UK Health
Security
Agency

Living with radiation

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Preface

Preface

Living with Radiation was first published in 1973, with six editions having been produced over the intervening years. The book fulfilled a clear need for information about radiation in our environment aimed towards an informed but non-technical audience. This information is still in demand and has been much plagiarised over the years. The UK Health Security Agency is delighted to update “Living with Radiation” as one of its first major public-facing publications on radiation protection.

We have drawn heavily on the previous versions, especially for the explanations of basic physics but other sections, such as the information about medical exposures and radiofrequency applications have changed considerably as advances in technology have been made.

We would therefore like to acknowledge the original authors of “Living with Radiation”, and those that have contributed to subsequent editions, who have made the job of updating this book so much easier.

Our task at the UK Health Security Agency is to protect people from a wide range of environmental hazards including ionising and non-ionising radiations. We achieve this in a number of ways, by conducting research, developing protection advice and improving services for a wide range of UK governmental and non-governmental organisations. Additionally, we work with the major international organisations relevant to radiological protection such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the International Commission on Radiological Protection (ICRP), the International Commission on Non-ionizing Radiation Protection (ICNIRP), the International Atomic Energy Agency (IAEA) and the World Health Organisation (WHO), amongst others. We believe that providing publicly accessible information is an important part of this role. This current edition will be the first to be made available in standard book format and as an online version; similar material is included in each format, and it is hoped that this widens accessibility further to reach a broad range of audiences.

Editorial Team: Elizabeth Ainsbury, Stephen Barnard, Una Findlay, Louise Fraser, Hannah Mancey, John Moody, Samantha Watson, and Simon Bouffler.

In addition, we acknowledge the contributions of numerous former colleagues from UKHSA and its predecessor organisations the current and previous versions of this publication.

The authors and editors would like to acknowledge the following individuals who contributed to this update: Sharon Deacon, Philip Plant, Holly Carter, Natalie Williams & Jon White.

02

Introduction

Author: Simon Bouffler

Introduction

Life on Earth has evolved and survived for two billion years while constantly exposed to radiation of various kinds. Indeed, light and heat from the sun are natural sources of radiation essential to life and our continued existence.

In the modern age, humans have harnessed radiation for use in industry, electricity generation, communications, medicine and even within the home. Without radiation in its various forms, life as we know it would be very different. We use radiowaves for mobile phones, X-rays in medicine and microwaves for cooking, among the very many other uses.

These radiations are generated by electrical devices and can be controlled or turned off, limiting or stopping the production of radiation. However, radiations emanating from naturally occurring minerals led to the discovery of radioactivity. In this case unstable atoms spontaneously emit various radiations to become more stable. The dawn of the nuclear age in the 1940s brought us novel radioactive materials that led to dramatic advances in medical diagnostics and treatment therapies. Such materials are also used in a wide range of processes and procedures, for example, in industry, oil exploration, and life science research.

These different types of radiation can be classified according to the effects they have on matter, including living cells. The two categories of radiation are ionising and non-ionising. Ionising radiation includes cosmic rays, X-rays, and the radiation from radioactive materials while non-ionising radiation includes ultraviolet radiation, light, heat, radio waves, and microwaves. Radiations may also be classified in terms of their origin as naturally occurring or artificial (human-made sources of) radiation.

Benefits and risks

The benefits from some forms of natural non-ionising radiation, notably heat and light from the sun, are enormous to all life on Earth, indeed such radiation is essential to life. However, there are no specific benefits from exposure to natural ionising radiation, and although a radiation may be of natural origin, this does not mean it is somehow less harmful than radiation of artificial origin. Indeed, excessive exposure to ultraviolet light is causally linked to skin cancers and likewise excessive exposure to the naturally occurring radioactive gas radon is linked to lung cancer.

While we make considerable use of both ionising and non-ionising radiations for the benefit of society, they can also be harmful, therefore, people must be protected from unnecessary or excessive exposures wherever possible. The greatest health concern about ionising radiation is that it can cause cancers in exposed people and subsequent inherited defects in later generations.

The likelihood of such effects depends on the amount of radiation that a person receives and is equally true whether the radiation is of natural or artificial origin. So, in circumstances that can be controlled, a careful consideration of the balance of the risks posed and the benefits gained from procedures that expose people to radiation is required.

Public anxiety

When the terms ‘radiation’ or ‘nuclear’ are used, people are reminded of the atomic bombs dropped on the Japanese cities of Hiroshima and Nagasaki towards the end of World War II or the nuclear accidents in Fukushima in 2011 and Chornobyl in 1986, understandably leading to concerns and anxiety. However, there are many uses of radiation that are of great benefit to individuals (e.g. in medical diagnostics and treatment) and society more widely (e.g. electrical power generation, communications). The effects of ionising and non-ionising radiations have become better understood during recent decades. This has led to the development of internationally agreed systems of radiological protection to protect people from sources of ionising and non-ionising radiations and where exposure cannot be eliminated, to better manage the residual risk and ensure it is as low as possible. The subject of radiation safety receives much public attention, partly because radiation is one of the many causes of cancer. Unlike other risk factors encountered during a lifetime that may pose a more tangible risk, ionising radiation cannot be seen, smelled, or tasted and only detected using specialised devices. This undoubtedly adds to public anxiety. The lack of reliable, authoritative, and publicly accessible information written in plain English about radiation, and with ever increasing concerns about the potential sources of misinformation in modern society on the subject, adds to this anxiety.

The aim of this book is to help fill this gap by providing information in a straightforward manner for those who are not experts. In the following chapters, we describe the sources and effects of radiation of all types and explain the principles and practices of radiological protection.

03

Concepts and quantities for ionising radiation

Authors: Jon Eakins and Rick Tanner

3.1 Structure of matter

Understanding the nature of ionising radiation, including the mechanisms by which it can cause harm, requires an appreciation of the interactions between radiation and matter at the atomic and sub-atomic levels. Much of our knowledge about the structure of matter at very small scales comes from an enormously productive period of scientific discovery that began in the late 19th and continued into the early 20th century. The discoveries were linked to the phenomenon of radioactivity, in part because those newly discovered types of radiation were used to investigate the structure and properties of matter.

Almost all matter on Earth is composed of **atoms**, which make up the different chemical elements, such as hydrogen, carbon, oxygen, iron, and lead. Each atom is extremely small, far too small to see with the naked eye, and only just distinguishable using the most powerful microscopes. For example, just a single gramme of graphite contains many billions of trillions of atoms of carbon (in fact, around 10^{23}).

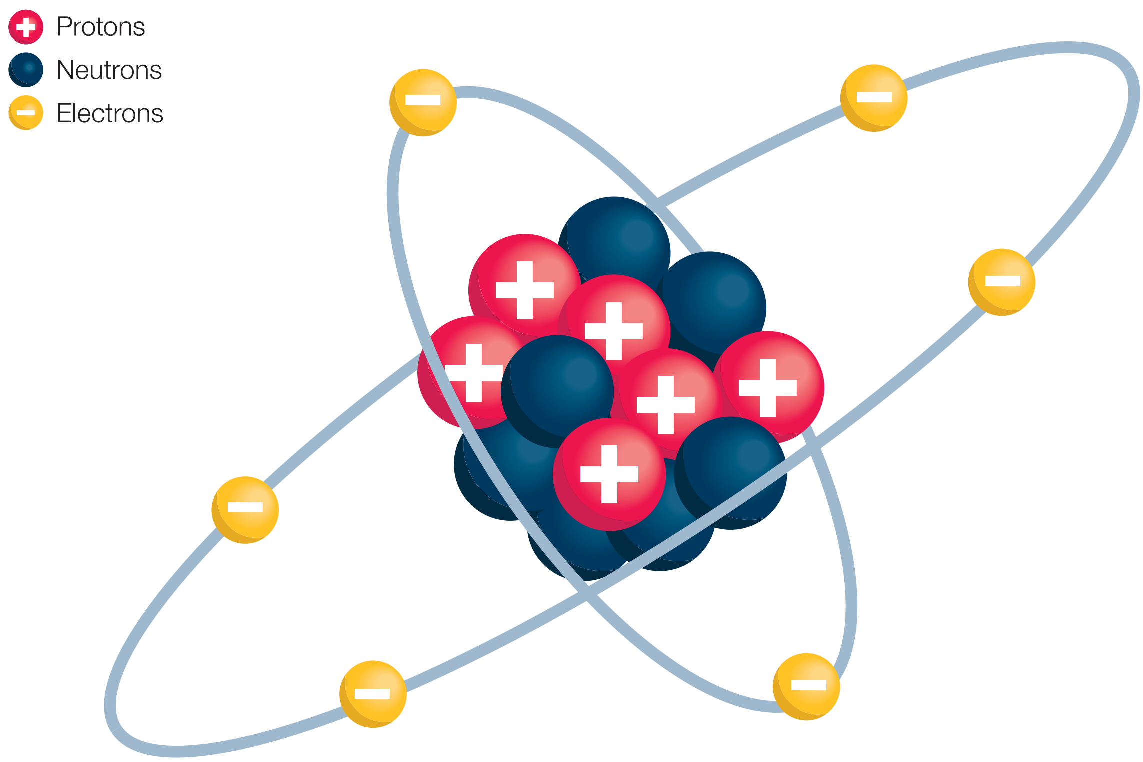
At the centre of each atom is a tiny, positively charged **nucleus** (plural: nuclei). The nucleus of the atom is typically ten thousand times smaller than the atom itself, but contains almost all of its mass. Within the nucleus there are two main types of **sub-atomic** particle: **protons** and **neutrons**. Each proton in the nucleus carries a single unit of positive electrical charge. The neutron has a mass that is almost the same as a proton, but carries no charge.

