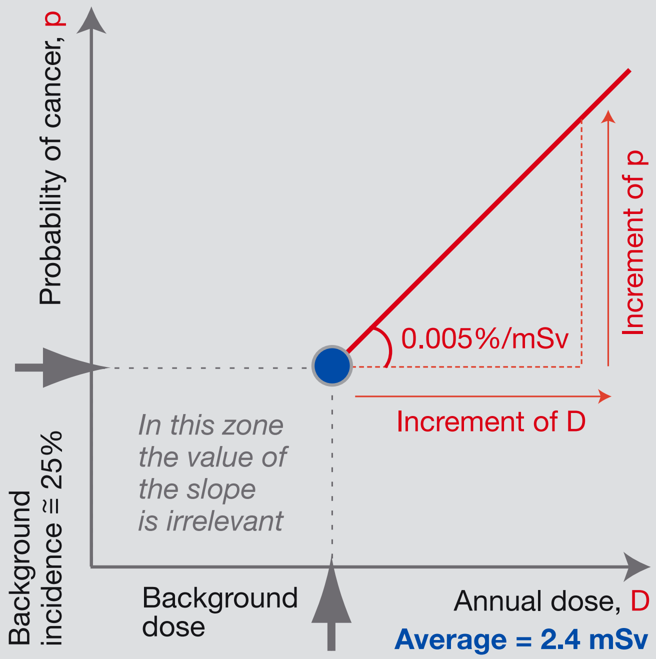
Risk factors for cancers

Most of the Japanese atomic bomb survivors and other exposed groups studied received high doses over short periods of time. Observations of the cancer incidence in these groups, along with estimates of the doses they received, indicate that, for high doses and high dose rates, there is a linear relationship between dose and risk. Thus, for example, doubling the dose would double the risk.

However, most radiation exposure involves low doses delivered over long periods. At these low levels of exposure, studies of cancer incidence in the exposed population do not provide any direct evidence about the relationship between dose and risk, because the number of extra cancers that might be expected to result from the radiation exposure is too small (compared to the total number of cancer cases in the population) to detect. It is, therefore, necessary to consider other scientific information about the effects of radiation on cells and organisms and to form a judgement as to the most likely form of the dose–risk relationship. For many years, the internationally accepted solution has been to assume that the relationship is linear for low doses, all the way down to zero (known as the 'linear–no threshold' or LNT hypothesis), i.e. that any radiation dose has a detrimental effect, however small. However, some radiobiological experiments have been interpreted as suggesting that low doses of radiation have no detrimental effect, because the body can successfully repair all of the damage caused by the radiation, or even that low doses of radiation may stimulate the repair mechanisms in cells to such an extent that they actually help to prevent cancer. Other experiments have been used as the basis for theories that low doses of radiation are more harmful (per unit of dose) than high doses, or that the hereditary effects of radiation could get worse from generation to generation.

After a major review of biological effects at low doses of ionizing radiation, UNSCEAR concluded in 2000 that "…an increase in the risk of cancer proportionate to radiation dose is consistent with developing knowledge and it remains, accordingly, the most scientifically defensible approximation of low dose response". However, UNSCEAR also accepted that there are uncertainties and stated that "… a strictly linear dose response relationship should not be expected in all circumstances".

Dose–risk hypothesis



For some types of strongly ionizing radiation, such as alpha particles, the *risk factor* is the same at low doses as at high doses, but for weakly ionizing radiation, such as gamma rays, there is considerable radiobiological evidence that the picture is more complicated. For these types of radiation, a linear relationship is a good approximation of dose response for both the low dose and high dose regions, but the risk per unit dose (the slope of the linear relationship) is less at low doses and dose rates than at high doses and dose rates. ICRP has estimated the risk factors for fatal cancers from low doses and dose rates in this way using a judicious reduction factor of two.

In reality, the risk to an actual person from a given dose will depend on that person's age at the time of the exposure and on their gender. For example: if a person receives a dose late in life, a radiation-induced cancer may not have time to appear before the person dies of another cause; and the risk of breast cancer is virtually zero for men and twice the listed 'average' value, 0.4×10^{-2} or 1 in 250 per Sv, for women. Furthermore, recent advances in knowledge indicate that a person's genetic constitution can influence their risk of cancer after irradiation. At present, we can identify only rare families who may carry increased risk, but experts may in future be able to take some account of such inherited traits.

ICRP risk factors for fatal cancers for the whole population

Tissue or organ	*Risk factor ($\times 10^{-2}$ Sv^{-1})*
Bladder	*0.30*
Bone marrow (red)	*0.50*
Bone surfaces	*0.05*
Breast	*0.20*
Colon	*0.85*
Liver	*0.15*
Lung	*0.85*
Oesophagus	*0.30*
Ovary	*0.10*
Skin	*0.02*
Stomach	*1.10*
Thyroid	*0.08*
Remainder	*0.50*
Total (rounded)	***5.00***

Risk factors are also different for different populations. This is partly because different populations have different distributions of ages. For example, since the average age of a population of workers is generally higher (and therefore their life expectancy is shorter) than that of the population as a whole, the risk factor for the former is somewhat lower than that for the latter. The ICRP risk factor for workers is 4×10^{-2} or 1 in 25 per Sv. Different risk factors can also result from differences in the prevailing incidence of cancer (or even particular types of cancer) from all causes, because the risk from radiation is assumed to be related to this prevailing incidence. For example, the risk factor for countries with a relatively high level of cancer mortality (e.g. developed countries) would be higher than for those where cancer is less common (e.g. developing countries). However, such differences are fairly small compared to the uncertainty in the ICRP risk factors, and therefore the ICRP values — which are based on 'averaging' over the characteristics of five disparate national populations — can reasonably be used internationally.

Hereditary disease

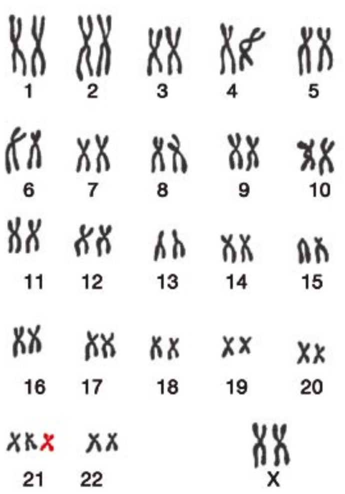
Apart from cancer, the other main late effect of radiation is hereditary disease. As with cancer, the *probability* of hereditary disease — but not its severity — depends on dose. Genetic damage arises from irradiation of the testes and ovaries, which produce sperm cells in males and the egg cells in females. Ionizing radiation can induce *mutations* in these cells or in the germ cells that form them, mutations which may give rise to harmful effects in future generations. Mutations occur as a result of structural changes to the DNA in single germ cells, which subsequently carry the hereditary information in the DNA through future generations. The hereditary diseases that may be caused vary in severity ranging from early death and serious mental defects to relatively trivial skeletal abnormalities and minor metabolic disorders.

Although mutations appear to arise in human beings without any apparent cause, natural radiation and other agents in the environment may also cause them and contribute to the prevailing occurrence of hereditary disease. There has, however, been no conclusive evidence in human offspring for hereditary defects attributable to exposure from natural or artificial radiation. Extensive studies of the offspring of the survivors of the atomic bombs, in particular, have failed to show increases of statistical significance in hereditary defects. Instead, the negative findings help to provide an upper estimate of the risk factor for them.

Large experimental studies have been made of the hereditary damage that ionizing radiation induces in animals, mainly mice. These have covered a wide range of doses and dose rates and clearly demonstrate that ionizing radiation does cause mutations. The results also show how often hereditary defects are induced by known doses. When considered with the findings for the atomic bomb survivors, this information allows estimates to be made of hereditary risk for human beings.

Against this background, ICRP has assessed the risk of severe hereditary disease in a general population exposed to low doses and dose rates. It estimated a risk factor of 1.0×10^{-2} Sv^{-1} or 1 in 100 per Sv for such diseases appearing at any time in all future generations. Mutations leading to diseases that are strictly heritable, such as haemophilia and Down's Syndrome, make up about half of the total: the remainder comes from a group of so-called multifactorial diseases, such as diabetes and asthma. This estimate of risk carries considerable uncertainty especially for the multifactorial diseases where the interplay of the genetic and environmental factors that influence the disorders is poorly understood.

Chromosome 21 abnormality in female with Down's Syndrome



Irradiation of the testes and ovaries only carries a risk of hereditary effects if it occurs before or during the reproductive period of life. Since the proportion of a working population that is likely to reproduce is lower than that in the general population, the risk factor for workers is smaller. The ICRP estimates the risk to a working population at 0.6×10^{-2} Sv^{-1} or 1 in 170 per Sv for severe hereditary diseases in all future generations.

More recent assessments indicate that the risks of hereditary effects may actually be lower than these earlier estimates, particularly for the multifactorial diseases. In its 2001 Report to the UN General Assembly, UNSCEAR presented a comprehensive review of hereditary risks of exposure to radiation. For a population exposed to radiation in one generation only, the risks to the first post-irradiation generation were estimated to be 0.3–0.5 per cent per Gy. This is between one-third and one half the ICRP estimate for all generations quoted above. The risks to generations other than the first are much lower than this. Put another way, this new estimate of risk per gray is of the order of 0.4–0.6 per cent of the baseline frequency of these disorders in the human population.

Communal risk

An important consequence of the assumption that risk is proportional to dose, without a low dose threshold, is that the collective effective dose becomes an indicator of communal harm. Under this concept it makes no difference mathematically whether, in a community of 50 000 people, each receives an effective dose of 2 mSv, or in a community of 20 000 people, each receives 5 mSv; the collective dose in each community is 100 man Sv, and the communal cost in each community may be five cancer deaths and one severe hereditary defect in future generations. Members of the smaller community, however, run the greater individual risk of fatal cancer. However calculations of collective dose should not be taken too far: the product of an infinite number of people and an infinitesimal dose is likely to be meaningless.

Irradiation in pregnancy

The risks to children irradiated while in the womb deserve special mention. If an embryo or foetus is exposed to radiation at the time when organs are forming, developmental defects such as a reduced diameter of the head or mental retardation may be caused. Studies on survivors of the atomic bombs who were exposed before birth have indicated that mental retardation mainly follows exposure during the period between 8 and 15 weeks after conception. There has been debate over the form of the relationship between dose and response and the existence of a threshold below which there is no effect. For exposures during the most sensitive 8–15 week period, however, ICRP assumes that the decrease in IQ depends directly on the dose without a threshold and with a loss of 30 IQ points per Sv. So, for example, exposure of the foetus to 5 mSv during this stage of pregnancy would lead to a loss in IQ of 0.15 point, which would be undetectable.

High doses to the embryo and foetus can cause death or gross malformation. The threshold for these effects is between 0.1 Sv and 1 Sv or more depending on the time after conception. Genetic risks to foetuses are judged to be the same as those for a fully reproductive population after birth, namely 2.4×10^{-2} Sv^{-1} or 1 in 40 per Sv. Irradiation before birth can also lead to an increased risk of malignancy in childhood. The risk of fatal cancer up to age 15 years is estimated to be about 3.0×10^{-2} Sv^{-1} or 1 in 30 per Sv, and the overall risk of cancer about twice this value.

For all of these reasons it is best for pregnant women to avoid diagnostic X rays of the abdomen unless a delay until the end of pregnancy would be undesirable. Indeed for all women of reproductive age where pregnancy cannot be reasonably excluded, it may be prudent to restrict diagnostic procedures that give high doses in the pelvic area to the early part of the menstrual cycle when pregnancy is least likely. Special restrictions apply to the doses that pregnant women may receive if they are employed in work with radiation sources, with the intention that the unborn child should receive the level of protection accorded to members of the public.

Harmful radiation effects

Circumstances of exposure	Health consequences	Sources of information
	Early effects	
High dose and dose rate *to much of the body* *to area of skin* *to testes and ovaries*	*Death* *Erythema* *Sterility*	*Human data from various sources*
	Late effects	
Any dose or dose rate *Risk depends on dose* *Appear years later*	*Various cancers*	*Risk factors for human beings estimated by extra-polating human data for high doses and dose rates*
Any dose or dose rate *Risk depends on dose* *Appear in offspring*	*Hereditary defects*	*Risk factors for human beings inferred from animal data and the absence of human evidence*
High dose at any rate *Various times to appear*	*Functional damage*	*Human data from various sources*
Dose in the womb *Appears in the child*	*Mental retardation*	*Limited human data*

Chapter 6 System of radiological protection

Approaches to protection against ionizing radiation are remarkably consistent throughout the world. This is due largely to the existence of a well established and internationally recognized framework.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) regularly reviews the natural and artificial sources of radiation in the environment to which people are exposed, the radiation exposure due to those sources, and the risks associated with that exposure. It reports its findings to the UN General Assembly on an ongoing basis.

The International Commission on Radiological Protection (ICRP) is a non-governmental scientific organization founded in 1928, which has regularly published recommendations for protection against ionizing radiation. Its authority derives from the scientific standing of its members and the merit of its recommendations. It bases its estimates of the probability of fatal cancer mainly on studies of the Japanese survivors of the atomic bombs and their assessment by bodies such as UNSCEAR.

The International Atomic Energy Agency (IAEA) has a statutory function to establish safety standards, where appropriate in collaboration with other relevant international organizations. In doing this, it relies heavily on the work of UNSCEAR and ICRP. It also has a responsibility for providing for the application of those standards at the request of a State and it does this through various mechanisms, including the provision of services and training.

General principles

For all human actions that add to radiation exposure, or practices, ICRP recommends a system of radiological protection based on three central requirements. Each of these involves social considerations — explicitly in the first two and implicitly in the third — so there is considerable need for the use of judgement.

ICRP system of radiological protection for practices

Justification of a practice

No practice involving exposure to radiation should be adopted unless it produces at least sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes.

Optimization of protection

In relation to any particular source of radiation within a practice, the dose to any individual from that source should be below an appropriate dose constraint, and all reasonable steps should be taken to adjust the protection so that exposures are "as low as reasonably achievable", economic and social factors being taken into account.

Application of individual dose limits

A limit should be applied to the dose received by any individual as the result of all the practices (other than medical diagnosis or treatment) to which he or she is exposed.

In some cases, as for example after an accident that releases radioactive material to the environment or when high indoor levels of radon occur, it may be necessary to intervene to reduce the exposure of people. Under such circumstances, ICRP recommends a system of radiological protection for intervention based on two further principles that mainly differ from the first set in that they omit dose limits for individuals. Specifying limits, however, might require measures out of all proportion to the likely benefit and would, therefore, be in conflict with the first principle. The application of this system again requires the exercise of judgement.