Surrounding the nucleus are a number of **electrons**, which each carry a single unit of negative electric charge, equal and opposite to that of the protons. The electron is an extremely small particle, nearly two thousands times lighter than a proton or neutron, but its electrical charge is important. For example, the equal opposite charges of the negative electron and the positive nucleus provide the attractive force that holds an atom together. The electron's charge is also behind the ability of a metallic conductor, such as copper, to carry an electrical current, and thus transport energy from one point to another. As will be explained later, electrons can also be used in electrical devices to produce the radiation called **X-rays**. In their natural state, atoms have equal numbers of positively charged protons and negatively charged electrons, and are therefore electrically neutral.

Atoms can be pictured as looking like the Solar System, with electrons orbiting the nucleus in a comparable way to the planets orbiting the Sun. See Atomic structure for carbon schematic diagram on page 10. Of course, this is just a convenient picture: even if we could see something this small, the atom would not really look like this, and the relative sizes of the nucleus, protons, neutrons and electrons and their orbits are not to scale. There are also other important differences with the 'Solar System' model, one of which being that the energy of any particular electron is restricted to a fixed 'orbit', meaning that the electrons can only occupy discrete 'energy levels' or electron 'shells'.

A convenient (albeit over-simplistic) picture of a material made of many atoms may be imagined as featuring a vast number of tiny 'islands' of positive charge (the nuclei), which are separated from each other by distances that are large compared to their very small sizes, and where that intervening space is filled by 'clouds' of negative charges (their orbiting electrons) surrounding them.

Atomic structure for carbon



The number of protons in the nucleus is termed the **atomic number**, which uniquely determines the type of chemical element. The simplest element is hydrogen with atomic number 1. The atomic number of the element carbon is 6, which means that there are six protons in the nucleus and six orbiting electrons. The nucleus of an atom of lead has 82 protons, so the atomic number of lead is 82.

Although the number of electrons and protons is equal in a natural (i.e. neutral) atom, the number of neutrons in the nucleus of a given element can vary to some degree. To distinguish atoms with different numbers of neutrons the **atomic mass number** is used, which is defined as the sum of the number of protons and neutrons in its nucleus. Atoms with the same number of protons, but different numbers of neutrons, are called different **isotopes** of that element. For example, a carbon atom having six protons and six neutrons has atomic mass 12, which is often written as carbon-12 or ^{12}C; this is, by far, the most common isotope of carbon. However, there are two other isotopes of carbon atoms that are found on Earth.

These are carbon-13 (or ^{13}C) which has one extra neutron in its nucleus, whilst carbon-14 (or ^{14}C) has two extra neutrons. The atomic mass numbers of ^{13}C and ^{14}C are 13 and 14 respectively. As all three of these isotopes have 6 protons in their nuclei, they are still the same element, carbon. Isotopes are very common in nature: over three quarters of the chemical elements found on Earth have more than one natural isotope. For example, the element tin has the most, with ten isotopes found in nature.

Atoms can combine together to form larger structures called **molecules**; the different ways in which elements join together, and the different ratios in which they do so, lead to the vast number of different chemical **compounds** that we see around us. For example two hydrogen (H) atoms and one oxygen (O) atom can combine to make one molecule of water. On the other hand, two hydrogen (H) atoms and two oxygen (O) atoms can combine to make one molecule of hydrogen peroxide. Chemists write these compounds as H_2O for water and H_2O_2 for hydrogen peroxide, to show their respective ratios.

The joining of the atoms may be achieved by a partial sharing of the electrons from each atom to form **chemical bonds**, with the mutual attractions between the constituent positively charged nuclei and their shared negatively charged electrons allowing the molecule to ‘stick together’. The making and breaking of these chemical bonds is a process known as a **chemical reaction**.

The element carbon can form bonds with many other elements; these include hydrogen, nitrogen and oxygen, allowing it to form the complex and sometimes very large **organic molecules** found in living organisms that enable life. These processes only involve the sharing of electrons, so they relate just to the underlying elements; they are therefore unaffected by different isotopes. For example, compounds containing ^{12}C atoms would be chemically identical if they were replaced by ^{14}C atoms.

Overall, material will contain enormous numbers of atoms, most of which may be joined to others in various chemical combinations.

3.2 Radioactivity

A given nucleus may be either **stable** or **unstable**. A stable isotope will remain the same over time, but if it is unstable it means that at some point it will suddenly change by undergoing **radioactive decay**. The average wait for that change could be a tiny fraction of a second to many billions of years, but once started, the process will be over very quickly. As a simple analogy, the situation may be thought of as comparable to a pencil balanced on its end: although it could stay that way for some time, the pencil would 'prefer' to be in a much more stable state, so sooner or later it will inevitably fall over, lying on its side.

Any nuclide that is unstable is a **radionuclide.** Essentially, an unstable nucleus has too many or too few neutrons for the number of protons that it contains. This causes it to be energetically unbalanced and unable to hold itself together indefinitely. Radioactive decay is the process by which an unstable nucleus of an atom undergoes a **nuclear transformation**, and in doing so it loses energy by emitting particles of **radiation**. After the decay the atom is usually a completely different element, which is referred to as the **daughter** of the original **parent** nucleus. The daughter nucleus may be stable or unstable, meaning that it too can undergo radioactive decay into a new nucleus (a 'granddaughter' of the original). That process continues until a stable nucleus is formed.

Individual unstable nuclei are assumed to decay randomly in time, and independently of their surroundings and environment[1]. When we look at a quantity of **radioactive material** containing enormous numbers of nuclei, what we see is an average effect: it is the outcome of a large number of nuclei undergoing radioactive decay in roughly the same timeframe.

3.2.1 Activity

The average number of decays per second from a large collection of nuclei is called the **activity** of that sample, which is given the International System of Units (SI) unit the **becquerel**, **Bq**: 1 Bq = one decay per second. One becquerel is actually a small amount of radioactivity, so multiples are often used.

The activity of a sample indicates its rate of decay: the higher the activity, the greater the number of nuclei undergoing transformations per second. This in turn relates directly to the rate of emission of particles from the **radioactive source**. Therefore, this rate will be linked to the level of any radiation hazard from the source, which is why activity is such a useful quantity.

Some countries use the curie (symbol: Ci) and its sub-divisions (millicuries and microcuries), for quantifying activity. One Curie corresponds to 37,000 million Bq, and represents the activity of one gramme of elemental radium. Radium is a natural but radioactive element first isolated by Marie Curie, who extracted only a fraction of a gramme from several tonnes of uranium ore residues.

[1] This is where the simple balanced pencil analogy quickly breaks down: that required some external force to cause it to topple (e.g. a gentle nudge, gust of wind etc.), but radioactive decay is assumed to be completely spontaneous.

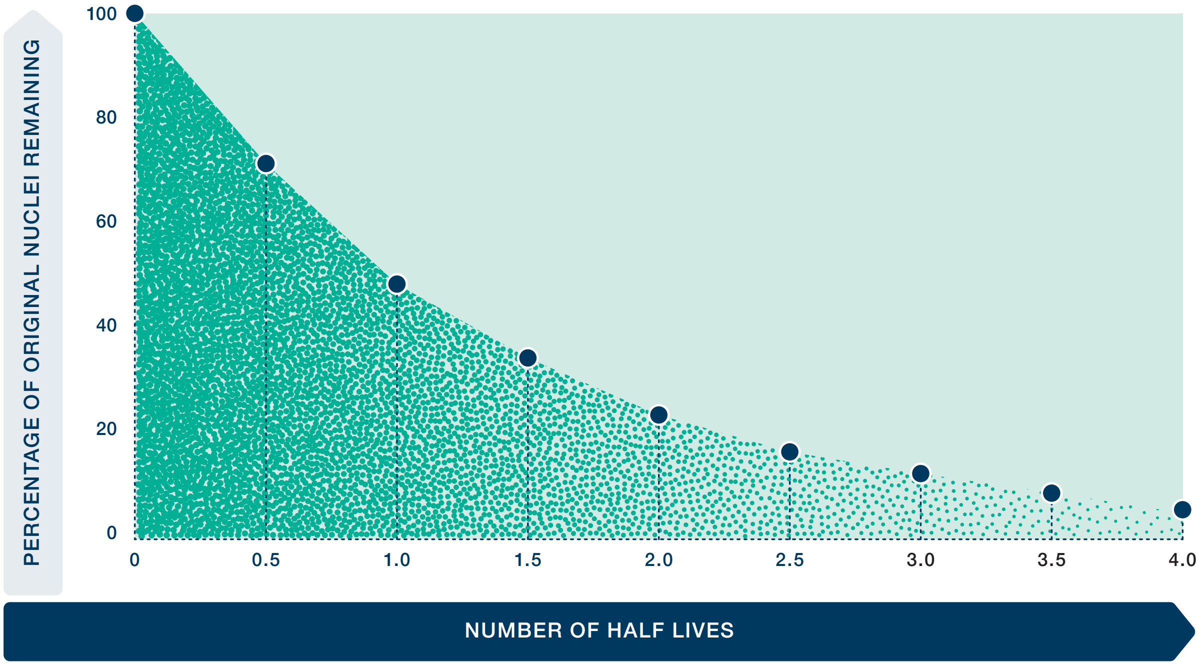
3.2.2 Half-life

Another very useful and often-quoted description for radioactive material is its **half-life**, which is defined as the time taken for the number of nuclei of a given type in a sample to halve as a result of radioactive decay. The half-life is typically denoted by the symbol $T_{1/2}$. Half-lives are a unique characteristic of each isotope: they are a fixed property of the radionuclide, dependent only upon the nuclear transitions that it undergoes.

The sizes of radionuclide samples do not affect the half-life: whatever mass of a given radionuclide we had, after one half-life there will be exactly half of that radionuclide left. This is contrary to the activity, which does scale with the size of the sample because the activity is proportional to the number of radioactive atoms it contains: so, after one half-life the activity of a sample will also have dropped by a half (assuming the daughter is stable). This is a useful property, because it means that if we measure the activity of a sample at some arbitrary time, we can predict its activity at any later time by determining how many half-lives have elapsed since the measurement.