Both systems of radiological protection are endorsed in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources or BSS, which are sponsored by the IAEA and five other international organizations.

ICRP system of radiological protection for intervention

Justification of intervention

The proposed intervention should do more good than harm, that is, the benefits resulting from the reduction in dose should be sufficient to justify the harm and the costs, including social costs, of the intervention.

Optimization of intervention

The form, scale, and duration of the intervention should be chosen so that the net benefit of the reduction of dose, that is, the benefit of the reduction in dose less the costs of the intervention, should be as large as reasonably achievable.

The ICRP system is widely incorporated into national legislation throughout the world. In this chapter, we shall concentrate mainly on the system of protection for practices: in later chapters, we shall discuss circumstances in which intervention may be necessary.

Scope of application

Practices are activities involving the deliberate use of radiation. Such uses are clearly defined and can be regulated. On the other hand we can generally do nothing practical to reduce the normal levels of dose from natural radiation, although it is appropriate to intervene when people are exposed to high levels of radon in their homes or at work. For workers, some control also needs to be exercised over exposures to radiation from ores and other materials, such as scales in oil and gas rigs, with elevated levels of naturally occurring radionuclides.

The use of radiation in medicine is mainly a matter of clinical judgement since medical exposures are intended to benefit patients. Setting limits on doses to patients would not be sensible: it might also limit the benefits. However, the principles of justification and optimization, discussed next, should apply in full, particularly as there is scope for reducing individual doses, and the collective dose from medical procedures is high.

Justification of practices

The first requirement in the system of radiological protection for practices emphasizes the obvious need to consider harmful costs in the light of the benefits. In most cases, radiation effects are just some of a number of possible harmful outcomes that make up part of the overall social and economic costs. If there are other ways to achieve the same end, with or without radiation, it is important to analyse the costs and benefits of the alternatives before making a final decision in favour of one or the other.

The issues that arise in the process of justification extend far beyond radiological protection and may be illustrated by the arguments about the *nuclear power* programme. The radiological consequences of the programme include the discharge of radioactive substances to the environment and the doses received by workers in the *nuclear power industry.* In addition, a full analysis would deal with the potential for nuclear reactor accidents, as well as the creation of *radioactive wastes*. Account should also be taken of doses and accidents to uranium miners (who are often in countries other than those using the uranium).

An assessment should then be made of the consequences of doing without the energy provided by nuclear power or of using alternative methods to produce it — with coal for instance. Generating electric power from coal creates large volumes of waste and releases gases that worsen the greenhouse effect. Coal-fired power stations also discharge toxic substances and natural radioactive materials, coal miners suffer

Aerial photo of uranium tailings retention structure, showing the central decant structure and evaporation ponds for removal of excess water Western Mining Corporation/ Australia

October 2002

September 2003

A nuclear power plant

occupational diseases, and there is the potential for mining accidents. A complete analysis would also need to consider several strategic and economic factors: 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 the willingness of people to work in a particular industry.

Proper justification is also required for the use of radiation in diagnostic medicine. Few of us would question the practice: the benefits are undoubted even though individual doses for some examinations, and collective doses generally, are high. Nevertheless each procedure needs to be judged on its own merits. A mass X ray screening programme for cancer that might cause more cancers than it was likely to reveal would clearly be unacceptable. For this reason, there is unlikely to be clinical justification for the routine screening of employees except in special circumstances, such as the prevention of tuberculosis. Medical irradiation during pregnancy in particular requires clear justification and careful techniques. Radiological examinations for legal or insurance purposes are usually unwarranted since they do not benefit the health of the exposed person.

Practices are proposed from time to time that fail to satisfy the test of justification: these include the production of toys and jewellery containing radioactive material and other devices such as security tags for which there are perfectly adequate non-radioactive alternatives.

Optimization of protection

Since we assume that no radiation dose is entirely free from risk, it is important to pay attention to all doses and to reduce them whenever it is reasonably achievable. Eventually the point must come when further reductions in dose become unreasonable, because social and economic costs would outweigh the value of the reductions. On the other hand, the benefits and risks associated with a particular practice are often not distributed evenly in society, and so this second requirement — the optimization of protection recommended by ICRP — also includes a constraint on the procedure, in the form of restrictions on doses or risks to people so as to prevent inequitable exposures from radiation.

Constraints are imposed on a practice involving exposure to radiation at the planning stage. For workers, the value of the dose constraint should be chosen so as to reflect the annual value of dose that can reasonably be reached in a particular industry or procedure; it may well be a small fraction of the dose limit. For members of the public, a typical constraint, 0.3 mSv in a year, can be used as a planning value for a new source of radiation exposure, such as a factory that intends to discharge radioactive material to the environment.

Optimization of protection has been increasingly influential during the past two decades throughout the world and, in most countries, the average annual dose to radiation workers is well below (i.e. by a factor of ten or more) the 20 mSv per year that ICRP has recommended. Some groups of workers receive doses a few times the average, and some workers receive more than 20 mSv/a, but the number doing so is a very small percentage of the total. Analysis by UNSCEAR shows that the average annual dose to workers from man-made sources is 0.6 mSv, whereas the average annual dose to workers from enhanced natural sources (e.g. in mining) is higher at 1.8 mSv.

In most countries the annual doses to individual members of the public from practices that cause exposure have been brought below 0.3 mSv in a year — the primary dose constraint recommended by ICRP for the public. Even the groups of people who are most exposed to radioactive discharges from nuclear facilities, because they live nearby or have particular eating habits, typically receive annual doses that are a fraction of this constraint.

Dose constraints or guidance levels are also appropriate for medical exposures of patients, the objective being to minimize doses in a sensible way. Some routine medical procedures can give significant doses (i.e. several mSv) and, importantly, can vary greatly from hospital to hospital. The use of guidance levels can provide a practical means of reducing doses to patients without a reduction in the diagnostic information available to physicians.

Limitation of doses

The third requirement for practices is an obligation not to expose individuals and their descendants to an unacceptable degree of risk. This is fulfilled by imposing strict dose limits and applying the principle of optimization of protection. The BSS specify dose limits for workers of 20 mSv per year (averaged over a five-year period, with no more than 50 mSv in any year) and for members of the public of 1 mSv in a year.

International dose limits and constraints (mSv/a)

Parameters	Workers	Public
Effective dose		
Prime limit	*20[a]*	*1*
Constraints	*–[b]*	*0.3[c]*
Equivalent dose		
Lens of eye	*150[a]*	*15*
Area of skin[d]	*500[a]*	*50*
Extremities[e]	*500[a]*	*50*

Notes

a For students and apprentices, three-tenths of these values.

b There are no agreed international values; constraints should be set according to the particular circumstance (e.g. type of industry or operation).

c Prospective value for a single new source of exposure.

d Averaged over any 1 cm^2 of skin regardless of area exposed.

e Forearms and ankles as well as hands and feet.

These prime limits, expressed in terms of effective dose, are intended to control the incidence of serious effects such as cancer and hereditary harm that involve an element of probability. Another set of limits, expressed in terms of equivalent dose, is to protect the eyes, skin and extremities against other forms of damage.

There are two common misconceptions about dose limits. The first is that they mark an abrupt change in biological risk, a line of demarcation between safe and unsafe. It should be clear from the discussion on dose and risk that this is not so. It should also be apparent from the fact that there are different dose limits for workers and members of the public. These limits differ because higher risks are deemed more acceptable for workers, who receive a benefit from their employment, than for members of the public, whose risk is involuntary. The second misconception is that keeping doses below the limits is the only important requirement in radiological protection. On the contrary, the overriding requirement is to keep doses as low as reasonably achievable. This is reflected in the increasing emphasis on investigation levels, which are, of course, set below dose limits.

The International Basic Safety Standards

The BSS, published in 1996, are based primarily on the ICRP system of radiological protection described above. These standards lay down detailed requirements for occupational, medical and public exposures, and specify dose limits and exemptions. They also specify requirements for ensuring the safety of radioactive sources and for dealing with nuclear emergencies. IAEA Safety Guides give more detailed guidance on how the requirements should be met in particular situations. Most countries apply these standards in their own legislation and regulatory requirements.

Regulatory infrastructure

The BSS specify technical, scientific and administrative requirements for the safe use of radiation. However, these requirements presuppose that certain basic arrangements are in place to control uses of radiation. These basic arrangements are sometimes referred to as ‘infrastructure for safety’, and include such things as laws and regulations on the use of radiation and radioactive materials, and a regulatory body responsible for making sure these are followed. In countries with nuclear power programmes, this infrastructure has normally been developed. But this infrastructure is necessary (albeit on a smaller scale) for any uses of radiation, not just nuclear power. Almost all countries make some use of radiation in medicine or industry. Around the time the BSS were published, the IAEA realized that many countries without nuclear power programmes did not have a proper safety infrastructure, and so a major project was initiated to assist them in improving their capabilities to manage these uses of radiation safely.

Organizations sponsoring the International Basic Safety Standards

Food and Agriculture Organization*

International Atomic Energy Agency*

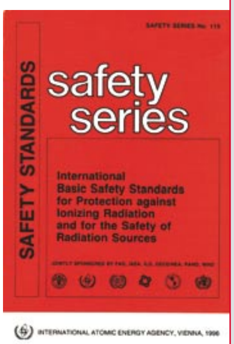
International Labour Organization*

Nuclear Energy Agency of the OECD

Pan American Health Organization*

World Health Organization*

* denotes United Nations Agency



Chapter 7 Natural radiation

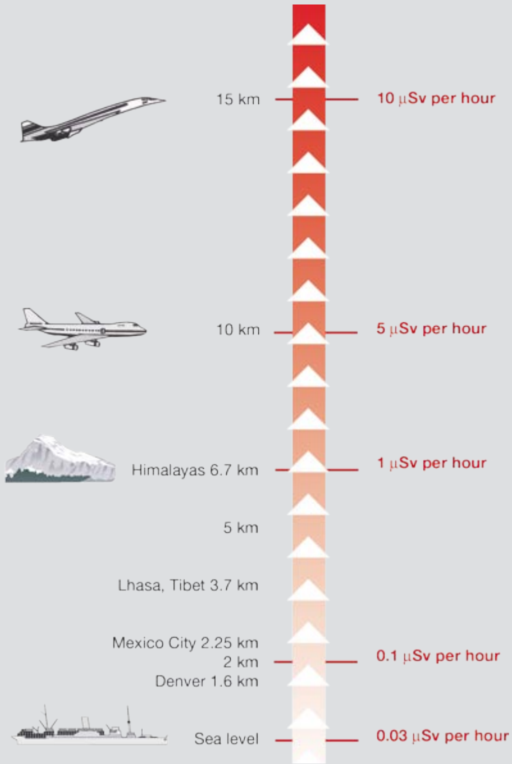
Natural ionizing radiation pervades the whole environment. Cosmic rays reach the Earth from outer space. The Earth itself is radioactive. Natural activity is present in food and drink and in the air. We are all exposed to natural radiation to a greater or lesser extent, and for most people it is the major source of radiation exposure. Nevertheless, humans, animals and plants have evolved in this background of natural radiation, and the general view is that it is not a significant risk to health — but there are exceptions.

Cosmic radiation

Cosmic rays are mainly protons of uncertain origin in space and very high energies that reach our atmosphere in fairly constant numbers. It is known, however, that some protons with lower energies come from the sun and are given off in bursts during solar flares. Protons are charged particles, so the number entering the atmosphere is affected by the Earth's magnetic field — more come in near the poles than the equator — so the dose rate increases with latitude. As they penetrate the atmosphere, the cosmic rays initiate complex reactions and are gradually absorbed so that the dose rate decreases as altitude decreases. Cosmic radiation is a mixture of many different types of radiation, including protons, alpha particles, electrons and other various exotic (high energy) particles. At ground level, cosmic radiation is primarily muons, neutrons, electrons, positrons and photons, and most of the dose comes from muons and electrons. UNSCEAR has calculated that the annual effective dose from cosmic rays at ground level is about 0.4 mSv, on average, allowing for variations in altitude and latitude.

Most people live at low altitudes, and so experience similar annual doses from cosmic radiation (apart from some variation with latitude). However, there are some significant population centres at considerable altitude (for example, Quito and La Paz in the Andes, Denver in the Rocky Mountains, Lhasa in the Himalayas), where residents may receive annual doses several times higher than those people living at sea level. The annual value for La Paz, for example, is five times the global average. The type of building in which a person lives may also affect the dose from cosmic rays to a slight degree. The intensity of cosmic rays at altitudes where aircraft fly is much greater than on the ground. At cruising altitude on an intercontinental flight, the dose rate can reach 100 times that on the ground. General air travel gives rise to a further annual dose of 0.01 mSv on average to some populations (the doses to some individual 'frequent

fliers' will be much higher than this average), but this does not affect the world average of 0.4 mSv.



Gamma radiation

All materials in the Earth's crust contain radionuclides. Indeed, energy from natural activity deep in the Earth contributes to the shaping of the crust and the maintenance of internal temperatures. This energy comes mainly from the decay of the radioactive isotopes of uranium, thorium and potassium.

Uranium is dispersed throughout rocks and soils in low concentrations of a few parts per million (ppm). Where it exceeds 1000 ppm or so in an ore, it may be economical to mine it for use in nuclear reactors. Uranium-238 is the parent of a long series of radionuclides of several elements, which decay in succession until the stable nuclide lead-206 is reached. Among the decay products in the series is an isotope of the radioactive gas radon, namely radon-222, which can reach the atmosphere, where it continues to decay. Thorium is similarly dispersed in the ground. Thorium-232 is the parent of another radioactive series, which gives rise to radon-220, another isotope of radon, sometimes called thoron. Potassium is far more common than either uranium or thorium and makes up 2.4 per cent by weight of the Earth's crust. The radionuclide potassium-40, however, constitutes only 120 ppm of stable potassium.

Annual effective doses from natural radiation

Based on Table 1 of UNSCEAR 2000 Report to UN General Assembly

Source	*Worldwide average Dose (mSv)*	*Typical range Dose (mSv)*
Cosmic radiation	*0.4*	*0.3–1.0*
Gamma radiation	*0.5*	*0.3–0.6*
Radon inhalation	*1.2*	*0.2-10*
Internal irradiation	*0.3*	*0.2–0.8*
Total (rounded)	*2.4*	*1.0–10*

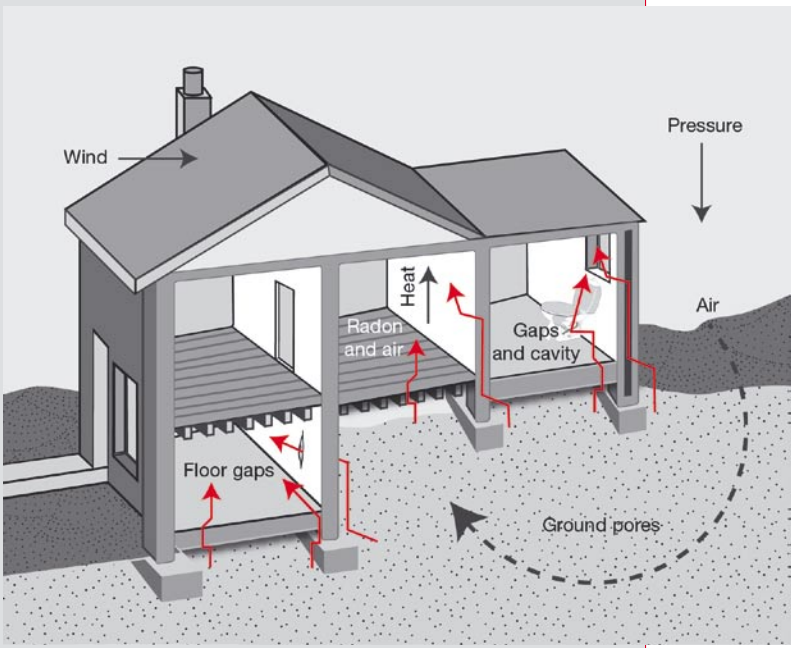
The radionuclides in the ground emit penetrating gamma rays that irradiate us more or less uniformly. Since most building materials are extracted from the Earth, they too are mildly radioactive, and people are irradiated indoors as well as out of doors. The doses they receive are affected both by the geology of the area where they live and the structure of the buildings in which they live, but the average effective dose from natural gamma rays is about 0.5 mSv in a year. Actual values vary appreciably. Some people may receive doses a few times higher or lower than the average. In a few places where the ground naturally contains relatively high concentrations of radionuclides, such as Kerala in India and parts of France and Brazil, the dose can be up to 20 times the global average. Although in general there is little that can be done to affect this dose, it would be sensible where possible to avoid building in locations or with materials with unusually high activity.

Radon inhalation

Radon gas is a particularly significant source of exposure to natural radiation. This is because the immediate decay products of radon-222 are radionuclides with short half-lives, which attach themselves to fine particles in the air, are inhaled, irradiate the tissues of the lung with alpha particles, and increase the risk of lung cancer. The same is true of radon-220 (thoron), but the degree of exposure of the lung is much less. When radon gas enters the atmosphere from the ground, it disperses in the air, so concentrations out of doors are low. When the gas enters a building, predominantly through the floor from the ground, the concentration of activity builds up within the enclosed space.

If buildings are well ventilated this accumulation of radon will not be marked. However, in many — generally colder — countries, buildings are constructed with more emphasis on retaining heat and preventing draughts. They are, therefore, often poorly ventilated, and radon concentrations indoors can be many times higher than those outdoors. Radon concentrations in buildings are also very dependent on the local geology and can vary a great deal between different parts of a country and even from building to building in the same area.

How radon enters a home



The worldwide average annual effective dose from the decay products of radon is estimated to be about 1.2 mSv. There are, however, pronounced variations about this value. In some countries (e.g. Finland) the national average is several times higher, and in particular homes in many countries occupants have received effective doses of the order of hundreds of mSv in a year. Given this, ICRP and IAEA have recommended the use of Action Levels (expressed in Bq m^{-3}) above which householders are advised to reduce radon levels in their homes. Typically these Action Levels should be in the range 200–600 Bq m^{-3}, which is about ten times the average value for the radon concentration in homes.

Anyone finding high radon levels in their homes can reduce it by preventing air from the ground entering the building. The most effective way to do so is to reduce the air pressure under the house with a small fan. As mentioned in Chapter 5, this circumstance is an example of intervention, in the ICRP sense, to reduce human exposure to ionizing radiation.

Internal irradiation

Radionuclides are found naturally in the diet

Other radionuclides from the uranium and thorium series, in particular lead-210 and polonium-210, are present in air, food, and water, and so irradiate the body internally. Potassium-40 also comes into the body with the normal diet. It is the main source of internal irradiation apart from the radon decay products. In addition, the interactions of cosmic rays with the atmosphere create a number of radionuclides, such as carbon-14, which also contribute to internal irradiation.

The average effective dose from these sources of internal irradiation is estimated to be 0.3 mSv in a year, with potassium-40 contributing about half. Information on how the total varies from one person to another is limited, although it is known that the potassium content of the human body is controlled by biological processes. The amount of potassium, and hence potassium-40, varies with the amount of muscle in the body, and is about twice as high in young men as in older women. There is little anyone could do to affect internal irradiation from the other radionuclides except by avoiding any food and water with a high radioactive content.

Total doses

The total average effective dose from natural radiation is about 2.4 mSv in a year, but doses can vary a great deal. Some national averages exceed 10 mSv in a year, and in some regions individual doses may exceed 100 mSv in a year, usually because of homes with particularly high levels of radon and its decay products.

Average doses are useful measures for comparing the health significance of radiation from natural and artificial sources, but they may need to be supplemented by additional data when there are, as with indoor radon, large variations about the average. The most helpful step might be to describe the frequency with which doses of a certain magnitude occur in the circumstances of interest.

Chapter 8 Medical uses of radiation

Ionizing radiation has two very different uses in medicine — for diagnosis and therapy. Both are intended to benefit patients and, as with any use of radiation, the benefit must outweigh the risk. We have touched on this matter of justification in Chapter 6.

Most people at some time in their lives have an X ray examination to help the physician diagnose disease or damage in the body. A much less common diagnostic procedure involves the administration of radionuclides to patients so that detectors outside the body can be used to observe how organs are functioning. Physicians use either of these procedures if they cannot make a diagnosis without them. Radiation doses are generally low, although they can be appreciable in certain procedures.

Much higher doses are required to treat malignant diseases or malfunctioning organs sometimes in combination with other forms of treatment. A beam of radiation may be used to irradiate the affected part of the body or a fairly high activity of a radionuclide may be administered to the patient.

The use of X rays for examining patients is called *diagnostic radiology* and the use of pharmaceuticals labelled with radionuclides for diagnosis or therapy is called *nuclear medicine*. When radiation beams are used to treat patients, the procedure is called *radiotherapy*.

Population per physician	***Number of examinations per 1000 people per year***	***Average annual effective dose, mSv***
< 1000	*920*	*1.2*
1000–3000	*150*	*0.14*
3000–10 000	*20*	*0.02*
> 10 000	*< 20*	*0.02*
World average	*330*	*0.4*

Radiation exposures from diagnostic medical procedures (UNSCEAR)

Taken from Table 2 of UNSCEAR 2000 Report to the General Assembly

Diagnostic radiology

First X ray of hand (Frau Röntgen)

In a conventional X ray examination, radiation from a machine passes through the patient. X rays penetrate flesh and bone to different degrees and produce images of the internal structures of the body on photographic film. In some cases, the images are captured and processed electronically. The value of these images explains why doctors conduct as many as one diagnostic X ray per person per year in developed countries.

The parts of the body most frequently examined are the chest, limbs, and teeth, each accounting for about 25 per cent of the total number of examinations. Doses are fairly low — about 0.1 mSv from a chest examination, for example. Effective doses from other types of examination, such as the lower spine, are higher because organs and tissues that are more sensitive to radiation are exposed to a greater degree. Examinations of the lower bowel using a barium enema result in a substantial effective dose around 6 mSv; only 1 per cent or so of all examinations are of this type.

Typical doses to patients from conventional X ray and computed tomography examinations

Derived from data in UNSCEAR 2000 Report, Annex D, Vol. 1 Tables 15 and 19

Examination	***Conventional X ray dose (mSv)***	***Computed tomography dose (mSv)***
Head	*0.07*	*2*
Teeth	*< 0.1*	*–*
Chest	*0.1*	*10*
Abdomen	*0.5*	*10*
Pelvis	*0.8*	*10*
Lower spine	*2*	*5*
Lower bowel	*6*	*–*
Limbs and joints	*0.06*	*–*

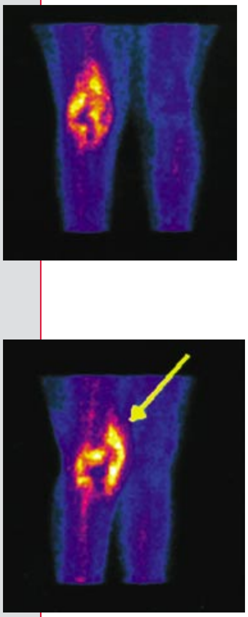
The use of computed tomography (CT) has increased considerably in recent years to the point where approximately 5 per cent of all procedures in diagnostic radiology in developed countries are CT scans. With this technique, a fan-shaped beam of X rays is rotated around the patient and registered on the opposite side by a row of detectors. An image of a slice or section through the patient is then reconstructed by a computer and conveys superior diagnostic information. However, doses in CT can be an order of magnitude or more higher than those from conventional X ray examinations.

CT scanning

CT examinations are significant contributors to collective dose from medical diagnosis, and in some countries their contribution is above 40 per cent of the total. Examinations of the lower bowel contribute about 10 per cent of the total collective dose and chest examinations about one per cent. It is clear from these figures that some relatively infrequent procedures can give a far greater dose to the population than the more common examinations. This is why a CT scan is not used where an ordinary X ray examination would suffice for a sound diagnosis.

The diagnostic procedure that gives the highest doses, however, is interventional radiology. This is where a physician performing a procedure inside the patient's body uses a series of X rays to 'see' into the patient in real time. This allows a procedure on an internal organ to be carried out without the major surgery that might otherwise have been needed to gain access to the organ. However, these procedures can give patient doses in the range 10–100 mSv and, if not carefully controlled can lead to similarly high doses to surgeons. In some cases, the doses from such procedures have been high enough to cause deterministic effects in patients and surgeons.

Technetium-99m scintigram of a patient with a right knee prosthesis and signs of infection (arrow)



Nuclear medicine

For a diagnostic procedure in nuclear medicine, the patient is given a radionuclide in a carrying substance, such as a pharmaceutical, which is preferentially taken up by the tissue or organ under study. Administration may be by injection, ingestion, or inhalation. The radionuclide emits gamma rays.

Most of the diagnostic procedures make use of the radionuclide technetium-99m. It has a half-life of 6 hours, gives off gamma rays with an energy of 0.14 MeV, can be conveniently prepared in the hospital, and readily labels a variety of carrying substances. A special detector called a gamma camera is used to observe how the organs or tissue behave or how quickly the radionuclide moves.

Individual doses from technetium scans are comparable to those in diagnostic radiology. The collective dose from nuclear medicine is, however, lower by more than an order of magnitude, because the number of procedures is much lower.

Typical doses to patients from common investigations of organs in nuclear medicine

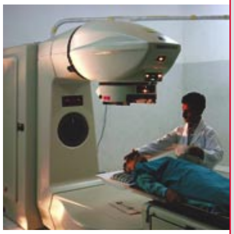
Rounded values, derived from data in UNSCEAR 2000 Report, Vol.1, Annex D, Table 42

Organ scan	***Effective dose (mSv)***
Brain	*7*
Bone	*4*
Thyroid, lung	*1*
Liver, kidney	*1*

When radionuclides are used for treatment rather than diagnosis, much greater activities are given to the patient and much higher doses are given to the target tissues or organs. The treatment of an overactive thyroid gland — hyperthyroidism — is probably the most common therapeutic procedure, the radionuclide used being iodine-131.

Although the radionuclides used for these procedures have short half-lives, medical staff need to take account of the fact that activity will remain in the body of a patient to whom a radionuclide has been given for some time after the procedure. This might need to be taken into account, especially after therapeutic procedures, in deciding when he or she can be discharged from hospital. Family and friends of the patient may also sometimes be advised by the hospital to take appropriate precautions against inadvertent exposure from this residual activity.

Radiotherapy



This technique is used to cure cancers or at least to alleviate the most distressing symptoms, by killing the cancerous cells. A beam of high energy X rays, gamma rays or electrons is directed towards the diseased tissue so as to give it a high dose while sparing the surrounding healthy tissue. If a tumour is deep in the body, the beam is pointed at it from several directions so as to reduce the incidental damage. Another form of treatment, in which a radiation source is placed in or on the body for a short period, is used for some cancers: it is called *brachytherapy*. As radiotherapy doses are strong, such treatment is only used when the outlook for a cure or relief is good and when other methods of treatment would be less effective.

Although radiotherapy can cure the original cancer, it may possibly cause cancer in other tissues or adverse hereditary effects in subsequent generations. Most people who receive radiotherapy are, however, past the age to have children and too old for delayed cancers to occur. So the aim of radiotherapy is to maximize the effectiveness of treatment while minimizing the adverse side-effects.

Tumours require absorbed doses of tens of gray to kill the cancer cells effectively. Prescribed doses to tissues are typically in the range 20–60 Gy. Considerable care is required to deliver accurate doses: too low or too high doses may lead to incomplete treatment or unacceptable side-effects. Rigorous quality assurance procedures are needed to make sure that equipment is properly set up and maintained. If this is not done, the consequences can be grave: a miscalibrated radiotherapy beam in Costa Rica in 1996 resulted in more than 100 patients receiving higher doses than intended, in many cases leading to death or serious injury. In 2001 in Panama, it was discovered that problems with data entry into the treatment planning system resulted in 28 patients being overexposed, several of whom died as a result.

Guidance levels for medical exposure

Since diagnostic radiology is so widely used and the collective dose so large, it is important to avoid unnecessary exposures and keep the essential exposures as low as possible. The decision whether to prescribe an X ray examination is a matter of medical judgement made in the best interests of the patient. The dose to the patient should be the lowest possible compatible with accurate diagnosis. Physicians need to take particular care to minimize doses in paediatric examinations.

Methods of minimizing doses include the use of good equipment that is well maintained, properly adjusted and skilfully operated, and having a programme of quality assurance in the X ray department. Doses from the same X ray examination may vary from patient to patient because of differences in size and shape, but they should generally fall below an agreed value. This, as we mentioned in Chapter 6, is called a reference or guidance dose, and the BSS contains guidance levels of dose, dose rate and activity for medical exposures.

Examination		*Entrance surface dose per radiograph (mGy)*
Lumbar spine	*AP*	*10*
Chest	*PA*	*0.4*
Skull	*PA*	*5*

Note: PA = posterior-anterior; AP = anterior-posterior projection.