The half-lives of radionuclides range from tiny fractions of a second to billions of years; indeed there are some natural isotopes with half-lives that are longer than the age of the known Universe. In fact, half-lives can be very wide-ranging even for the same element: for example, $T_{1/2}$ for ^{220}U is 6 x 10^{-8} seconds whilst $T_{1/2}$ for ^{238}U is 4.5 x 10^{9} years, even though both are isotopes of uranium.

Graph showing exponential decay out to 4 half-lives



3.2.3 Radioactive decay: An example

Returning to the example of the isotopes of carbon, although they behave identically during chemical reactions (because each contains 6 electrons), their nuclei differ. In fact, whilst ^{12}C and ^{13}C are stable, the ^{14}C nucleus is slightly unstable and eventually will undergo a nuclear decay. The ^{14}C nucleus contains too many neutrons (8) relative to the number of protons (6) to be stable. What happens during the decay can be described as one of the excess neutrons in the nucleus transforming into a proton and an electron, with the electron then ejected from the nucleus and, indeed, completely out of the atom at very high speed. The resulting nucleus now has one more proton and one fewer neutron than it did before the transformation. The atomic mass number is still 14 but the atomic number is now 7 (up one from 6): the ^{14}C nucleus has in fact turned into a nitrogen-14 nucleus, containing 7 protons and 7 neutrons. The highly energetic electron that was emitted is called **beta radiation**, which will be discussed in more detail in section 3.3.2. After 5,730 years, only half of the original ^{14}C atoms will be left undecayed. After another 5,730 years only a quarter would be left, and after yet another 5,730 years only one eighth of the original number would remain. This period of 5,730 years is the **half-life** of ^{14}C, and is a unique and fundamental property of its radioactive decay.

Since the Earth is much older than this, the obvious question is: why is there any ^{14}C left on the planet? The reason is that ^{14}C is being constantly created in the Earth's upper atmosphere by the action of cosmic radiation, and this maintains a balance. In fact, this constant renewal is fundamental to the process of 'carbon dating' that is so usefully applied in the study of ancient plants, organisms and human remains. When an organism is alive, it breathes in and metabolises the ^{14}C in its environment, so its living tissues remain in balance with the atmosphere. But, this balance is disrupted upon its death, after which no new ^{14}C from the atmosphere is absorbed. The ^{14}C trapped inside the tissues then decays, but is not replenished. So, if scientists can measure what fraction is left after some time, they are able to figure out how many half-lifes must have passed since the organism died. Because the half-life of ^{14}C is known, it is therefore possible to estimate how old it must be.

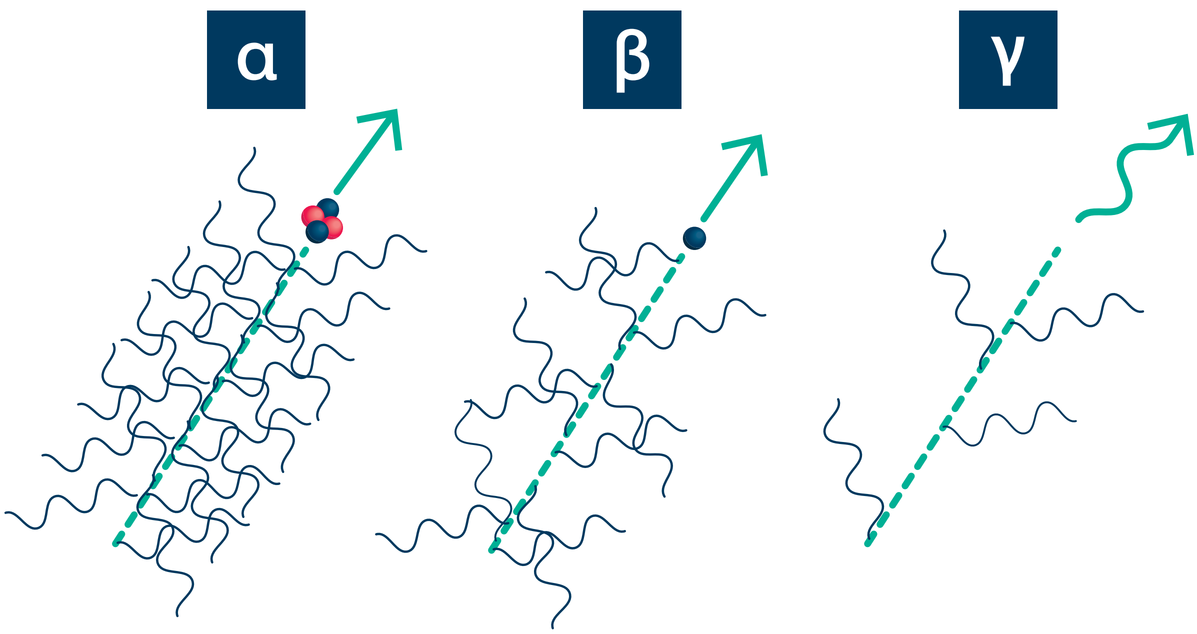
3.3 Ionising Radiation

The description of radioactivity given above focussed on the changes to the nuclei, without too much consideration of the radiation that was emitted during the decay. But this radiation is extremely important in many ways, because it is **ionising**. There are different types of ionizing radiation, but they all have one thing in common: they carry energy away from the atom and into the surrounding environment. Sometimes that energy gets deposited in people, which can cause harm and is why radioactive materials can be hazardous.

As they pass through matter, particles of ionising radiation are able to 'rip' electrons out of their atoms. Because the atom now contains fewer electrons than protons, it is no longer electrically neutral, instead becoming a positively charged **ion**. The positive ion, and negatively charged electron that was liberated and are now free to travel through the material on their own. This has consequences that can be both useful or harmful; for example these ionized particles can be measured by specialist equipment, and therefore underpin the essential technology with which radiation can be detected. However, they are also potentially dangerous: if the material is biological tissue, the energy deposited by ions and electrons can damage the cells or disrupt chemical reactions, preventing the tissue from functioning properly.

Generally speaking, the more electric charge the particle of radiation has and the slower it is moving, the denser the trail of ionisation left in its wake. The most common types of ionizing radiation are alpha particles, beta particles, positrons, highly energetic photons, and neutrons. When photons originate from inside the nucleus they are known as gamma rays, but when originating from electrons they may be called X-rays. A beta particle is an energetic electron. A positron is an example of an anti-particle, which may be thought of as a sort of 'mirror image': a positron is the exact opposite of an electron, identical in every way apart from having a single unit of positive charge instead of the electron's single unit of negative charge. These types of radiation are discussed in the following sections.

Schematic of tracks of ionisation left by alpha, beta and photons



Tracks from alpha, beta and gamma radiation beams and the associated secondary electrons they generate.

3.3.1 Alpha Radiation

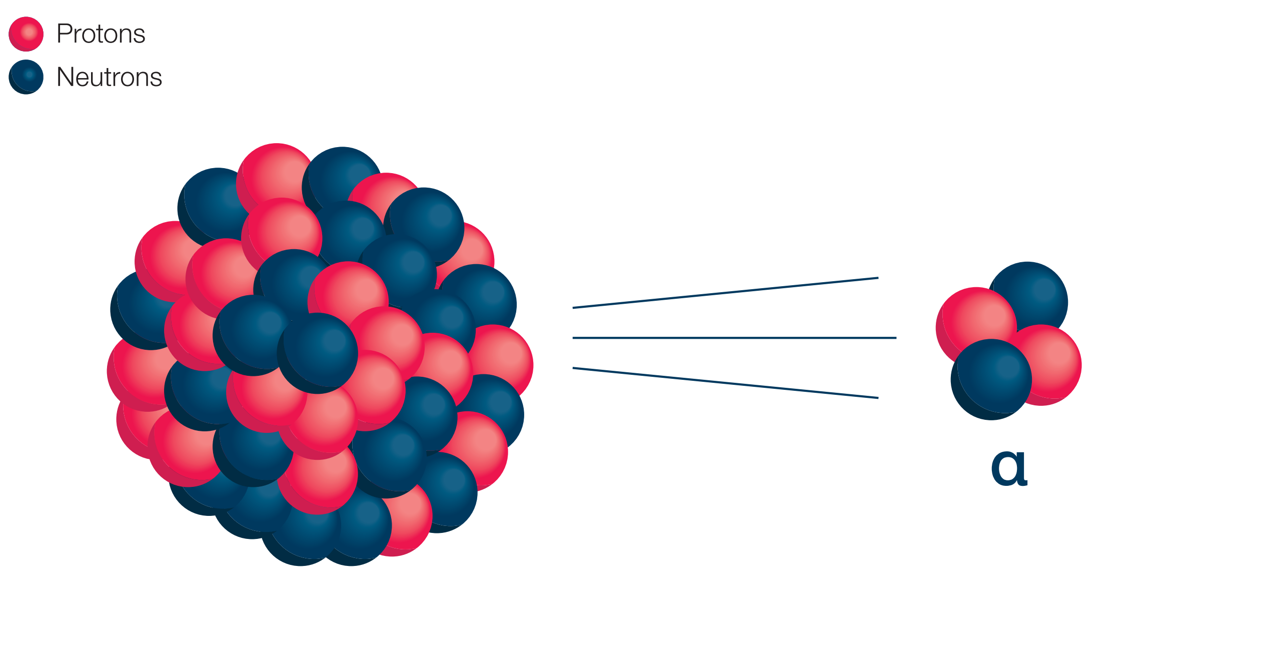
An **alpha particle** (denoted by the Greek letter α) is the radiation emitted when a radioactive nucleus transforms via an alpha decay. The alpha particle consists of two protons and two neutrons bound together, which happens to be the same as the nucleus of a helium-4 atom. After an alpha decay of a parent radionuclide, its daughter is a new element with an atomic number that is 2 fewer than that of its parent and an atomic mass number that is 4 fewer. In many cases, the daughter is also an unstable radionuclide. The alpha particle is emitted at very high speed, so carries energy from the nuclear transformation out of the atom as **kinetic energy**; the amount of this energy is absolutely tiny by normal standards, but at the atomic scale it is very significant.

The composition of alpha particles makes them fairly heavy compared to most other radiation particles. They have a double positive charge because each of the protons has a single unit of positive charge. As a consequence, they interact strongly with the charges contained in the atoms of any matter they pass through and, although initially travelling extremely fast (>1000 km/s), they slow down very rapidly and are quickly stopped, leaving a dense trail of ionised atoms behind them. In fact, their range in air is only a few centimetres and they can be stopped entirely by something as thin as a sheet of tissue paper. This means that alpha emitters outside the body pose no direct radiation hazard, since the alpha radiation cannot penetrate the dead layer of the skin. However, if alpha emitting radionuclides are taken into the body, such as by inhalation or ingestion, then all the energy of the emitted alpha particles is deposited in the surrounding tissues. In this case, alpha emitters actually present the greatest risk to biological organisms, including humans.

Alpha decay is generally only seen with heavy nuclei, i.e. elements with atomic numbers above 82 (which corresponds to the element lead), that have too many protons relative to the number of neutrons to be stable. These heavy nuclei include uranium-238 and thorium-232, which are two very long lived natural radioisotopes, as well as technologically important **man-made** radioisotopes, such as plutonium-239.

As the alpha particle slows down when it travels through materials, it captures two orbital electons from the surrounding material, thus creating a normal atom of neutral helium. Helium is rare in the atmosphere, because it is lighter than air and can escape into space, but is used in various special technological applications where low temperatures are needed (liquid helium is used) and for filling balloons. A common source of helium is from oil wells, where the gas is generated undergound over millions of years by the radioactive decay of natural uranium and thorium in the surrounding rocks.

Nucleus emitting an alpha particle showing two protons and two neutrons



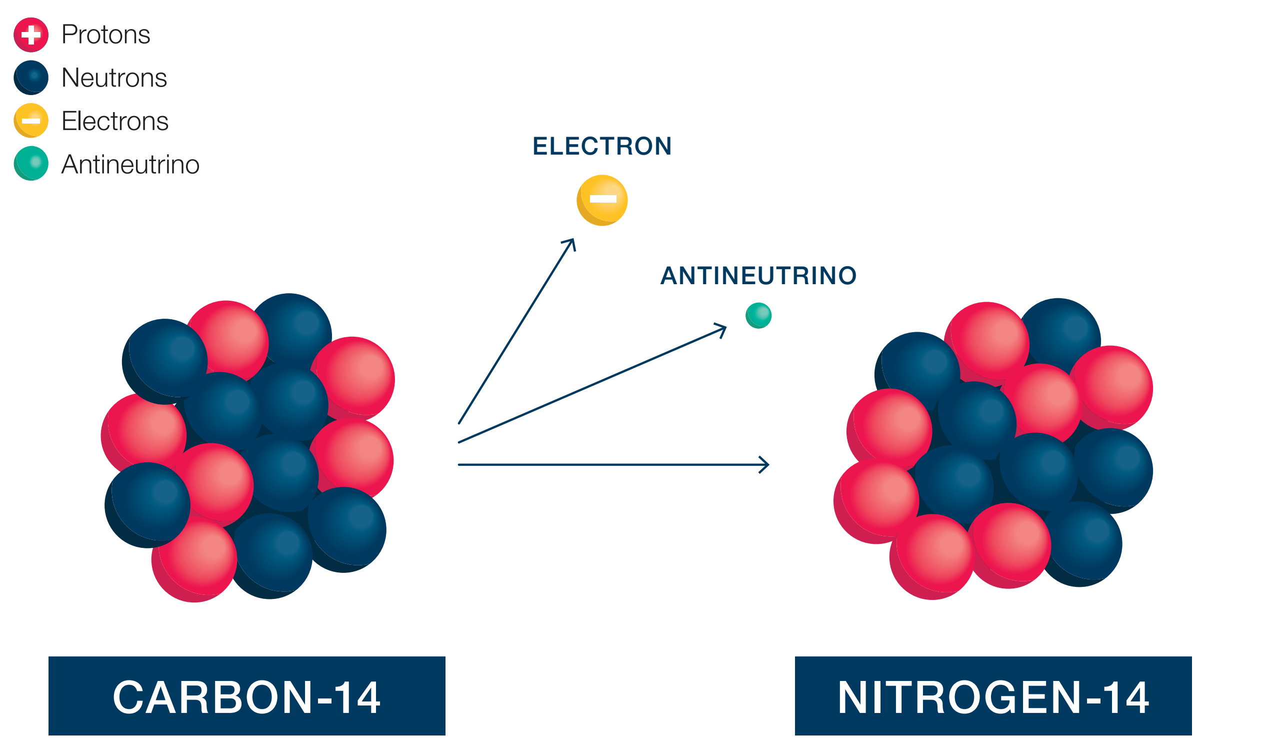
3.3.2 Beta radiation

A **beta particle** (denoted by the Greek letter β, or sometimes β^- to denote its negative charge) is the name given to the high energy electron emitted when a radioactive nucleus undergoes beta decay, during which a neutron transforms into a proton and an electron (and also another tiny particle called an antineutrino, but which is irrelevant for radiological protection purposes). After a beta decay of a parent radionuclide, its daughter is a new element with an atomic number that is 1 greater than its parent but an atomic mass number that is the same. Beta decay is generally seen in **neutron rich** radionuclides, i.e. those that have too many neutrons relative to the number of protons to be stable; an example is ^{14}C, which is unstable, unlike stable ^{12}C and ^{13}C. The beta particle carries kinetic energy out of the atom, and so is initally travelling at a very high speed.

Being electrons, beta particles have a single unit of negative electric charge and are relatively light (~8,000 x less massive than an alpha particle, for instance). This means that their ranges in matter are much greater than those of alpha particles, but they do still undergo many interactions with the charges contained in surrounding atoms and so are quickly slowed and stopped, leaving behind a trail of ionised atoms and free electrons (albeit not as dense as that from alpha particles). For example, the beta particle emitted by ^{14}C will travel a few tens of centimetres in air before being slowed completely by its interactions with air molecules, and can alternatively be stopped by just a thin sheet of plastic. Some other beta emitting isotopes, for intance phosphorus-32 and strontium-90, emit higher energy betas that have a range of about one metre in air, or alternatively require about ten millimetres of plastic to absorb them. When the beta particle finally stops, which could be a very long way away from the emitting atom, it is completely indistinguishable from all the other electrons in all the surrounding atoms.

Beta particles are described as being moderately penetrating radiation. Apart from the very lowest energy sources, beta emitters outside the body pose a direct radiation hazard, especially to shallow organs such as the skin and the lens of the eye.

Carbon-14 nucleus emitting a beta particle



3.3.3 Photons

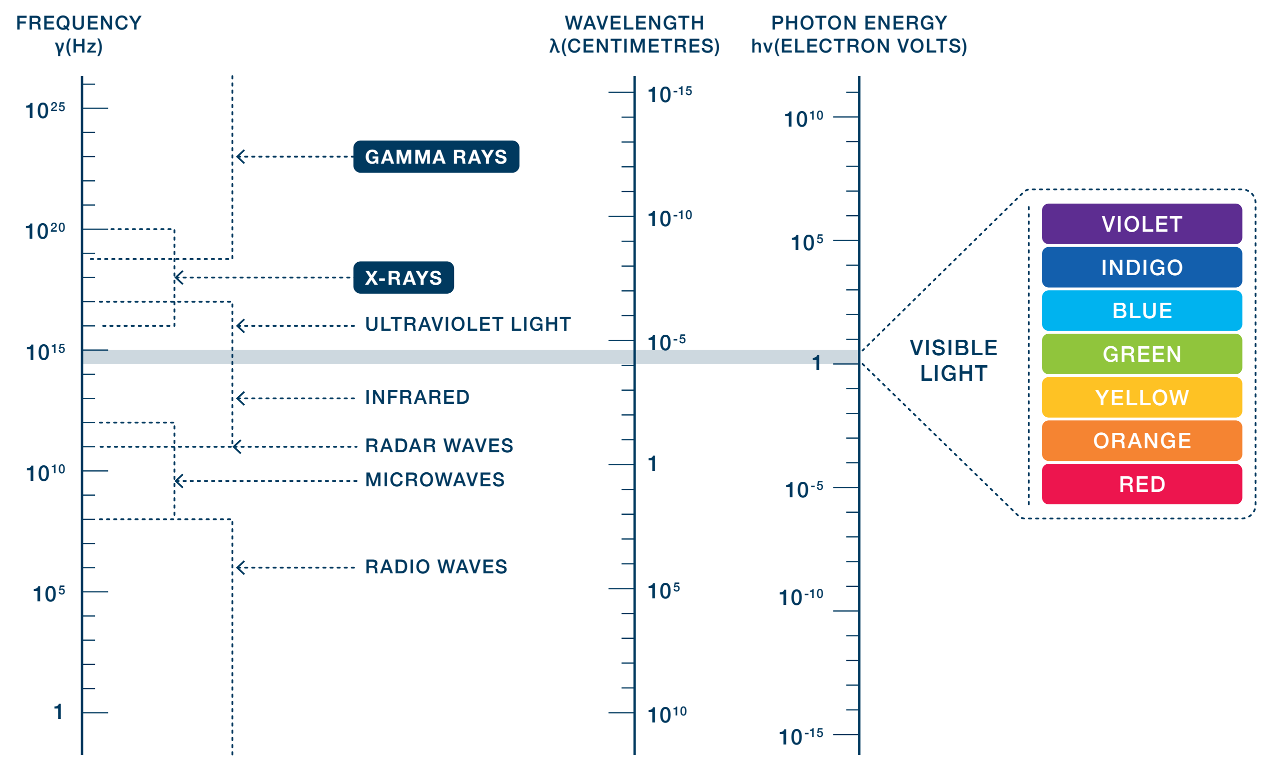
Electromagnetic radiation is generated whenever an electric charge moves through an electric or magnetic field. Electromagnetic rays cover a very wide range known as the **electromagnetic spectrum**, which includes the radio waves we use for communication and the visible light that we see as the colours of the rainbow. However, it also includes radiation that is ionizing, and hence can potentially cause harm.