IAEA dose guidance levels for diagnostic radiography for a typical adult patient

Source: The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (1996) Schedule III, page 279

Total Doses

Given the large number of diagnostic X ray procedures carried out, particularly in developed countries, the collective dose from this practice is quite high. UNSCEAR has estimated a collective dose of 2500 million man Sv from all diagnostic procedures. The reality is, however, that young people do not have many X rays and that the likelihood of needing an examination increases with age. This implies a lower probability, in general, of any consequential cancers being expressed.

Common uses of radiation in industry

Radiography of welds and joints

Security inspection of bags and parcels

Level gauging of container contents

Sterilization of some medical supplies

Static elimination in paper production

Analysis of specimens for quality control

Chapter 9 Occupational exposure to radiation

Exposure to ionizing radiation occurs in many occupations. Artificial sources of radiation are commonly used in the manufacturing and service industries, in areas of defence, in research institutions, and in universities, as well as in the nuclear power industry. Moreover, we have seen in Chapter 8 that they are extensively used by physicians and health professionals.

Some workers are also exposed to natural sources of radiation in such circumstances that a measure of supervision and protection is required. This is particularly true of exposure to radon in mines and in ordinary premises throughout areas where radon levels are high. With the relatively high dose rates experienced in air travel due to elevated levels of cosmic rays at flying altitudes, some consider that supervision is also required for air crew, although it is less clear to what extent their exposures can readily be reduced.

Industrial radiographer wearing TLD badge

Film and TLD dosimeters

Many people who are exposed to radiation in their work wear personal monitoring devices (or dosimeters) such as a small photographic film or some thermoluminescent material in a special holder. There is also increasing use of electronic devices for this purpose. These register the radiation incident on the body from external sources and yield an estimate of the dose received by the wearer.

For airborne activity in the workplace, whether of artificial or natural origin, it is usually best to sample the air that the worker breathes, measure it, and then estimate the internal dose. In some cases, it may be possible to measure activity in excreta and infer the dose or indeed measure the activity in the body directly with sensitive detectors. The objective always is to get the best possible estimate of dose.

Average annual effective doses in different occupations (UNSCEAR)

Data for 1990–1994 Source: UNSCEAR Report 2000, Vol. 1, Annex E, Tables 12, 16, 22 and 43

Source	Dose (mSv)
Artificial sources	
Nuclear industry	
Uranium mining	*4.5*
Uranium milling	*3.3*
Enrichment	*0.1*
Fuel fabrication	*1.0*
Nuclear reactors	*1.4*
Reprocessing	*1.5*
Medical uses	
Radiology	*0.5*
Dentistry	*0.06*
Nuclear medicine	*0.8*
Radiotherapy	*0.6*
Industrial sources	
Irradiation	*0.1*
Radiography	*1.6*
Isotope production	*1.9*
Well-logging	*0.4*
Accelerators	*0.8*
Luminizing	*0.4*
Natural sources	
Radon sources	
Coal mines	*0.7*
Metal mines	*2.7*
Premises above ground (radon)	*4.8*
Cosmic sources	
Civil aircrew	*3.0*

Artificial sources

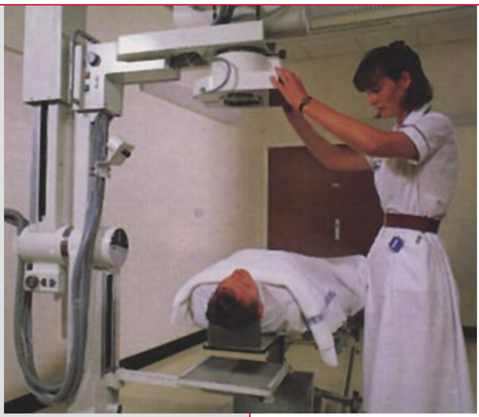
There are about 800 000 workers in the nuclear industry worldwide, and over 2 million workers exposed in medical facilities. UNSCEAR has compiled data on doses received by these workers and others such as industrial radiographers. The collective dose to nuclear industry workers is about 1400 man Sv, while that for medical radiation workers is about 800 man Sv. There are fewer workers in industrial uses of radiation, therefore the collective dose is lower at about 400 man Sv. However, these workers get the highest individual doses in some countries.

The average dose overall to occupationally exposed workers from artificial sources is less than 1 mSv in a year. The average in the nuclear industry tends to be a little higher than this, while the average for medical staff is slightly less. Doses have declined steeply in the last decade primarily because of the widespread introduction of ICRP recommendations and the BSS.

With the exception of mining, average doses from most types of occupational exposure from artificial sources, including the nuclear industry, are now below about 2 mSv in a year.

Doses in the health professions — medical, dental and veterinary — are generally very low, but there are still matters of concern. Some clinical procedures with diagnostic radiology require the physician to be close to the patient and at risk of appreciable exposure. X ray equipment and procedures in veterinary practices are frequently inadequate.

Natural sources

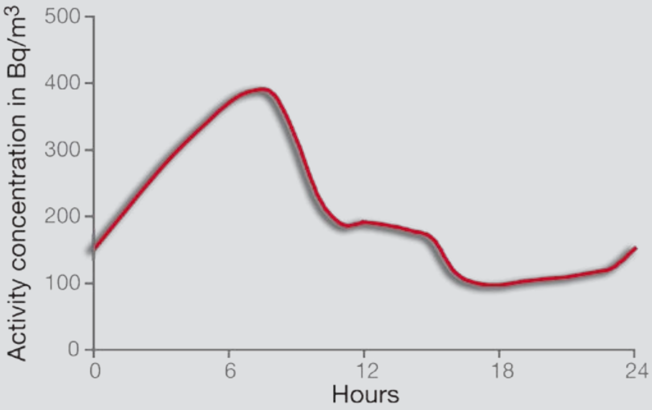


Medical radiographer wearing film badge

Occupational exposure to enhanced natural sources of radiation occurs mainly in mines, buildings and aircraft. Almost 4 million coal miners are monitored for radiation exposure. Fewer people (about a million worldwide) work in mines other than coal mines and in the processing of ores with levels of natural activity appreciably above average. The doses incurred are, nevertheless, monitored routinely.

Radon levels — and doses — are low in coal mines because the ventilation is usually good. Few if any miners exceed 15 mSv in a year. The state of ventilation in metal and other mines is not always as satisfactory, so the average dose is much higher and a fraction of the workforce does exceed this dose.

About one-fifth of the people considered to be occupationally exposed to enhanced natural radiation work in shops, offices, schools, and other premises in radon-prone areas. Within these areas, the average dose is appreciable. The average dose for such workers is almost 5 mSv per year — higher than for the other groups of occupationally exposed workers. However, it should be remembered that this group is unusual in that its members are identified, precisely because they receive high doses, rather than because they have the same occupation. Radon levels vary markedly from day to day because of the way buildings are heated and ventilated, so short measurements of radon in air may be misleading. The best remedy for high radon levels is the same as in houses — reduced air pressure under the floor.



Variation in indoor radon concentration in a house with moderate levels
J. Miles/NRPB

Doses to aircrew from cosmic rays depend on the routes flown and the amount of flying time. On average, the annual dose is around 3 mSv, but it could be twice as much for long flights continually at high altitudes. By the nature of the radiation and the operations, such doses are unavoidable.

Effective dose during air travel

Source: Exposure of Aircraft Crew to Cosmic Radiation, a report of the EURADOS Working Group 5 to the Group of Experts established under Article 31 of the Euratom Treaty. European Commission

Cities	Effective Dose (μSv)
Vancouver ➢ Honolulu	14.2
Frankfurt ➢ Dakar	16.0
Madrid ➢ Johannesburg	17.7
Madrid ➢ Santiago de Chile	27.5
Copenhagen ➢ Bangkok	30.2
Montreal ➢ London	47.8
Helsinki ➢ New York (JFK)	49.7
Frankfurt ➢ Fairbanks, Alaska	50.8
London ➢ Tokyo	67.0
Paris ➢ San Francisco	84.9

Total doses

The collective effective dose from occupational exposure to ionizing radiation is about 14 000 man Sv in a year worldwide, and workers can receive a few mSv in a year in some industries. Somewhat more than 80 per cent of this collective dose is from enhanced natural sources; less than 20 per cent is from man-made sources. The worldwide average dose to workers dealing with artificial sources is 0.6 mSv, and to workers exposed to natural sources it is 1.8 mSv. Combining these figures, the overall global average worker dose is 1.3 mSv per year. However, spread over the entire population, this implies an annual dose of about 0.002 mSv, a relatively minor contribution to the overall value of 2.8 mSv from all sources.

Chapter 10 Environmental pollution

We have seen in Chapter 7 that natural radionuclides pervade our environment. This chapter deals with the artificial radionuclides that have been widely dispersed by events such as tests of nuclear weapons in the atmosphere and the Chernobyl accident and by the deliberate discharge of radioactive wastes from nuclear and other installations. Such radionuclides find their way from air and water onto the ground and into foodstuffs and so deliver radiation doses in various ways to human beings.

Pathways of human exposure to radiation from the release of radionuclides to the environment

Rain washing radioactive materials out of the air

External radiation direct from cloud

External dose direct from radioactive materials deposited on the ground

Internal dose from eating and drinking radioactive materials in food

Internal dose from water intake

Nuclear weapon tests

When nuclear weapons were tested above ground, they propelled a variety of radionuclides from hydrogen-3 (tritium) to plutonium-241 into the upper atmosphere. From there, the radionuclides transferred slowly to the lower atmosphere and then to the Earth's surface. Around 500 atmospheric explosions were conducted before the limited test ban treaty was enacted in 1963, with a few more until 1980. The concentrations of radionuclides in air, rain and human diet are now much lower than the peak values in the early 1960s.

Globally, the most important radionuclides from testing in terms of human exposure are now carbon-14, strontium-90 and caesium-137. Minute quantities of these are ingested with food and drink. Residual activity from radionuclides in the ground that emit gamma rays also causes a slight degree of human exposure. Internal and external irradiation contribute about equally to the global average effective dose of 0.005 mSv in a year. This compares with a peak of more than 0.1 mSv in 1963. Some groups of people who receive significantly higher doses from global fallout than average have been identified. For example, it was found in the 1960s that reindeer and caribou herders in northern Europe and Canada received significantly higher doses than other people, because they eat the meat of animals that eat lichen, which is a very efficient collector of airborne caesium-137. The global collective dose from weapon tests fallout is now about 30 000 man Sv annually, assuming a world population of 6 000 million.

Site, country (country that conducted tests, if different)	***Type(s) of weapons test***	***Highest individual dose to local people at time of tests (mSv)***	***Collective dose (man Sv)***
Nevada, USA	*Atmospheric and underground*	*60–90*	*470*
Bikini and Enewetak, Marshall Islands (USA)	*Atmospheric*	*1100–6000*	*160*
Semipalatinsk, Kazakhstan (USSR)	*Atmospheric and underground*	*2000–4000*	*4600–11 000*
Novaya Zemlya, Russian Federation (USSR)	*Atmospheric*	*low*	*low*
Maralinga and Emu, Australia (UK)	*Atmospheric*	*1*	*700*
Christmas Island, Australia (UK)	*Atmospheric*	*low*	*low*
Reganne, Algeria (France)	*Atmospheric*	*unknown*	*unknown*
Lop Nor, China	*Atmospheric*	*0.1*	*unknown*
Mururoa and Fangataufa, French Polynesia (France)	*Atmospheric and underground*	*1–5*	*70*

In addition to assessments over many years of the doses from widespread dispersion of radionuclides from atmospheric testing of nuclear weapons, studies have been carried out by the IAEA on the longer term local effects of weapons testing in the atmosphere and underground. The results of these studies are summarized in the table opposite, and estimates have been made of the maximum annual radiation doses that would occur if people lived on some of these sites now. For the uninhabited atolls of Mururoa and Fangataufa in the South Pacific, where most of the testing was underground, the dose would be no more than 0.25 mSv even if the atolls were inhabited. At Bikini Island, also in the Pacific, the potential doses could have been up to 15 mSv, but remedial measures are being applied to reduce that figure by about 90 per cent before the islanders return.

Remnants of nuclear testing at Semipalatinsk: A goose tower built to observe nuclear tests.

For Semipalatinsk in Kazakhstan, where about one hundred atmospheric tests were conducted, a preliminary assessment showed that the maximum annual dose could be as high as 140 mSv if people were to live in the most heavily contaminated areas. Nobody does so at present, but with the potential for such high doses there is a need either to clean up the contamination or to make sure people cannot spend significant amounts of time in the most contaminated areas. There is an international effort, involving several UN organizations, to improve conditions for people in the Semipalatinsk area. The radioactive contamination on the test site is only one of the problems, but it will need to be addressed.

A lake produced by a nuclear explosion during an excavation experiment V. Mouchkin/IAEA

Chernobyl accident

An explosion in a nuclear reactor at the Chernobyl nuclear power plant on 26 April 1986 caused the release of substantial quantities of radionuclides during a period of ten days. Airborne material was dispersed throughout Europe from the site in Ukraine. As the contaminated air spread throughout Europe and beyond, local weather conditions largely determined where the radionuclides were to fall. Rainfall caused more radionuclides to be deposited in some areas rather than others.

The accident had a catastrophic effect locally and high radiation exposures of emergency workers led to the deaths of 31 people, including 28 firemen. The firemen received large external doses from deposited radionuclides, between 3 and 16 Sv, and contamination on their skin led to severe erythema, mostly due to beta emitters. A further 209 people were hospitalized of whom 106 were diagnosed as having acute radiation sickness. Fortunately all of these people recovered and were able to leave hospital within a few weeks or months.

High volume air sampler

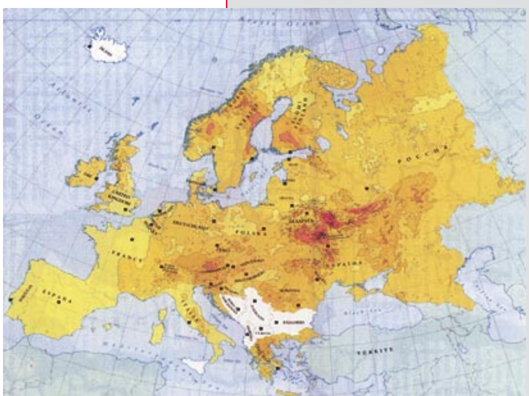
In terms of doses to people in the vicinity and beyond, the most significant radionuclides were iodine-131, caesium-134 and caesium-137. Almost all the dose was caused by external irradiation from radionuclides on the ground, by inhalation of iodine-131 giving rise to thyroid doses, and by internal irradiation from radionuclides in foodstuffs.