When electrically charged particles (e.g. protons, alpha particles) are rearranged in the electric field existing within the nucleus, the electromagnetic energy given off is called **gamma radiation**. When electrons are accelerated in an external electric field, or decelerated by interacting with the charges within matter, the emitted electromagnetic radiation is called an **X-ray**. In both instances, the type of radiation is the same: a massless, electrically neutral, 'packet' of energy called a **photon**, which always travels at the speed of light.

Alpha and beta particles are stopped easily when they pass through matter because they have an electric charge: this interacts with the charged nuclei and electrons in the surrounding atoms, transferring kinetic energy from the particles in the process and slowing them down, and leaving dense tracks of ionised atoms and free electrons behind them. However, photons have no charge and interact only relatively weakly with matter, which means they are generally highly penetrating, and their trail of ionisation is more sparse. Some photons are capable of passing through several metres of solid concrete or many hundreds of metres of air, and hence shielding of photon sources can be difficult; great thicknesses of heavy materials such as lead are often needed to adequately protect from them. Photon sources outside the body typically pose a direct radiation hazard to all organs, including those deep within the torso.

Each photon has energy that is inversely proportional to its wavelength. The penetrating power of the radiation is also related to the energy of the photon. Having the shortest wavelengths, gamma and X-ray photons are the most energetic parts of the electromagnetic spectrum, and are the most able to penetrate matter. Gamma ray photons are usually more energetic than X-ray photons, but that is not always the case.

Electromagnetic spectrum showing main regions with MeV/photon and wavelengths



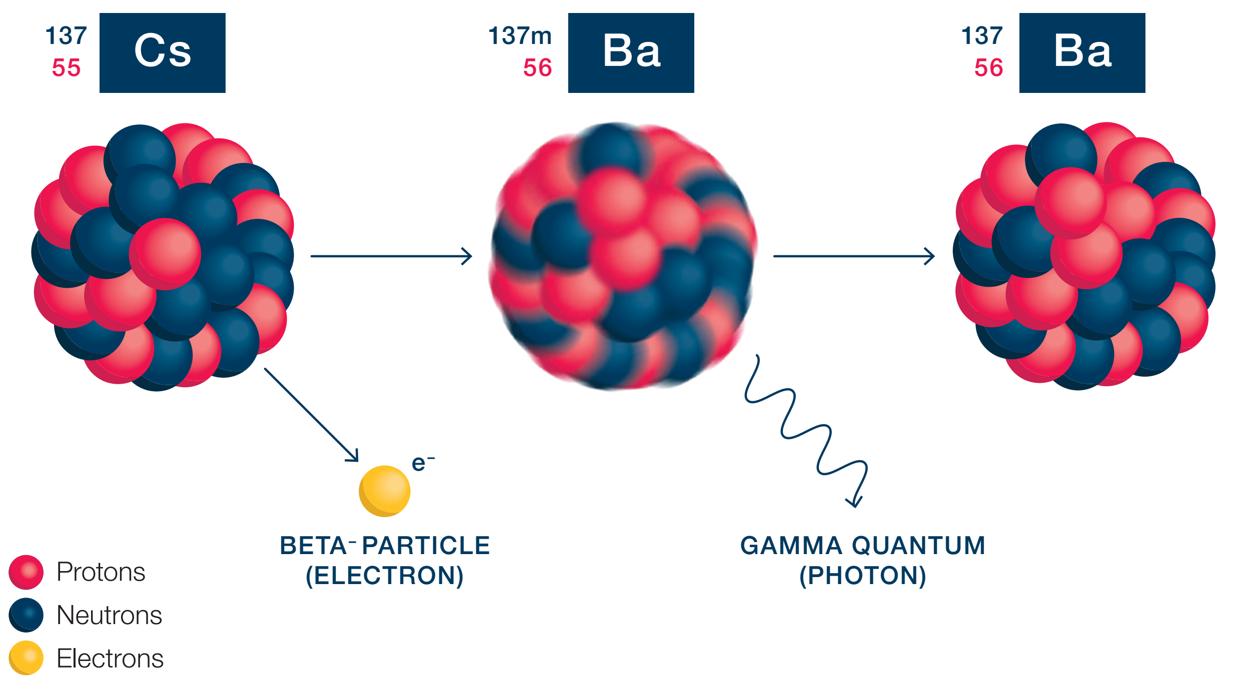
3.3.3.1 Gamma radiation

It is not only alpha or beta particles that may be emitted as a result of the decay of radionuclides. In many cases, gamma radiation (denoted by the Greek letter γ) is also released as a consequence of the positive electric charges jostling about inside the nucleus when it transforms. Gamma radiation is a form of electromagnetic radiation that is part of the electromagnetic spectrum at the shortest wavelengths, and is often very penetrating.

The radionuclide caesium-137 is a well known by-product of the operation of nuclear reactors (see Chapters 11 and 12) and is present in the environment as a result of discharges from nuclear sites and also from **fallout** from atmospheric nuclear weapons testing and nuclear accidents. The half-life of caesium-137 is 30 years and decay is initally by emission of a beta particle, leaving a barium-137 atom. However, in the majority of these decays the barium nucleus is produced in an 'elevated energy state' and the nucleus is said to be **metastable**, denoted by barium-137m or ^{137m}Ba. One way of considering this is that, although ^{137m}Ba has the right balance of protons and neutron to be stable, the decay has left them with far too much energy, which needs to be released so that the nucleus may 'relax' into a more stable, lower energy state; think of a heated pan of water, which has to let off steam to cool down. The ^{137m}Ba rapidly undergoes its own transformation to a stable ^{137}Ba nucleus, and in the process gives off its excess energy in the form of gamma radiation. Given this, caesium-137 is therefore often called a **beta-gamma** emitter.

Americium-241 is a man-made or **artificial** radionuclide. It is well known for its use in tiny quantities in the sealed sources contained in smoke alarms, as found in the workplace and in the home. Americium-241 undergoes alpha decay to form neptunium-237, and the detector works by sensing the absorption of these alpha radiations by small smoke particles that drift through its chamber. Gamma radiation is also given off during the decay, so americium-241 is actually an alpha-gamma emitter. These gamma rays are not a hazard to the owner of smoke alarm, as they are relatively low energy and therefore not very penetrating; they are much less powerful than those from caesium-137, for example.

Beta gamma decay of caesium-137 showing intermediate excited Ba-137m atom, beta particle and the gamma ray photon



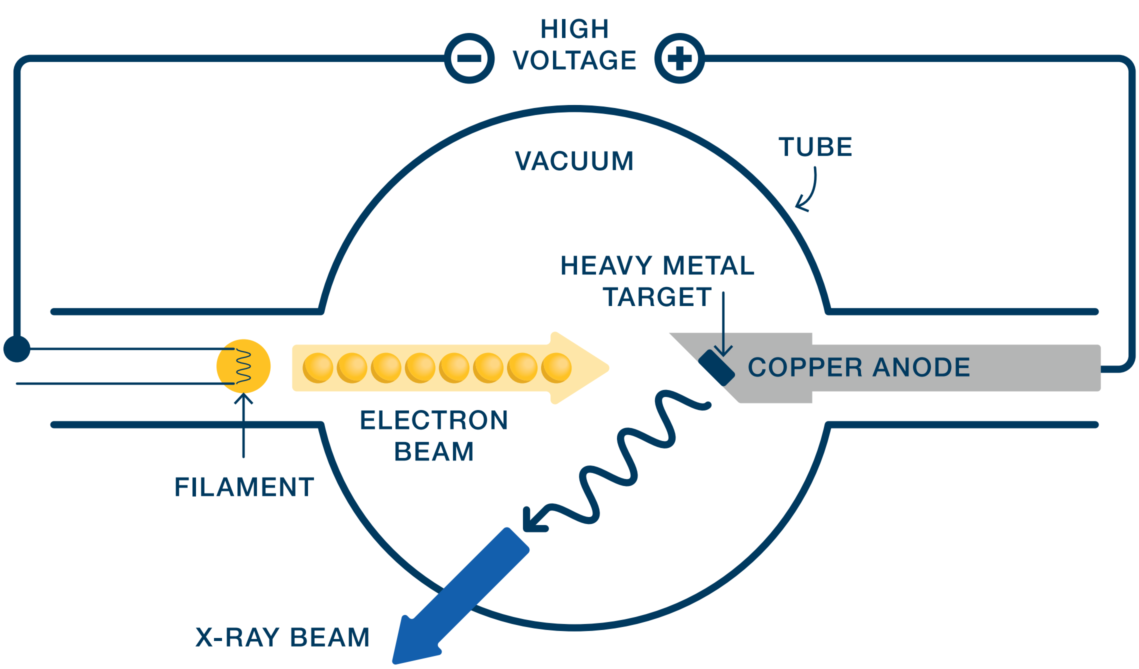
Very intense gamma sources may be constructed using a large quantity of a specific radionuclide, and may be used for specific tasks, such as radiation sterlization of apparatus. These may typically consist of a large chamber containing an intense, high-energy gamma source, such as cobalt-60 or caesium-137. When industrial equipment or medical tools are passed through this chamber, usually via automated systems, the intense gamma rays from the source kill any bacteria or micro-organisms that are present on them, thereby rendering the objects ‘clean’. Effective shielding is needed around the chamber to ensure that the gamma radiation is contained and does not pose a hazard to workers.

3.3.3.2 X-rays and electron beams

In 1895, the German physicist Wilhelm Röntgen studied the radiation emitted from a partially evacuated **cathode-ray tube**, through which an electrical current was being passed. Within the tube it was already known that there was a type of radiation called **cathode rays** passing through, transiting, from the negative electrode (cathode) to the positive electrode (anode). These cathode rays were eventually identified as the beam of electrons carrying the electrical current. Röntgen named the radiation he detected outside the tube **X-rays**, so-called because the ‘X’ denoted their unknown origin at the time. However, later research revealed these to be photons, in this case the electromagnetic radiation produced when the negatively charged electrons from the beam are quickly decelerated within the metal anode, a process known as bremsstrahlung (German for ‘braking radiation’).