Nuclear power plant at Chernobyl V. Mouchkin /IAEA

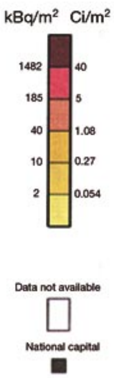
Following the accident, over 100 000 people were moved from their homes in what are now Belarus, Ukraine and the Russian Federation, and various areas became "restricted" because of the levels of fallout on the ground. A vast clean-up operation was mounted at the Chernobyl reactor site itself involving over 750 000 people. The people doing the decontamination work became known as "liquidators", and some of them received doses above the ICRP dose limit of 50 mSv. Such exposures may be justified in accident situations and ICRP recommends that exposures should not exceed 500 mSv in such circumstances. This ensures that workers could not experience any deterministic effects of radiation exposure, and published data from monitoring teams show that the average doses were kept below 165 mSv in the first year after the accident. In subsequent years, they were gradually reduced to below 50 mSv.

2000 UNSCEAR Report to UN Assembly

There have been exhaustive studies of populations in the vicinity of Chernobyl and elsewhere, looking for possible health effects from the accident. The only significant effect that has so far been shown to be caused by radiation is in children in regions of Belarus and Ukraine, who have an increased incidence of thyroid cancer due to intakes of iodine-131, particularly through drinking milk contaminated with iodine. Iodine-131 is a short lived radionuclide (8 days half life) known to concentrate in the thyroid, and using monitoring and other data it has been possible to estimate risk factors for this health effect in children. In 2000, UNSCEAR published a review of the effects of the Chernobyl accident. Their scientific assessments indicated that there had been about 1800 cases of thyroid cancer in children who were exposed at the time of the accident. Fortunately, in the great majority of cases, it is not a fatal condition, although it is a serious illness.



Distribution of ^{137}Cs following Chernobyl accident



UNSCEAR found no scientific evidence of increases to date in the incidence of any other health effects that could be related to radiation exposure. This does not mean that there will not be any other effects — the most highly exposed individuals have an increased risk of suffering radiation-associated effects in the future — but UNSCEAR concluded that the great majority of the population are not likely to experience serious health consequences attributable to radiation from the accident.

The other serious health effects seen in local populations appear to be the result of the stress and anxiety caused by the accident, including the fear of radiation itself. Although these effects are different in kind to the thyroid disorders mentioned above, they are no less real and occurred widely throughout Europe in regions affected by the fallout. For example in Scandinavia, doses of about 0.1 mSv were received on average during the first few weeks after the accident, and many people reported to their doctors feelings of nausea, headaches, diarrhoea and some skin rashes. Following a century of scientific study of the effects of radiation, it can be concluded that it is not possible that such low doses could lead directly to the effects reported. However, a potent fear of radiation is obviously real for some people, and this was one of the lessons of the Chernobyl accident.

Radioactive discharges

Radionuclides of artificial origin are discharged to the environment by the nuclear power industry, military establishments, research organizations, hospitals and general industry. Discharges of any significance should be subject to statutory control; they must be authorized and monitored. Owners or operators of the facilities from which radionuclides are discharged carry out monitoring programmes, as do some regulatory agencies.

The nuclear power industry discharges the most activity. At each stage of the *nuclear fuel cycle*, a variety of radionuclides are released in the form of liquids, gases, or solid particles. The nature of the effluent depends on the particular operation or process.

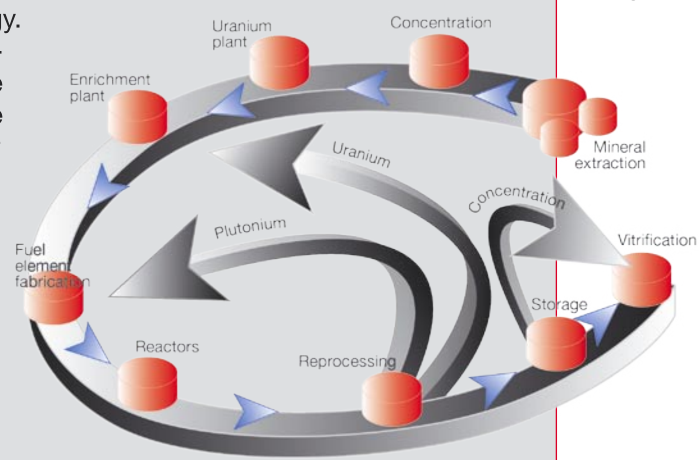


Diagram of nuclear fuel cycle showing fuel fabrication, reactor operation, fuel reprocessing, and waste management

Each year, nuclear power reactors generate about 20 per cent of the world's electrical energy. During routine operation of nuclear installations, the releases of radionuclides are low and normally exposures have to be estimated with environmental transfer models. For all nuclear fuel cycle operations, including mining and milling, fuel fabrication, reactor operation and fuel reprocessing, the local and regional exposures are estimated by UNSCEAR to be about 0.9 man Sv per gigawatt-year (GW a). The present world nuclear energy generation is about 250 GW a annually, and so the total collective dose from a year's generation of nuclear energy is about 200 man Sv. Generally individual doses are low, being below 1 μSv in a year. However certain individuals might receive higher doses because of where they live and what they eat and these should be subject to dose constraints, the maximum value being 300 μSv in a year.

In the case of accidents where there has been significant local contamination, the local doses can be significantly greater than the dose constraint. Where appropriate, measures are taken to minimize doses to people, such as the establishment of restricted areas in the vicinity of Chernobyl. Such measures can reduce both the individual and collective doses substantially.

Discharges from fuel reprocessing facilities give annual doses to the most exposed people — those who eat local seafood — up to 0.14 mSv mainly from *actinides*. Discharge to air of strontium-90 and other radionuclides leads to individual doses that are less than 0.05 mSv annually from the consumption of local milk and vegetables. The collective dose from airborne discharges, mainly due to carbon-14 in foodstuffs, is approximately 500 man Sv annually. From liquid discharges, it is about 4000 man Sv annually mainly due to caesium-137 in fish.

Annual doses due to discharges from the nuclear fuel cycle

Stage of cycle	***Type of effluent***	***Most exposed people (mSv)***	***Collective dose (man Sv)***
Fuel fabrication	*Airborne*	*0.01*	*350*
	Liquid	*0.01*	
Reactor operation	*Airborne*	*0.001*	*380*
	Liquid	*0.004*	
Fuel reprocessing	*Airborne*	*0.05*	*4500*
	Liquid	*0.14*	

Although radioactive discharges to the environment are now strictly controlled in most countries, in the past they have not always been managed as they should have been. In particular, some military facilities operating during the Cold War adopted waste management methods that would be unacceptable for a modern civilian facility. As a result of the operation of one such example, the Mayak facility near Chelyabinsk in the Russian Federation, areas around the plant and downstream on the Techa River have very high levels of contamination, and some local people may have received very high doses (up to 1 sievert or more) over their lifetimes.

Depleted uranium

Munitions using depleted uranium (DU) were used during the Gulf War in 1991 and in the conflicts during the 1990s surrounding the break-up of Yugoslavia. The risks of harm to military personnel on a battlefield should be put in context of the other self-evident risks, but the use of depleted uranium ordnance has raised concerns about subsequent health consequences, both to service personnel and to the public after the conflict.

As has already been discussed, uranium occurs naturally in the environment. It is widely dispersed in the Earth's crust, and in fresh water and sea water. As a result, we are all exposed to uranium isotopes and their decay products, and there are wide variations in doses received depending on local circumstances. DU is a by-product of the uranium fuel cycle where natural uranium is enriched to provide suitable fuel for nuclear power. It is called depleted because it has had some of its uranium-235 isotope removed. A large fraction of decay products of the uranium isotopes is removed during the fuel enrichment process.

Depleted uranium in munitions is in a concentrated metallic form, and there are understandable concerns about elevated levels in the environment due to spent munitions. There are also worries about people handling intact depleted uranium metal. Assessments of dose to military personnel who entered a tank shortly after it was hit by a DU weapon indicate possible doses of up to a few tens of mSv from inhalation of vapours and dust. In contrast, doses to people exposed some time afterwards to resuspended dust in the same local environment are likely to be a thousand times less, typically a few tens of μSv. Contact doses when handling bare DU metal are approximately 2.5 mSv/h, primarily from beta radiation, which is not penetrating and so affects only the skin. Even so, the collection of bare DU munitions needs to be discouraged and, if possible, avoided completely.

Doses from depleted uranium are, therefore, real and, in some circumstances, they could be appreciable for military personnel. Doses to people in the post-conflict phase are likely to be much lower and should be relatively easy to avoid.

Managing contaminated areas

As we have seen (and will see from other examples in later chapters), areas in various parts of the world have become contaminated with radionuclides as a result of various human activities. In cases where the level of contamination is high, measures might be needed to ensure that the area is safe for people to live or use for other purposes. For small areas, it might be possible to do this by removing contaminated soil and other materials, but for large areas the amount of material would be too large.

Pasture land nearby Semipalatinsk test site in Kazakhstan

Other ways of protecting people include restrictions on access to or use of areas, for example, preventing house building on areas affected by mining wastes that could produce high radon levels. Chemical treatments can also be used to reduce the amount of activity that gets from soil into food. Examples of this include giving 'Prussian blue' — a chemical that increases the rate at which caesium is excreted by the cow so that it does not get into milk and meat — to cows grazing on contaminated grass in the Chernobyl area and treating the soil on Bikini Island with potassium to stop the trees absorbing caesium.

Total doses

With the exception of some military facilities and those mentioned above, no other facilities that discharge artificial radionuclides to the environment cause doses much above 0.02 mSv in a year to the most exposed people; nor do they make a significant contribution to collective dose. On average, therefore, the maximum effective dose from the discharge of artificial radionuclides, other than some military facilities, is about 0.14 mSv in a year and the collective effective dose about 5000 man Sv in a year or 0.001 mSv when averaged throughout the entire global population.

Extracting oil from rapeseed provides new productive uses for land in Belarus contaminated by the Chernobyl accident
V. Mouchkin/IAEA

Chapter 11 Nuclear power

Nuclear reactors have been producing electricity since the 1950s and, in early 2003, there were 441 nuclear reactors operating in 30 countries with a total installed capacity of 359 GW.

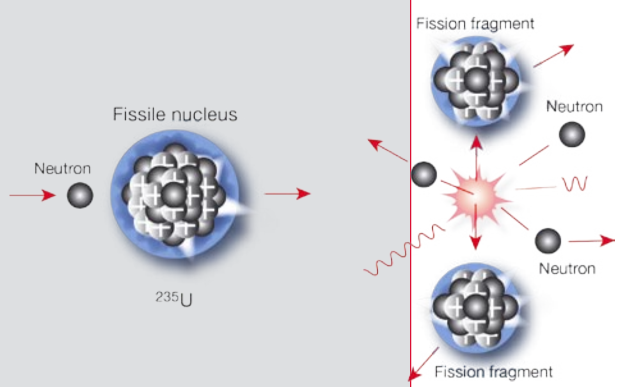
Nuclear reactors

Nuclear reactors depend on a reaction between neutrons and the atomic nuclei of the fuel for their operation. Uranium, the fuel for almost all reactors, consists principally of two isotopes, uranium-235 and uranium-238. In natural uranium, the fuel for early reactors, those isotopes are in the proportion of 0.7 per cent and 99.3 per cent, respectively, by weight. The *enriched uranium* used in most currently operating reactors contains about 2.5 per cent of uranium-235.

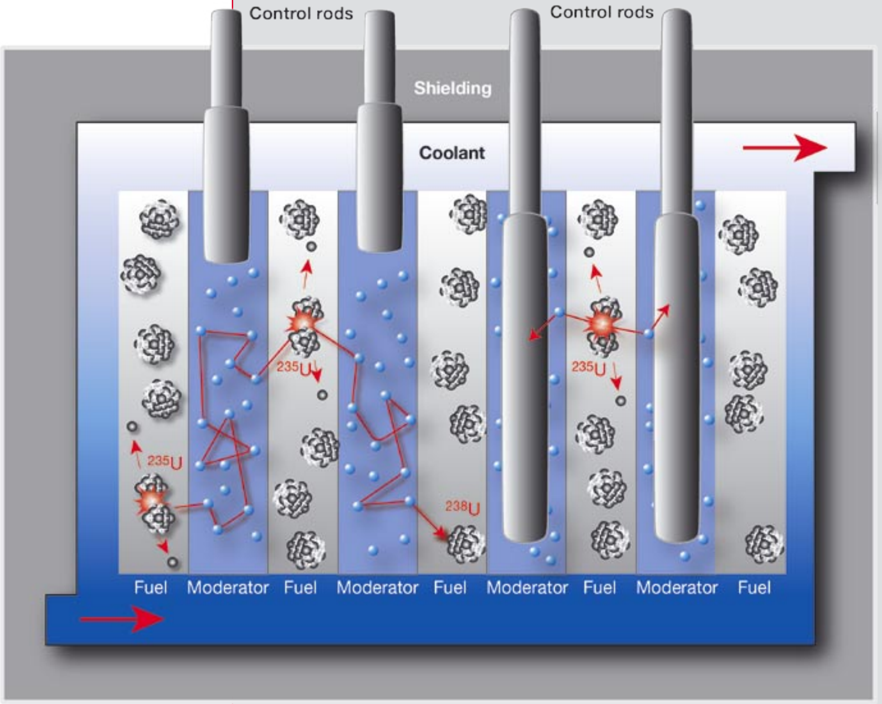
Energy is released when a uranium-235 nucleus absorbs a neutron and undergoes *fission*, that is, it splits into two large energetic fragments or *fission products*, accompanied by the release of several high energy or *fast neutrons* and some gamma radiation. The neutrons are slowed in the reactor so that they induce further fissions in the uranium-235. Such neutrons are often called *thermal neutrons* and the reactors that rely upon them *thermal reactors*. By contrast, when a nucleus of uranium-238 absorbs a fast neutron, it becomes uranium-239, which ultimately decays to form plutonium-239. This will also fission or capture neutrons to form isotopes of additional actinides, such as americium or curium. Consideration is currently being given to fuelling some reactors with mixed oxide fuel (known as MOX), which contains enriched uranium mixed with plutonium recovered from spent fuel by reprocessing. This is seen as a way of recycling fuel and controlling stockpiles of plutonium that can be used to make nuclear weapons.

The fuel in a nuclear reactor is assembled in an array called the core, which also contains the *moderator*, a material, generally water or graphite, that slows or thermalizes the neutrons. A coolant, usually water or gas, conducts heat away from the fuel and then passes through heat exchangers to make steam. The steam then drives turbine generators to make electricity.

Schematic diagram of uranium-235 fission



The fuel is sealed in metal containers, and the core is contained in a pressure vessel (or, in some designs, fuel elements are contained in separate pressure tubes). Massive concrete shielding helps to absorb the intense radiation emitted by the core during and after operation. Most reactors also have an additional containment building surrounding the reactors and usually the heat exchangers.



Schematic diagram of nuclear reactor

Fresh fuel is only mildly radioactive and can be handled without shielding. Once in the reactor, however, there is an enormous increase of activity due mainly to the fission products that have been generated in the fuel; this means that an accident at the reactor could release significant amounts of radioactive material. After removal from the reactor, the spent fuel remains hot and must be cooled to prevent melting, as well as shielded to reduce radiation exposure.

Although safety is a crucial issue for all nuclear power plants, there has been a particular focus since the Chernobyl accident and the breakup of the USSR on the safety of WWER and RBMK reactors. Thanks to the efforts of specialists in eastern Europe and the former Soviet Union supported by many international co-operation projects, great progress has been made in upgrading the safety of these reactors.

The main types of reactor are:

Pressurized water reactors (PWRs), boiling water reactors (BWRs) and *WWER reactors* (a Soviet reactor design similar to a PWR), all of which use water as moderator and coolant;

Heavy water reactors such as the Canadian-designed CANDU reactors, which use heavy water (water in which the hydrogen atoms have been replaced with deuterium, an isotope of hydrogen) as a moderator and coolant;

Gas cooled reactors, which use carbon dioxide gas as a coolant and usually graphite as moderator; and

Water-cooled graphite-moderated reactors of the RBMK design developed originally in the USSR.

Chapter 12 Waste management

In Chapter 10 we described the discharge of effluents from the nuclear fuel cycle, but there are also other radioactive wastes. These come not only from the various parts of the nuclear fuel cycle — from the mining and processing of uranium to the dismantling of old nuclear installations — but also from medical, industrial and research activities involving radioactive materials.

Exempt waste contains such a low concentration of activity that it does not need to be treated differently from ordinary non-radioactive waste;

Low/intermediate level waste consists of items such as paper, clothing and laboratory equipment that have been used in areas where radioactive substances are handled, as well as contaminated soil and building materials, along with more active materials used in the treatment of gaseous and liquid effluents before they are discharged to the environment, or the sludges that accumulate in the cooling ponds where spent fuel is stored;

Short lived waste contains mainly radionuclides with relatively short half-lives (less than 30 years), with only very low concentrations of long lived radionuclides;

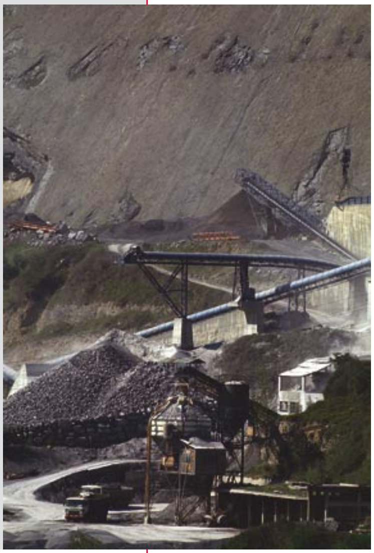
NORM (naturally occurring radioactive material) waste consists of often very large amounts of waste containing fairly low concentrations of naturally occurring radionuclides (though these concentrations are often higher than those found in nature). This type of waste is generated in the mining and processing of uranium and other minerals, such as phosphates used in fertilizers;

Alpha waste (or transuranic waste) — waste containing alpha emitting radionuclides such as isotopes of plutonium — is treated as a separate category in some countries; and

High level waste refers only to spent fuel from a reactor (in countries where this is regarded as a waste) or to the highly active liquid produced when spent fuel is reprocessed. The volume of this type of waste is very low, but its activity is so high that it generates considerable heat.

Different countries classify wastes in different ways, but a number of general categories can be identified

NORM waste is produced in mining and fertilizer processing



Type of waste	Typical sources	Characteristics	Disposal
Exempt waste	Contains very limited amounts of radionuclides	Can be treated as normal refuse	Normal municipal refuse disposal facilities
Mining waste	Mine tailings	Huge volumes	Mine tailings dams — return high grade tailings underground
NORM waste	Waste from minerals processing scale from pipes or equipment	Enhanced levels of naturally occurring radionuclides	Mine tailings for low grades, on surface storage for higher grades
Low/ intermediate level waste	Contaminated paper, clothing, laboratory equipment, contaminated soil and building materials Ion exchange materials from treatment of effluents sludges from cooling ponds	Limited heat generation	Shorter lived in near surface disposal facilities or intermediate depth mined caverns (from around 60 to 100 m depth) Longer lived stored pending development of deeper disposal facilities
Alpha waste	As low/intermediate level waste, but with alpha (especially plutonium) contamination	Treated as a special category in some countries	Geological disposal, consideration being given to intermediate depth storage (tens of metres)
High level waste	Spent fuel (when treated as waste) Highly active liquor from reprocessing	Need heavy shielding and cooling	Geological disposal (a few hundred metres deep in stable geological formations)

The aims of *waste management* are to process the wastes in such a way as to make them suitable for storage and disposal, and to store or dispose of them so that there are no unacceptable risks to present and future generations. Here *disposal* implies simply that there is no intention to retrieve them, rather than that it would be impossible to do so.

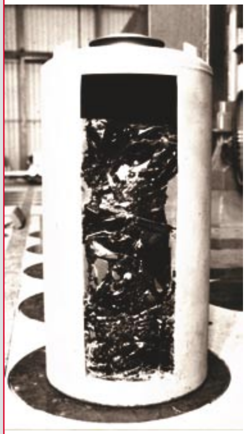
In many countries, short lived waste is disposed of in near surface repositories, which are normally either lined trenches several metres deep or concrete 'vaults' constructed on or just below the ground surface. The disposed waste is covered with a few metres of earth, and often a clay cap to keep water out. A similar disposal method is used in some countries for the disposal of large amounts of NORM waste, such as tailings from the mining and milling of uranium. For example, Sweden operates a repository under the bed of the Baltic Sea at Forsmark for its more active (but mostly short lived) low/intermediate level waste.

Underground repository in Sweden

Many low/intermediate level wastes do not occur in a form that is immediately suitable for disposal; they have to be mixed into an inert material such as concrete, bitumen or resin. In the past, some countries disposed of these wastes into the ocean, but since that has been prohibited by the London Convention, these wastes are normally stored awaiting decisions on the method of disposal. Among the most likely options is a repository deep underground in good geological conditions. Although many countries have plans for geological repositories of this type, only the USA is currently operating one, the Waste Isolation Pilot Plant (WIPP) in New Mexico, for wastes containing actinides.

Where the intention is to dispose of spent nuclear fuel directly rather than reprocess it, the spent fuel is stored, either at reactor sites or in special central facilities. This is partly to allow the fuel to cool, but clearly it must continue until a disposal facility is available. High level liquid waste from reprocessing operations is normally kept in special cooled tanks, but facilities to solidify it by incorporation in vitreous material are being built. The glass blocks will be stored for several decades to allow them to cool before eventual disposal, probably deep underground.

Vitrified high level radioactive waste



Decommissioning

Decommissioning is the process that takes place at the end of the working life of a nuclear facility (or part of a facility), or any other place where radioactive materials were used, to bring about a safe long term solution. This might include decontaminating equipment or buildings, dismantling facilities or structures, and removing or immobilizing remaining radioactive materials. In many cases, the ultimate objective is to clear the site of all significant radioactive residues, but this is not always possible or necessary.

The Greifswald and Rheinsberg decommissioning project in Germany
J. Ford/IAEA

After removal of nuclear fuel, reactor vessel is shielded for decommissioning work

Negatively pressurized compaction room, where dismantled pieces are compacted and placed in specialized containers

To date, relatively few full scale commercial nuclear facilities have been completely decommissioned. However a great deal of experience has been gained from the decommissioning of a wide variety of facilities, including a few nuclear power plants, several prototype and research reactors, and many laboratories, workshops, etc. The fact that many nuclear reactors around the world are approaching the end of useful life has focused attention on the issues associated with decommissioning.

Decommissioning requires strict control of operations to optimize the protection of workers and the public. For dealing with the most radioactive parts of a facilities, particularly reactor cores, remote handling techniques have been developed. Dismantling of large facilities also generates large volumes of ‘waste’. Some of this will be low/intermediate level radioactive waste and needs to be managed accordingly. However, there may also be large amounts of structural materials — such as steel and concrete — that are not significantly radioactive. Special procedures may be needed to ‘clear’ such materials as exempt, meaning that they do not have to be treated as radioactive waste.

Disposal criteria

There has been considerable discussion of the criteria to be used in judging the acceptability of waste disposal methods both from a radiological protection point of view and from the wider social perspective. The consensus would seem to be that people in future generations should be protected to the same degree as they would be at present. However, it is difficult to translate this requirement into practical standards of radiological protection. For example, activity may only emerge from a deep repository many thousands of years later, and we have no idea what the habits or ways of life of our descendants will be so far into the future.

A second requirement is to apply the principle that all exposures should be as low as reasonably achievable once economic and social factors have been taken into account. This means that the various options for managing a particular type of waste — including treatment, immobilization, packaging and disposal — should be compared on the basis of the associated risks, costs and other less quantifiable, but no less important factors. Some of this comparison will be within the scope of radiological protection, but other influences could determine the eventual decision.

The difficult question for society about waste disposal is what weight to give now to a mathematical probability of harmful effects in the distant future. This problem is not unique 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. This response must of course be tempered by the uncertainties of making predictions of potential effects centuries and millennia from now.

Other waste management practices

Some other waste management practices in the past were, for various reasons, not as good as they should have been, and this has resulted in some cases of actual or potential long-term contamination of the environment.

Again, one example comes from military operations. Nuclear powered submarines from the northern fleet of the Soviet Union (and later the Russian Federation) have been taken out of service over the years. Many of these submarines are currently in dock awaiting proper management, but in some earlier cases the Soviet Union put waste from submarine reactors, and even reactor fuel, into the sea, notably the Kara and Barents Seas in the Arctic. Between 1993 and 1997, The International Arctic Seas Assessment Project, co-ordinated by the IAEA, reviewed the situation and concluded that, because of the slow release of radioactivity from the solid wastes and the dilution provided by the sea, the doses to members of the public would be very low (less than 0.001 mSv per year). Military personnel stationed in the area could get significantly higher doses, similar to the doses already received from natural sources (up to a few mSv per year).

Unrehabilitated uranium tailings in Tajikistan F. Harris/IAEA

Several areas around the world are affected by large deposits of waste from the mining and processing of radioactive ores. This is most commonly from uranium mining, but in some areas the abundance of naturally occurring radionuclides is such that spoil from other types of mining (some of it as early as the Middle Ages) is also a significant radiological hazard. A number of industries, such as the manufacture of fertilizers and the oil and gas industries, also produce wastes of a similar nature. The radionuclides involved are all of natural origin, and hence it is only comparatively recently that these wastes have been recognized as a radiological problem. The levels of radionuclides in the ores were typically higher than average and have often been increased by chemical or physical processes, so they are significantly higher than usually found in nature (though their activity concentrations are not very high compared with those of nuclear waste). Furthermore, the radionuclides have extremely long half-lives, and there are often extremely large amounts of waste.

These wastes can be managed safely, for example in engineered, clay-capped impoundments, and countries such as Canada, the USA, Germany, and Australia have adopted such methods. However, some developing countries, e.g. central African countries and some of the central Asian republics that were formerly part of the Soviet Union, do not have the resources to handle such huge amounts of material in this way. The IAEA, among others, is helping these countries to find safe solutions.

Chapter 13 Emergencies

Despite all the safety measures applied in using radiation and radioactive materials, accidents can happen.

An emergency may arise at a nuclear installation and lead to the accidental release of radioactive material, its dispersion beyond the boundary of the site, and the need for urgent measures to protect the public. In some circumstances, the release may be brief, in others prolonged. Significant accidents have happened in 1957 at Windscale (in the UK) and at Kyshtym (then USSR, now Russian Federation), in 1979 at Three Mile Island (USA) and in 1986 at Chernobyl (then USSR, now Ukraine). Although such accidents may be rare, it is prudent to be prepared for them.

Demolition and removal of rubble from a house contaminated during the Goiânia accident

Much more common are emergencies involving radiation sources from medical, industrial, research, and military applications. Over recent years, the IAEA has received an average of three or four reports each year of emergencies where people have been exposed to high doses because such sources have been lost, stolen, abandoned, or operated wrongly. Since the 1987 accident at Goiânia, Brazil, in which four people died from exposure due to a medical radiation source found in an abandoned building, there have been more than a dozen fatal accidents worldwide involving radiation sources. *(see Table on page 66)*

The Tokaimura accident in 1999 was unusual in that it involved a sustained nuclear reaction, started inadvertently in chemical processing of enriched uranium . The only release of radioactive material was a very small amount of very short-lived radionuclides. The radiological hazard in this accident was the direct radiation — especially the neutron radiation — coming from the vessel in which the reaction was taking place. Because it was not foreseen that such a reaction could happen, the building did not have the protective shielding that would have been present in a nuclear power plant, and so the radiation caused significant doses outside the building.

Because some types of emergency can have consequences outside the country where the accident occurs, there are legally binding international agreements relating to emergencies. All of the countries with operating nuclear power plants (and more than 50 others) are parties to the Convention on Early Notification of a Nuclear Accident, which requires them to notify nearby countries if they have an accident that might affect those countries. They must also notify the IAEA, who will then help to disseminate information about the situation. Over 80 countries are also party to the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, whereby they undertake to provide assistance in such an emergency if any country requests it. Again, the IAEA has an important role defined by the Convention, to disseminate information and co-ordinate assistance.

Nuclear emergencies

To ensure that there is adequate protection against accidents, national nuclear licensing authorities require detailed safety analyses of major nuclear installations such as reactors. These analyses identify potential accident sequences that might lead to the release of radionuclides. Emergency plans are based on consideration of the sequence leading to the largest release that can reasonably be foreseen, but they could be strengthened and extended in the unlikely event of a more severe accident.

Should an accident occur at a reactor, for example, various radionuclides in gaseous, volatile, or particulate form could be expelled to the atmosphere. They would then be carried away in a radioactive plume by the wind and be dispersed and diluted. Some would fall to the ground, particularly if it were raining. The concentration of radionuclides in the air would decrease rapidly downwind from the site, as would the resulting hazard. Even so, appreciable quantities of radionuclides could be deposited on the ground at considerable distances.