Since these early investigations, there have been enormous technological advances in the design of **X-ray tubes**, leading to very specialised equipment optimised for use in medical, industrial, or other work areas. Such is the reliability of modern equipment that in some situations, such as medical **radiotherapy**, X-ray sources have substantially replaced the powerful radioactive gamma ray sources that were used for treatments in the past, with the energies of the X-rays extending to over 10 MeV.

An early x-ray tube + a schematic showing anode, cathode, etc.



A range of physical mechanisms can give rise to X-ray production. For example, X-rays can be produced by passing a beam of electrons through an external electric or magnetic field. This phenomenon is exploited in synchrotrons (particle accelerators used in research) by rapidly accelerating electrons around a circular cavity constrained by powerful magnets, to give off very powerful X-rays also known as **synchrotron radiation**. X-rays can also be created naturally, for instance, as a result of their interactions with the charges contained inside atoms, beta radiations (being high speed electrons) lose kinetic energy and slow down as they pass through matter, creating X-rays as they do so. This can lead to problems when shielding beta sources, because the shield becomes a source of secondary photon radiation that may then also need to be controlled. Likewise, when any ionizing radiation knocks an electron out of an atom, X-rays may be produced when the remaining electrons rearrange themselves to fill the 'hole'. The involvement of an atom's orbital electrons in this process means that the X-rays produced have energies characteristic of the specific chemical elements that are present. Characteristic X-rays can also be detected during the decay of radioactive isotopes, as the orbital electrons subsequently reorganise themselves to balance any changes to the positive charge of the nucleus during its transformation. Typically, these types of X-ray are relatively low in energy and may only provide a minor component of the overall radiation dose from radionuclide sources.

Cathode rays that produce X-rays in an X-ray tube can be modified so that X-rays escape the equipment as an **electron beam**. These beams have various applications. For example, they are used in medical therapy, where a 'linear accelerator' (often abbreviated to 'LINAC') is used to produce both electron and X-ray beams that can be switched for different types of treatment. Alternatively, industrial welders can use the simple heating effect of the electron beam to join metal components together.

A medical LINAC and industrial welding

3.3.4 Neutrons

Free neutrons can also be released as radiation from nuclei by various physical processes. **Nuclear fission** involves the disintegration of a single, heavy, unstable nucleus into two lighter nuclei, along with the ejection of a few highly energetic ‘fragments’ such as neutrons and the release of large amounts of gamma radiation energy. Sometimes, these neutrons may go on to strike neighbouring heavy nuclei within the sample, causing them also to fission. This process may continue in what is known as a **chain reaction**. Uranium and plutonium isotopes are examples of fissile materials, and their fission has been exploited in nuclear reactors (see Chapter 12) as well as in nuclear weapons.

Schematics of uranium fissioning and releasing neutrons, and a D-T fusion reaction

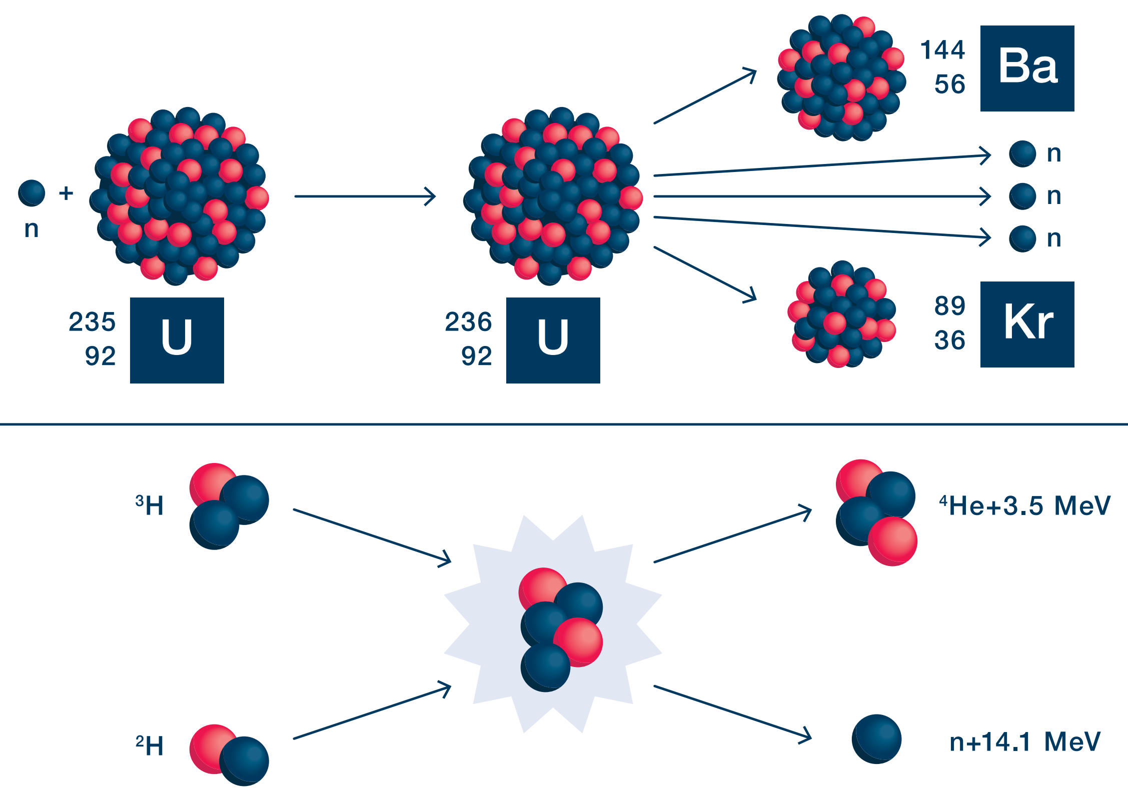


Figure depicting two nuclear processes that lead to the emission of neutrons. Fission, top: heavy nuclei can split into to lighter nuclei plus a few high energy neutrons. Fusion: bottom: two light nuclei, in this case deuterium (H-2) and tritium (H-3) can fuse to make helium (He-4) and an even higher energy neutron.

Nuclear fusion involves the joining together of the nuclei of light elements, such as hydrogen and helium, in a process that also releases large amounts of energy in the form of fast neutrons and gamma rays. Fusion is what powers the stars, including our Sun, and is behind the destructive ability of ‘hydrogen’ bombs. Controlled fusion has also been reproduced on Earth in experimental reactors, albeit only for short periods of time; the development of commercially viable fusion reactors that are capable of meeting our electricity needs is an area of significant international research and collaboration.

Nuclear fusion is also utilized on a much smaller scale within a **neutron generator**. These are elaborate electrical devices that accelerate isotopes of hydrogen (stable deuterium, ^{2}H; or radioactive tritium, ^{3}H) into a target that also contains isotopes of hydrogen. The resulting nuclear reactions form nuclei of tritium or ^{3}H, as well as giving off neutrons that have various practical applications within industry.

Much more managable neutron sources are also available for laboratory or commercial use. One type incorporates americium-241 mixed with beryllium-9 in a capsule. The alpha particle emitted from the decaying americium nucleus is absorbed by the beryllium nucleus in a nuclear reaction, which transforms it into a ^{12}C nucleus, and produces a free neutron that is emitted from the source capsule. Other mixtures are also used as sources, including capsules containing ^{226}Ra, ^{238}Pu or ^{239}Pu with ^{9}Be or isotopes of lithium or boron; these work via similar nuclear reactions to provide neutrons of alternative energies.

Neutrons have mass but no electrical charge, and interact only weakly with matter. As a result of this, they do not interact with the cloud of electrons orbiting atoms, instead only losing energy when they collide with their tiny nuclei. Neutrons tend therefore to have long ranges in matter, hence they are particularly difficult to shield against. Neutron sources outside the body typically pose a direct radiation hazard, including to the organs deep within the torso and the lens of the eye. Furthermore, because neutron emission is often also accompanied by gamma radiation, those associated photons pose an additional risk. This situation is complicated by the fact that materials that make good photon shields may make poor neutron shields (and vice versa), and in some cases may even exacerbate the problem as more radiation is released when the neutrons pass through certain materials.

3.3.5 Positrons

Energetic electrons can be emitted as radiation during the beta decay of nuclei containing too many neutrons. However, an opposite type of decay can occur in nuclides that are **proton rich**, which contain too many protons relative to neutrons to be stable. In **beta plus** decay (denoted by β^+, to indicate its positive charge), also known as **positron decay**, a proton transforms into a neutron and a positron which is identical to an electron but of opposite charge. After a β^+ decay of a parent radionuclide, its daughter is a new element with an atomic number that is 1 lower than its parent but an atomic mass number that is the same. Typically, β^+ decay arises in light and medium mass nuclei, with other types of decay favoured in heavier proton rich isotopes.