Depiction of plume dispersion and deposition

Radioactive material carried by wind

Direct radiation

Inhalation

Rain washing material out of plume

Contamination of food

Direct radiation from contamination

Countermeasures

It may be necessary to take action to reduce the radiation dose to the people living near to an accident site. Various countermeasures could be undertaken singly or in combination. Some of these measures — urgent countermeasures — really need to be initiated before there is a release of radioactive material, if they are to be effective. This means that decisions must be taken on the basis of what is happening at the plant (and what is predicted to happen), rather than waiting until a release is detected. This could sometimes mean that countermeasures are taken as a precaution that might turn out to have been unnecessary, but this is preferable to acting too late.

People may be advised to stay indoors or even leave home until the plume has blown over or the release has been stopped. People could take non-radioactive iodine tablets to prevent radioactive iodine reaching the thyroid gland. It may also be necessary to introduce temporary restrictions on the distribution of milk and vegetables and other foods produced locally. Some simple countermeasures might be taken after the plume has passed, such as hosing roads and paths or cutting and removing grass from gardens so as to remove surface activity.

When the emergency has passed, it may be necessary to introduce other countermeasures during a prolonged recovery period so as to protect the public from the residual activity.

There are elaborate and well-rehearsed plans for dealing with nuclear emergencies in countries with nuclear installations and also in many other countries that might be affected by an accident in a neighbouring country. Every nuclear site should have an emergency plan and let the local people know about it. The plan will involve the operator's staff, the local governmental authorities and the emergency services. National government departments and agencies will also become involved: each will deploy its radiological resources and expertise.

A typical emergency plan would envisage the following sequence of events. In the early stages of an accident, the operator will advise the police on measures to protect the public. Soon a co-ordinating centre away from the site will be set up at which those people with defined responsibilities and technical advisors will decide upon actions to protect the public. These will include environmental monitoring, as well as appropriate countermeasures. Arrangements will be made to brief the news media.

As noted above, because nuclear accidents can affect large areas, the Convention on Early Notification of a Nuclear Accident also requires any country having an accident that could affect its neighbours to notify the IAEA and any countries that could be affected.

The need for emergency planning is not restricted to nuclear installations. Wherever radiation sources are used there should be appropriate contingency plans to cope with the types of emergency that could happen. These need not be on the scale required for a nuclear power plant, but they should address any accidents that could conceivably occur.

Counter-measures in an emergency

Sheltering indoors from the plume

Temporary evacuation of homes

Administration of iodine tablets

Ban on contaminated foodstuffs

Intervention standards

Taking countermeasures after accidents is another example of the procedure that ICRP calls intervention. We have seen in Chapter 5 that intervention must be justified and optimized. It is only necessary to add that countermeasures must be taken to avoid doses high enough to cause obvious injury in anyone exposed — but especially children.

The BSS specify intervention levels of dose for the introduction of countermeasures to protect the public. These are used to identify which actions would be most suitable in particular circumstances.

International intervention levels for countermeasures

Countermeasure	*Organ*	*Dose level to be averted*
Sheltering	*Whole body (effective)*	*10 mSv in 2 days*
Evacuation	*Whole body (effective)*	*50 mSv in 1 week*
Iodine administration	*Thyroid*	*100 mGy*

Action levels for some foods and for water (Bq/kg)

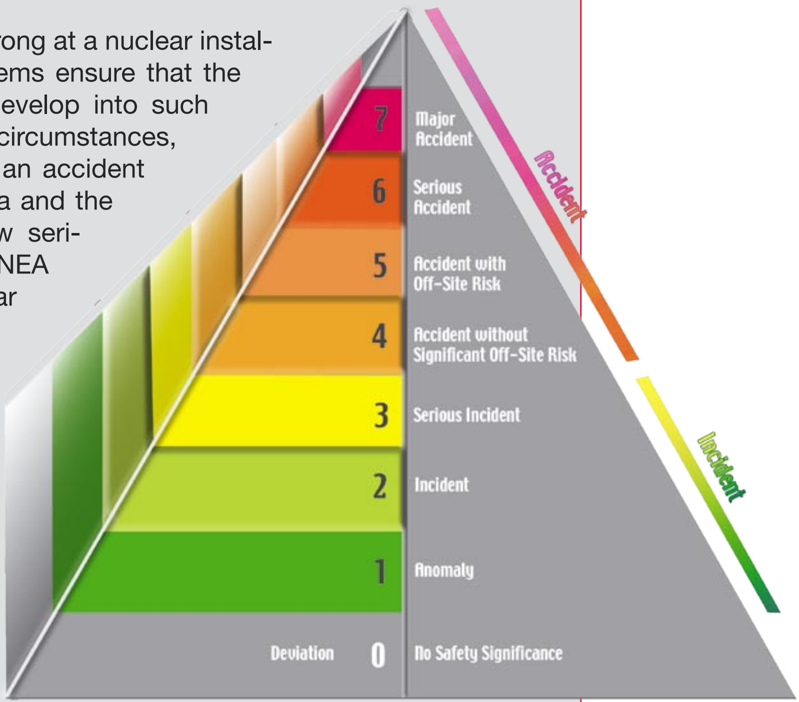
Important radionuclides	*Milk, infant foods and drinking water (Bq/kg)*	*Other foods (Bq/kg)*
Strontium-90		*100*
Iodine-131	*100*	
Plutonium-239	*1*	*10*
Caesium-137	*1000*	*1000*

Source: The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Schedule V, Table V-I

One outcome of the Chernobyl accident was the introduction of action levels for radioactive contamination of food by the Codex Alimentarius Commission of the FAO and WHO. These action levels, set out for the first year following an accident, are for international trade purposes, but also provide useful guidance to national authorities on local consumption of food products.

Public information

In most cases, when something goes wrong at a nuclear installation, the various levels of safety systems ensure that the situation is controlled and does not develop into such an accident. It is only in very unlikely circumstances, where several safety systems fail, that an accident (event) may result. To provide the media and the public with a simple indication of how serious an event is, the IAEA and OECD/NEA have developed the International Nuclear Event Scale (INES). Events are rated on a scale of zero to seven: a rating of zero means that there was a problem but that the safety systems worked properly and corrected it before there was any risk to workers or the public, whereas a rating of seven means a major nuclear disaster on the scale of the 1986 Chernobyl accident.



The International Nuclear Event Scale (INES)

For prompt communication of safety significance

Other radiological emergencies

As with nuclear accidents, there are two sides to dealing with the risk of emergencies involving radioactive sources: doing as much as possible to prevent accidents, but also being prepared to respond should an accident happen.

Accidents involving radioactive sources can be prevented by ensuring that only those who are properly qualified and trained use and look after the sources. Established procedures should be followed to make sure that the source is used correctly and is not lost, damaged or stolen, or otherwise allowed out of the responsible user's control. This requires that national authorities have a proper and reliable system in place to keep track of where sources are and who is responsible for them. Over the past few years, the IAEA, through its technical co-operation programme, has made significant efforts to help countries develop such systems for controlling the sources under their jurisdiction. Despite some progress accidents continue to occur, indicating that there is still work to be done.

The IAEA is helping Georgia search for radioactive sources abandoned in remote areas P. Pavlicek/IAEA

When accidents do occur, measures may be needed to recover control of the source involved and make it safe, to treat people who have been exposed as a result of the accident, and to investigate how the accident happened and hence learn how accidents can be avoided in the future. In many recent cases of this type, the countries concerned have requested assistance from the IAEA under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency to carry out one or more of these measures.

Chapter 14 Risks from radiation sources

In normal everyday use, radiation sources and technologies are used by professionals in well managed, properly regulated institutions. As described previously, radiation sources can be generating devices, such as X ray machines or particle accelerators used in medicine. The sources can also be radioactive materials sealed in a secure capsule or housing. Some sources, particularly those used in nuclear medicine and research are radioactive materials in an unsealed form. Problems can arise if radiation sources are involved in accidents, and if they become damaged or lost.

Accidents involving radiation sources

Radiation sources are widely used in industry and accidents can occur either as a result of poor management or sometimes because of bad judgement.

A large number of accidents involving radiation sources and radioactive materials have been reported over the past half century. People have died from causes attributed to excessive radiation exposure, and many more have suffered serious, sometimes disabling injuries. In some cases, the associated environmental damage has been notable, and restoration financially costly. A common denominator of the major accidents is a breach of safety or security requirements. Another common thread is that for the most part they could have been prevented through the enforcement of international safety standards that were developed and issued for that purpose.

Blistering of the right hand following radiation injury

Between 1945 and 1999 there were some 140 serious reported accidents involving excessive radiation exposure in the nuclear industry, military facilities, hospitals, research facilities, and general industry. The most frequent occurrence (about 70 in total) is the mishandling or misappropriation of sealed sources used for radiography in industry and radiotherapy in hospitals. Some of the most serious health consequences have been caused by therapy sources being taken from discarded hospital equipment by people who did not appreciate the acute radiation hazard that could result. Unfortunately, there are also cases of unintentional overexposures of patients from radioactive sources in medicine, usually caused by human error or inappropriate calibration procedures.

The following table gives information on the most serious accidents that resulted in fatalities reported between 1987 and 2001.

Recent Fatal Radiation Accidents (1987–2001)[a]

Year	Location	Type of Source	Deaths caused by radiation exposure		
			Workers	Public	Patients
1987	Goiâna, Brazil	Removed teletherapy source		4	
1989	San Salvador, El Salvador	Industrial sterilizer	1		
1990	Zaragoza, Spain	Radiotherapy accelerator			several[b]
1990	Soreq, Israel	Industrial sterilizer	1		
1991	Nesvizh, Belarus	Industrial sterilizer	1		
1992	China	Lost cobalt-60 source		3	
1992	USA	Brachytherapy			1
1994	Tammiku, Estonia	Source removed from waste repository		1	
1996	San José, Costa Rica	Radiotherapy			several[b]
1997	Sarov, Russian Federation	Critical assembly	1		
1999	Tokaimura, Japan	Criticality accident	2		
2000	Thailand	Lost cobalt-60 source		3	
2000	Egypt	Lost cobalt-60 source		2	
2001	Panama	Radiotherapy overexposures			several[b]

Notes:

[a] In nuclear facilities and non-nuclear industry, research and medicine

[b] The individuals affected in these cases were patients receiving radiotherapy for cancer, and therefore the number of deaths attributable to overexposure is not known.

The numbers of patients overexposed were 26 (Zaragoza), 115 (San José) and 28 (Panama).

In each case, overexposure is considered likely to have been a direct or major cause of several deaths.

Lost sources causing contamination incidents

Many sources are sealed devices, with the radioactive material firmly contained or bound within a suitable capsule or housing; others consist of radioactive materials in an unsealed form. Sealed radioactive sources should only present a risk of exposure to external radiation. However, damaged or leaking sealed sources, as well as unsealed radioactive materials, may lead to radioactive contamination of the environment and the intake of radioactive substances into the human body.

Melting of disused radioactive sources accidentally sent with scrap metal for recycling is of particular concern. The table below gives an assessment of the major contamination incidents that have involved sources appearing in the recycled metal industry.

Major contamination incidents involving lost sources

Type of source mislaid	***Number of reported incidents worldwide (1983–1998)***	***Recycled metal industry involved***
Cobalt-60	*15*	*Steel (14), Copper*
Caesium-137	*30*	*Steel (27), Aluminium (2), Lead*
Iridium-192	*1*	*Steel*
Radium-226	*3*	*Aluminium (2), Steel*
Thorium-232	*3*	*Aluminium (2), Steel*
Americium-241	*3*	*Aluminium, Copper, Gold*
Others	*4*	*Aluminium, Copper, Zinc, Lead*
Total	***59***	

Each of these incidents had a significant economic impact on the industry involved, and some also led to environmental and health consequences. In addition to those listed, there are many more cases of lost sources being discovered by radiation monitoring equipment installed by the metal recycling industry. The installation of radiation detectors at recycling facilities is becoming common practice in many countries, and, therefore, the number of serious contamination incidents is expected to decrease.

Radioactive Dispersal Devices

Although some of the events described above involved the theft of sources by people who didn't realize the risk, deliberate attempts to use radioactive sources as a terrorist weapon are extremely rare. Since the 11th September, 2001 terrorist attacks in the USA, there has been much speculation about the possibility of terrorists making a radioactive dispersal device or 'dirty bomb' using conventional explosives and a stolen radioactive source. Such a bomb could not cause a nuclear explosion, but could disperse radioactive material over an area up to a square kilometre or so. While this might, like the accidents described previously, cause a small number of local casualties, the overall radiation effects would be limited. The wider the material is dispersed, the more diluted it will be and the lower the doses are that people could receive. Nevertheless, severe social disruption could arise. The construction of such a device would be likely to entail dangerously high radiation doses to the terrorists, but would be possible if they were able to obtain a source and were not concerned for their own safety. This possibility reinforces the need for effective measures to ensure that radioactive sources are kept securely under control until they are disposed of permanently.

Chapter 15 Transport of radioactive materials

Radioactive materials are routinely transported all around the world by air, sea, road and rail. These materials include those associated with the nuclear fuel cycle — from uranium ores to spent fuel and radioactive waste — but also radionuclides for nuclear medicine and research, and radioactive sources for industry and radiotherapy. Although the safety record of these transports is excellent, they sometimes cause concern in the areas through which they pass. For example, a number of countries have expressed particular concern about ships carrying radioactive waste passing through or close to their territorial waters.

Transport of irradiated nuclear fuel elements

Regulations are, therefore, needed not just to ensure that the chances of an accident, which could result in radioactive material being dispersed in the environment, are kept to a minimum, but also to ensure that the workers involved in transport — including those loading and unloading shipments as well as drivers/pilots — are protected. Because much of this transport is international, transport safety was one of the first areas in which the IAEA developed safety standards. The IAEA Regulations for the Safe Transport of Radioactive Material were first published in 1961 and have been revised periodically since.

The Regulations govern the necessary packaging, shielding, labelling and other precautions that must be taken when transporting various types of radioactive material, including tests that packages must undergo to prove that they can withstand possible accidents. The requirements are graded according to the level of activity of the materials to be transported. In general, more hazardous radioactive materials need more extensive and more robust packaging and stricter quality and administrative controls.

The IAEA's Transport Regulations are widely accepted as the global standard for the transport of radioactive materials. In some cases, the Agency's Regulations are incorporated into national laws or regulations. Other countries write their own regulations governing transport of radioactive materials, but make them consistent with the IAEA Regulations. Another way in which the Agency's Regulations are applied is through international regulations on the transport of hazardous goods. The regulations for the different modes of transport are issued by different organizations, particularly the International Civil Aviation Organization (ICAO) for air transport, the International Maritime Organization (IMO) for transport by sea, and regional organizations such as the Inland Transport Committee of the UN Economic Commission for Europe for transport by land and inland waterways. These organizations' regulations cover all types of hazardous material, and the parts that deal with radioactive materials are based on the IAEA Transport Regulations.