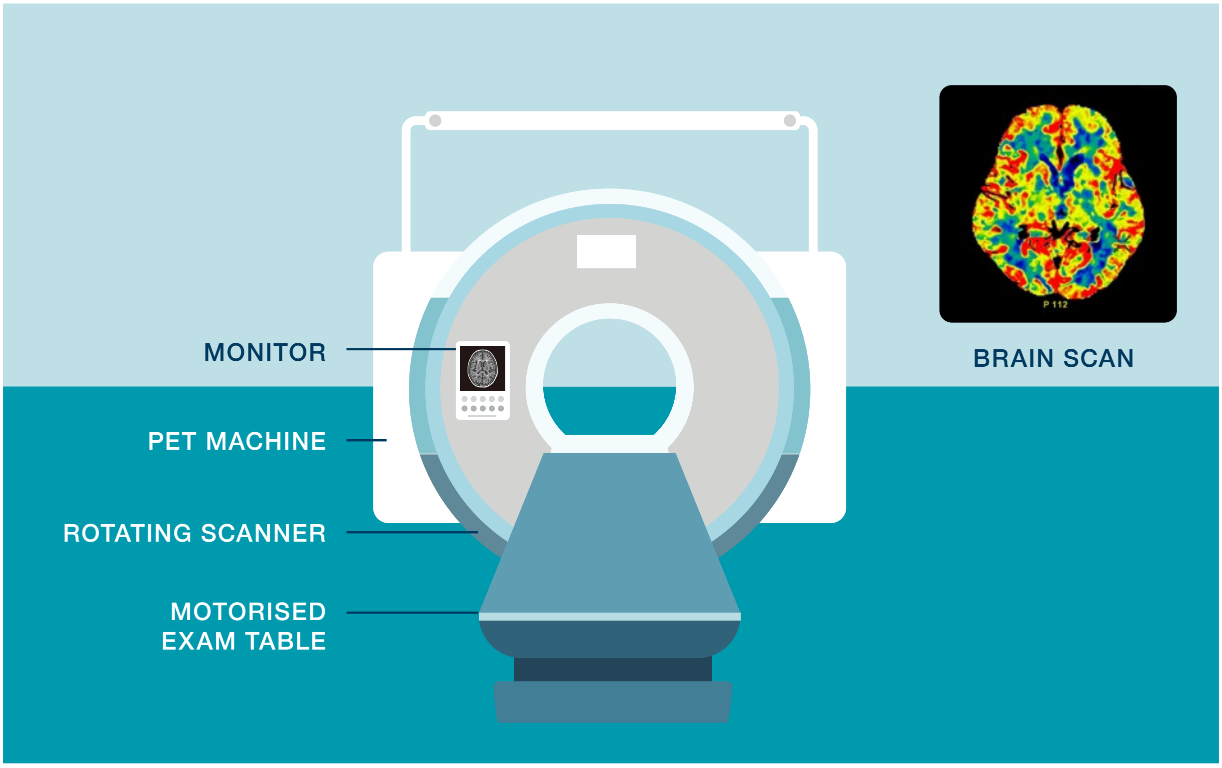
The positron was discovered some years after the discovery of the electron. Because they are very light and have a single unit of positive charge, positrons undergo many interactions with the surrounding atoms as they are slowed and stopped, They have ranges that are nearly identical to those of electrons of equivalent kinetic energy, leaving behind similar tracks of ionised atoms. However, their fates differ greatly. Being an **anti-particle**, a positron will ultimately combine with a normal electron, during which both particles are annihilated: the combined mass (m) of the positron and electron will be converted into electromagnetic energy (E) according to Einstein’s famous equation $E=mc^2$, where c is the speed of light. The energy usually appears as two identical photons that travel in opposite directions and have a specific, characteristic energy.

Overall, positrons are described as being moderately penetrating radiation. Positron emitters outside the body pose a direct radiation hazard, especially to shallow organs such as the skin and the lens of the eye. However, because their annihilation always results in the production of penetrating photons, they will also pose an indirect hazard to all other organs of the body, including those deep within the torso.

An example of a positron emitter is ^{11}C, a radioactive isotope of carbon that decays into boron-10 with a short half-life of 20 minutes. Because they are chemically identical, ^{11}C may be attached to molecules in place of 'normal' ^{12}C to produce **radiolabeled compounds**. Such compounds are often administered in small quantities to patients in hospitals for use in an imaging technique called **positron emission tomography (PET)**. For PET examinations, the radio-labelled compounds are typically chosen to be preferentially taken-up by the specific organs and tissues of particular interest, where the ^{11}C is left to decay. The opposite directions of the two annihilation photons from each positron, and the fact that they always travel in more-or-less straight lines at the same speed, means that if both can be detected by sophisticated equipment, the precise location where they were produced may be reconstructed. This allows doctors to assess the shape and function of the organs of interest.

Other radionuclides commonly used in PET scans include nitrogen-13, oxygen-15, fluorine-18 and gallium-68, bound to different chemical compounds to achieve different clinical ends. Positron emitters typically have short half-lives and are not found in usable amounts in nature, unlike natural β^- emitting radionuclides, so they always have to be man-made. Some PET radionuclides (e.g. ^{11}C) are created in a large machine called a **cyclotron**, while others (e.g. gallium-68) use a sophisticated **generator**.

PET brain scan image



3.3.6 Other radiations

There are other particulate radiations that exist in nature or can be produced using special machines. For example, although radionuclides that decay by proton emission are not found naturally, beams of protons may be generated using particle accelerators. Such proton beams are now being used in very specialist healthcare centres for some types of radiotherapy treatments.

Other particulate radiations, such as **heavy ion beams**, have also been investigated for medical purposes but are not in routine use in the UK. In this context, 'heavy ions' are the nuclei of atoms heavier than helium, and these types of radiations are also generated in some specialised nuclear physics research laboratories. Their large positive electrical charge and mass means they can be accelerated and given large amounts of kinetic energy but stop quickly in matter (including biological tissue), leaving very dense tracks of ionized atoms, which again offers scope for radiotherapy or other applications.

These types of particulate radiation are rare on Earth, but are more common in the wider Universe. In fact, they are one of the main radiation hazards to which astronauts are exposed when they leave the protective layer of the Earth's atmosphere.

3.4 Energy of radiations

Charged particles, such as alpha and beta particles, are emitted with differing kinetic energies that depend on the particular radionuclides producing them, and they lose energy nearly continuously in matter as they are slowed by many interactions with the positive and negative charges contained within atoms. Gamma radiation, X-rays, and neutrons are also emitted at different energies that depend on how they were produced. Their energy loss is less frequent but more 'violent' as they instead experience a sequence of discrete 'collisions' with the surrounding atoms.

The energies of relevance here are extremely small in comparison with those typically encountered on the human scale, so in radiation physics the **electron volt** is often used to quantify the energy of ionizing radiation. The electron volt (eV) is defined as the kinetic energy that an electron would acquire if it were accelerated across a potential (voltage) difference of one volt. It is a tiny amount of energy , but significant in terms of an atom. It takes an energy transfer of typically between one and ten electron volts to ionize an atom by ejecting or 'kicking out' an orbiting electron from it. In contrast, **non-ionising** electromagnetic radiations, such as infra-red, microwaves and radiowaves, cannot cause this effect because their energy per photon of electromagnetic radiation is too low.

Beta particles are typically emitted with initial energies ranging up to about 2 MeV (two million electron volts). Most alpha particles have an initial energy within a fairly narrow range of 3-7 MeV, while gamma ray photon energies can also typically range up to a few MeV. These are the energies of radiations from radioactive decay processes. Conversely, typical neutron energies can extend across a very wide range, i.e. from the meV to MeV scales. Neutrons also have biological impacts across this entire range: they interact exclusively with the nucleus, and can trigger nuclear reactions that release far more energy that that of the neutron.

Higher energy particles are emitted by extra-terrestial processes (cosmic radiations), and can also be produced in machines such as linear accelerators, cyclotrons and synchrotrons. The Large Hadron Collider and similar machines can accelerate sub-atomic particles to close to the speed of light, giving them energies far greater than the particles emitted from any natural radioactive decay process.

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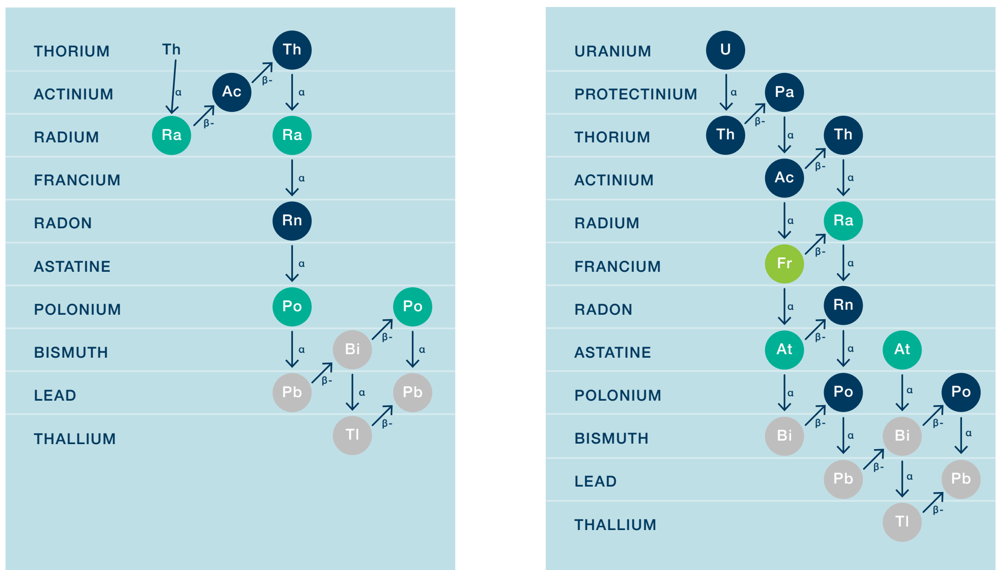
[2] 1 eV = 1.6×10^{-19} J, where J denotes the SI unity of energy, the joule. It would require over 100 billion billion electron volts of energy to raise the temperature of a teaspoon of water by 1°C.

3.5 Natural decay chains

Many man-made isotopes are associated with relatively simple decay modes, either from a radioactive parent to its stable daughter (e.g. carbon-14 decaying to nitrogen-14), or two-stage decays like caesium-137 decaying to barium-137m and then stable barium-137. However, the isotopes of the naturally occuring heavy radioactive elements often occur in long, complex **decay chains**. The heads of these schemes are very long lived **primordial radionuclides**, notably uranium-238, uranium-235 and thorium-232, that were created in stars long before the Earth was formed. It takes on average 4.5 billion years (its half-life) for a uranium-238 atom to decay, but once the process has started decay continues through a series of quicker nuclide transformations, during which the atom becomes various isotopes of thorium, protactinium, radium, radon, lead, polonium, astastine, thalium and bismuth. Only when the atom has decayed to a stable isotope of lead does the process end.