It is generally accepted that compliance with the IAEA Transport Regulations (either directly or via other regulations) assures the safety of workers and the public. However, there are often questions about whether the Regulations are complied with for particular shipments. IAEA surveys have suggested that they are widely implemented. As a way of demonstrating that they do comply, Member States can ask the IAEA to conduct an appraisal of their implementation of the Regulations. An international peer review team visits the country, studies their arrangements and then reports their findings and recommendations.

Testing ability of spent fuel transport container to withstand impact of train crash

Appendix A. Glossary

Absorbed dose The energy imparted by ionizing radiation to a suitably small volume of matter divided by the mass of that volume. Unit gray, symbol Gy. 1 Gy = 1 joule per kilogram.

Actinides A group of 15 *elements* with *atomic number* from that of actinium (89) to lawrencium (103) inclusive. All are *radioactive*. Group includes uranium, plutonium, americium, and curium.

Activity The rate at which nuclear transformations occur in a *radioactive material*. Used as a measure of the amount of a *radionuclide* present. Unit becquerel, symbol Bq. 1 Bq = 1 transformation per second.

Alpha particle A particle consisting of two *protons* plus two *neutrons* (i.e. the *nucleus* of a helium *atom*) emitted by a *radionuclide*.

Atom Unit of matter consisting of a single nucleus surrounded by a number of *electrons* equal to the number of *protons* in the nucleus. The smallest portion of an *element* that can combine chemically with other atoms.

Atomic mass The mass of an *isotope* of an *element* expressed in atomic mass units, which are defined as one-twelfth of the mass of an *atom* of carbon-12. (An atomic mass of 1 is equivalent to about 1.66×10^{-27} kg.)

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

Becquerel See *activity*.

Beta particle An *electron* or *positron* which has been emitted by an atomic *nucleus* or *neutron* in a nuclear transformation.

Brachytherapy The use of sealed radioactive sources in or on the body for treating certain types of cancer.

Chromosomes Rod-shaped bodies found in the *nuclei of cells* in the body. They contain the *genes*, or hereditary constituents. Human beings possess 23 pairs.

Collective dose The total *radiation dose* incurred by a population. Frequently used for *collective effective dose*.

Collective effective dose The quantity obtained by adding the *effective doses* received by all of the people in a defined population (often all of the people exposed to *radiation* from a particular source). Unit man sievert, symbol man Sv. Frequently abbreviated to collective dose.

Consumer products Devices such as smoke detectors, luminous dials, or ion generating tubes that contain a small amount of *radioactive* substances.

Cosmic rays High energy *ionizing radiation* from outer space. Have a complex composition at the surface of the Earth.

Decay The process of spontaneous transformation of a *radionuclide* or the decrease in the activity of a *radioactive* substance as a result of this process.

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

Decommissioning Administrative and technical actions taken to allow the removal of regulatory controls from a facility. *Decommissioning* typically includes dismantling the facility, but this need not be the case.

Depleted uranium Uranium containing a lesser mass percentage of uranium-235 than the 0.7 per cent found in *natural uranium*. A by-product from the production of *enriched uranium*.

Diagnostic radiology The use of radiation (e.g. *X rays*) or radioactive materials in medicine for identifying disease or injury in patients.

Disposal In relation to *radioactive waste*, emplacement in an appropriate *facility* 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 a measure of the energy deposited by *radiation* in a target. See the more specific terms *absorbed dose, equivalent dose, effective dose* and *collective effective dose.* Frequently used for *effective dose*.

Effective dose A measure of *dose* designed to reflect the amount of *radiation detriment* likely to result from the *dose*. Obtained by multiplying the *equivalent dose* to each tissue or organ by an appropriate tissue weighting factor and summing the products. Unit sievert, symbol Sv. Tissue weighting factors are tabulated in Chapter 2.

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

Electromagnetic radiation Radiation consisting of electrical and magnetic fields oscillating at right angles to each other. Ranges from very long wavelengths (low energy) such as radio waves, through intermediate wavelengths such as visible light to very short wavelengths (high energy) such as *gamma rays*.

Electron A stable elementary particle having a negative electric charge of 1.6×10^{-19} C and a mass of 9.1×10^{-31} kg.

Electron volt Unit of energy employed in radiation physics. Equal 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 containing a greater mass percentage of uranium-235 than the 0.7 per cent found in *natural uranium*.

Equivalent dose A measure of the *dose* to a tissue or organ designed to reflect the amount of harm caused to the tissue or organ. Obtained by multiplying the *absorbed dose* by a radiation weighting factor to allow for the different effectiveness of the various types of *radiation* in causing harm to tissue. Unit sievert, symbol Sv. Radiation weighting factors are given in Chapter 2.

Erythema Reddening of the skin caused by dilation of blood vessels. Can occur as a result of high *radiation doses*.

Excitation A process by which *radiation* imparts energy to an *atom* or *molecule* without causing *ionization*. The energy may be absorbed by the *nucleus* or the *electrons*, and may be released in the form of *radiation* when the *atom* or *molecule* ‘relaxes’.

Fallout Airborne radioactive material from the testing of nuclear weapons or nuclear accidents deposited on the Earth’s surface.

Fast neutrons High energy (i.e. fast moving) *neutrons*, such as those produced by nuclear *fission*. In reactor physics, conventionally defined as neutrons with kinetic energies greater than 0.1 MeV. Corresponding velocity of about 4×10^{6} m/s

Fast reactor A *nuclear reactor* in which fission is induced predominantly by *fast neutrons*.

Fission Nuclear fission. The division of a heavy nucleus into two (or, rarely, more) parts with masses of equal order of magnitude, usually accompanied by the emission of *neutrons* and *gamma radiation*.

Fission products *Nuclides* produced by nuclear fission or by the subsequent *radioactive decay* of the *nuclides* thus formed.

Free radical An uncharged *atom* or group of atoms having one or more unpaired electrons which were part of a chemical bond. Generally very reactive in a chemical sense.

Fusion Thermonuclear fusion. The merging of two light *nuclei*, resulting in the production of at least one nuclear species heavier than either initial *nucleus*, together with excess energy.

Gamma ray Penetrating electromagnetic radiation emitted by an atomic nucleus during radioactive decay and having wavelengths much shorter than those of visible light.

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

Genes The biological units of heredity. They are arranged along the length of *chromosomes*.

Gray See *absorbed dose*.

Half-life For a *radionuclide*, the time required for the *activity* to decrease, by a radioactive decay process, by half. Symbol $t_{1/2}$.

Ion An *atom*, *molecule* or fragment of a *molecule* that has acquired an electric charge through the loss or capture of *electrons*.

Ionization The process by which an *atom* or *molecule* acquires or loses an electric charge. The production of *ions*.

Ionizing radiation For the purposes of *radiation protection*, *radiation* capable of producing ion pairs in biological material(s). Examples are *alpha particles, gamma rays, X rays* and *neutrons.*

Irradiation The act of being exposed to radiation. It can be intentional, for example through industrial irradiation to sterilize medical equipment, or accidental, for example through proximity to a source that emits radiation. Irradiation does not usually result in radioactive contamination, but damage can occur depending on the dose received.

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

Man sievert See *collective effective dose*.

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

Moderator A material used in *thermal reactors* to reduce the energy and speed of the *fast neutrons* produced as a result of *fission* to become *thermal neutrons* that can cause further *fission*.

Molecule A group of *atoms* bonded to each other chemically. 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 having no electric charge, a mass of about 1.67×10^{-27} kg and a mean lifetime of about 1000 seconds

Non-ionizing radiation *Radiation* that is not *ionizing radiation*. Examples are *ultraviolet radiation, visible light, infrared radiation* and *radiofrequency radiation.*

Nuclear fuel cycle All operations associated with the production of nuclear energy, including: mining and milling, processing and enrichment of uranium; manufacture of nuclear fuel; operation of *nuclear reactors*; reprocessing of nuclear fuel; any related research and development; and all related *waste management* activities (including *decommissioning*).

Nuclear medicine The use of *radionuclides* for diagnosing or treating disease in patients.

Nuclear reactor A device in which a self-sustaining *nuclear fission* chain reaction can be maintained and controlled. (A reactor employing *fusion* reactions is a thermonuclear reactor.)

Nucleus (of an atom) The positively charged central portion of an *atom*. Contains the *protons* and *neutrons*.

Nucleus (of a cell) The centre of a human cell that controls its functioning. Contains the important genetic material: *DNA*.

Nuclide A species of *atom* characterized by the number of *protons* and *neutrons* and the energy state of the *nucleus*.

Order of magnitude A factor of ten or so, or an approximate value of a quantity, given to the nearest power of ten.

Photon A quantum of *electromagnetic radiation*.

Positron A stable elementary particle having a positive electric charge of 1.6×10^{-19} C and a mass of 9.1×10^{-31} kg (i.e. similar to an *electron*, but positively charged).

Pressurized water reactor A *thermal reactor* using water as both *moderator* and coolant. The water is maintained under pressure to prevent boiling.

Probability The mathematical chance that a given event will occur.

Proton A stable elementary particle having a positive electric charge of 1.6×10^{-19} C and a mass of 1.67×10^{-27} kg.

PWR *Pressurized water reactor*.

Radiation Energy, in the form of waves or particles, propagating through space. Frequently used for *ionizing radiation* in the text, except when it is necessary to avoid confusion with *non-ionizing radiation*.

Radiation detriment The total harm that would eventually be experienced by an exposed person or group and their descendants as a result of their *exposure* to *radiation*.

Radioactive Exhibiting *radioactivity*. For legal and regulatory purposes, the meaning of *radioactive* is often restricted to those materials designated in national law or by a *regulatory body* as being subject to regulatory control because of their *radioactivity*.

Radioactive waste For legal and regulatory purposes, material for which no further use is foreseen that contains or is contaminated with *radionuclides* at concentrations or *activities* greater than levels set by the *regulatory body*.

Radioactivity The phenomenon whereby atoms undergo spontaneous random disintegration, usually accompanied by the emission of *radiation*.

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

Radiation protection (or **radiological protection**) The *protection* of people from the effects of *exposure* to *ionizing radiation*, and the means for achieving this.

Radionuclide A *radioactive nuclide.*

Radiotherapy The use of radiation beams for treating disease, usually cancer, in patients.

Regulatory body An organization designated by the government as having legal authority for regulating nuclear, radiation, radioactive waste and transport safety.

Risk The probability of a specified *health effect* occurring in a person or group as a result of *exposure* to *radiation*.

Risk factor The *lifetime risk* or *radiation detriment* assumed to result from *exposure* to unit *equivalent dose* or *effective dose*. Unit Sv^{-1}.

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

Sievert See *effective dose* and *equivalent dose*.

Silicon diode A device made of a silicon compound in which current flows when exposed to *ionizing radiation.* The current is converted to electrical pulses which are counted. The number of pulses is related to *dose*.

Thermal neutrons *Neutrons* in thermal equilibrium with the medium in which they exist, i.e. they have the same average thermal energy as the surrounding *atoms* or *molecules*. 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.

Thermal reactor A *nuclear reactor* in which fission is induced predominantly by *thermal neutrons*.

Thermoluminescent material Material which, when heated, releases visible light in proportion to the amount of *radiation* to which it has been exposed.

Waste management All administrative and operational activities involved in the handling, *treatment*, *conditioning*, *transport*, *storage*, and *disposal* of *radioactive waste*.

Wavelength The distance between successive crests of an *electromagnetic wave* passing through a given material.

X ray Penetrating electromagnetic radiation emitted by an atom when electrons in the atom lose energy, and having wavelengths much shorter than those of visible light. Cf *gamma ray.*

Appendix B. Symbols and Units

Scientific notation

It is often more convenient to express the numbers encountered in radiological protection in scientific, rather than decimal notation because of their magnitude. This involves the use of significant figures within desired limits and multiplication by the appropriate power of ten. Examples are shown.

Converting decimal to scientific notation

Decimal	Scientific
1 230 000	1.23×10^6
100 000	10^5
3 531	3.53×10^3 [a]
15.6	1.56×10^1
0.239	2.4×10^{-1} [b]
0.001	10^{-3}
0.000 087	8.7×10^{-5}

Notes:
[a] To three significant figures.
[b] To two significant figures.

Prefixes

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

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
10^{21}	zetta	Z	10^{-21}	zepto	z
10^{24}	yotta	Y	10^{-24}	yocto	y

Mass and atomic numbers:

carbon-14 by $^{14}_{6}C$

barium-140 by $^{140}_{56}Ba$

lead-210 by $^{210}_{82}Pb$

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 usual to indicate the mass number and atomic number of a particular nuclide by a superscript and subscript. 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, for example, sievert *per* hour can be written either as Sv h^{-1} or as Sv/h.

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*	*t½*	*half-life*

Units

Some time ago, the units for the main ionizing radiation quantities were changed to those used in this text. Readers may come across old units: this table shows how to convert them to the new units.

Relationship between old and new ionizing 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*
Equivalent dose[a]	*rem*	*rem*	*sievert*	*Sv*	*1 rem = 0.01 Sv*

Note:
[a] Was dose equivalent

Selected References

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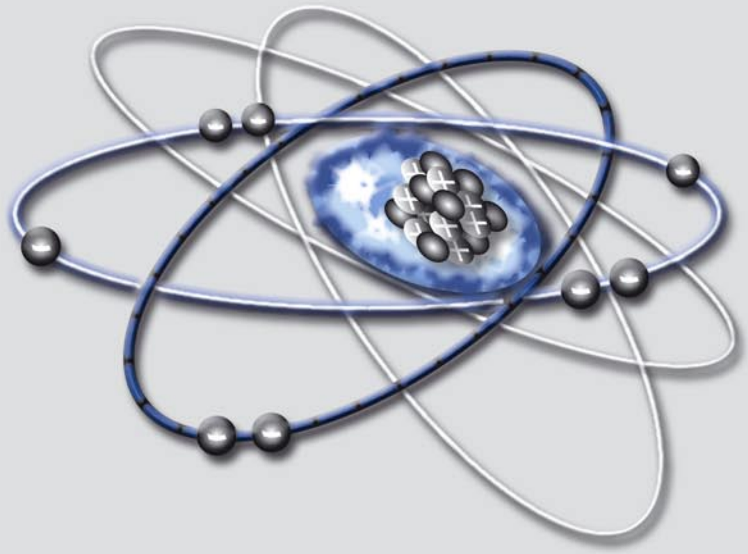

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