How long the atom spends as a particular isotope depends on the half-life of that radionuclide. In some cases it is very short, whereas for others it can be much longer. If the half-life of a given isotope is sufficiently long, it may be possible to extract that element from the mixture containing uranium and its decay products. This is what was done by Marie Curie and others in the discovery of radioactivity over a hundred years ago. Until the invention of the cyclotron in 1929 and the nuclear reactor in 1939, these naturally extracted radio-elements, especially including radium, were the only types of powerful radiation source that were available other than X-ray tubes.

U-238 and Th-232 decay schemes



An important member of the uranium-238 decay chain is the isotope radon-222. This is an alpha emitter that decays rapidly though a series of short-lived bismuth, lead and polonium isotopes, which give off alpha, beta and gamma emissions. The main significance of this is that radon is a gas and radon-222 has a short half-life of 3.8 days, long enough for it to be able to seep out of rocks, soils or other materials containing its parent isotope (radium-226) and enter buildings or other partially ventillated occupied areas (e.g. undergound mines). Within these enclosed spaces, the amounts of radon gas and its short-lived decay products can sometimes build to very high levels. The decay products of radon-222 tend to attach themselves to microscopic dust particles in the air that, when inhaled, can be deposited in the lungs and the airways, delivering alpha, beta (and some gamma) radiation to those body tissues. Indeed, exposure to radon gas is, on average, the single largest source of human exposure to ionizing radiation, with most of this exposure being received when we are indoors or underground (see more in Chapter 8 and 10).

3.6 Radiation, sources and contamination

Isotopes such as carbon-14, caesium-137, or americium-241 all possess the fundamental atomic property of **radioactivity**. These radiation sources will continually emit radiation and cannot be 'turned off', although their activity, and therefore the intensity of the radiation, will reduce with their half-life and eventually all the radioactive atoms will have decayed. In contrast an X-ray tube, for example, is an electrical device that will stop producing X-rays as soon as the power is cut. This in itself suggests that it may be safer to use an X-ray source than a radioactive substance, and increasingly this has been done in some applications, for example in research, but it is not feasible for all applications.

Radiation is emitted from any and all of the radioactive atoms within a material, so if a homogenous sample of radioactive material were to break up into smaller pieces, each of those pieces would also be radioactive. The activity of each piece would be proportional to its size, where the combined activity of all the pieces would equal that of the original single lump.

The physical or mechanical properties of some materials may lead to them fragmenting easily into many small radioactive pieces, which could subsequently become dispersed over a larger area. Likewise, volatile or gaseous radioactive materials will also have a tendency to spread if they are not contained. If there is dispersion of radioactive substances in a workplace or in the general environment then we have **radioactive contamination**, with the obvious hazards and risks to people and animals that this would entail. To avoid this situation, wherever possible in technological applications, a **sealed radioactive** source is used that is designed and constructed to trap the radioactive material and be capable of withstanding any foreseeable conditions to which it could be subjected (short of deliberate attempts to damage it). However, there is a limit to how robust such a source capsule (or other physical form) can be, because it is not useable if its walls are made so thick that the radiation cannot get out. This means that sealed sources of highly penetrating radiation such as gamma rays can frequently be designed to withstand severe conditions, including fires, whereas some alpha and beta sources are often more easily damaged.

RPA monitoring for contamination

Modern small self-shielded cyclotron

Airport X-ray baggage inspection system

On the other hand, there are situations where we must use a dispersible radioactive source. One example is in nuclear medicine in a hospital, where a radionuclide is incorporated into the body for diagnostic purposes or therapy: the radioactive substance is likely to be contained in a solution that is administered intravenously into the patient via an injection. In addition, technologies such as nuclear fuel fabrication and fuel reprocessing inevitably produce radioactive by-products that are in dispersible form. In both cases, stringent controls and safety measures are enforced to minimize risks to workers, members of the public (including patients), and the environment.

Very high energy radiations can themselves produce **induced radioactivity** in materials. Induced radioactivity is a consequence of nuclear reactions between the incident radiation and the nuclei of the 'target' atoms, which can be changed into different isotopes that may be radioactive. On one hand, this can carry similar risks to contamination, in the sense that radiation becomes emitted by 'secondary' objects rather than just the original single source; these new sources are potentially less well-characterized than those that produced them, and require extra resources to control. Nevertheless, induced radioactivity is actually how many useful radioisotopes are manufactured, for example in cyclotrons. The nuclear reactions that cause induced radioactivity can only take place if the energy of the incident radiation is above a specific minimum **threshold**, which is typically very high, below which no radioactivity is induced at all. Neutrons too can induce activity by the process of neutron activation, which is another common method for manufacturing certain radio-isotopes, but the process needs a substantial source of **neutrons**, such as a nuclear reactor.

In contrast, it is important to stress that most of the common radiation sources we use do not cause the things they expose to become radioactive. A well known example of this is a modern X-ray baggage inspection system at an airport: items are imaged using the X-ray beam, but neither the baggage nor the machine they pass through become radioactive or contaminated by the process. Similarly, the X-rays used in medical imaging, including dentistry, also do not lead to any radioactivity in, or contamination of, the patient.

04

Exposure to ionising radiation

Authors: Jon Eakins and Rick Tanner

Types of radiation exposure

Exposures to ionising radiation can be broadly divided into exposures to radiation from outside the body, i.e. **external exposure**, and radiation from sources incorporated inside the body, i.e. **internal exposure**. The main types of radiation that are significant for external exposures are electromagnetic radiations (X-ray and gamma ray photons), and particles such as neutrons, electrons (beta particles) and positrons (positively charged electrons). For internal exposures, alpha particles are also important.

Radiations coming from outside the body are called **external radiations** or sometimes **direct radiation**. Gamma rays, X-rays and neutrons are generally deeply penetrating and expose all parts of the body.

Beta particles are less penetrating and mainly expose shallow sensitive regions, such as the skin and lens of the eye, but pose little risk to deeper tissues. Positrons are equally less penetrating so they also pose risks mainly to the skin and eye lens, however, they additionally produce highly penetrating photons when their paths terminate, which can irradiate deeper organs. Alpha particles, however, generally cannot penetrate the dead layer of the skin, even if the source is in contact, so they are not regarded as an external radiation hazard. External radiation exposures can be controlled by minimising the activity of the source or the power of the X-ray tube, minimising the time of exposure, increasing the distance from the source, and using shielding. Simply moving away from the source reduces the exposure immediately.

Shielding of alpha, beta, gamma/X-ray and neutron radiation schematically

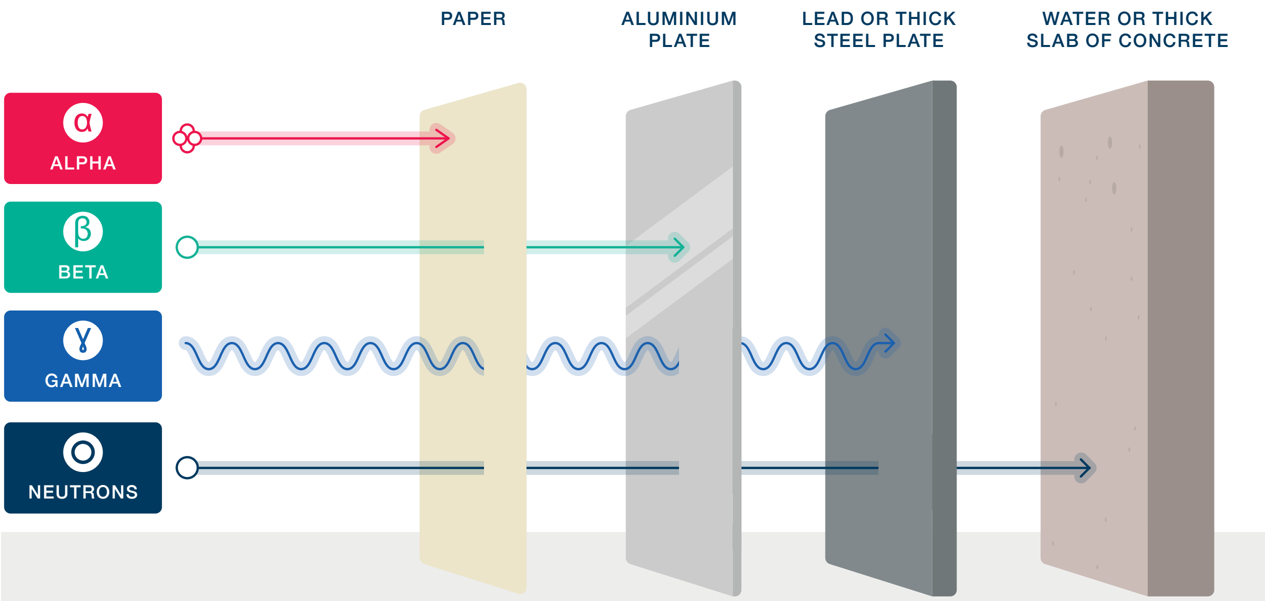


Diagram showing shielding of alpha, beta, gamma/X-ray and neutron radiation schematically.

Internal radiation can present a risk when radioactive substances are taken into the body by inhalation, ingestion, entry into a wound, or via injection in some nuclear medicine procedures. The radioactivity is therefore contained within the exposed person and is only cleared by radioactive decay and normal biological processes of excretion. For example, for a given activity, gamma ray emissions are the least hazardous, partly because the photons are long-ranged and so much of the emitted radiation escapes the body and does not interact much with the tissues. Beta and positron emitters are an intermediate hazard, whilst alpha emitters are the most hazardous. For both beta and alpha emitters the radiation generally cannot escape the body, and their energy is instead delivered to the nearby body tissues, potentially causing damage. The energy deposition from alpha emitters is also over a much shorter range than that from electrons, so the damage can be much more concentrated. Because internal contamination can concentrate in specific organs or parts of the body, internal exposures cannot only increase the risk of cancer, but significantly impact on the health of an organ or tissue.

Internal versus external radiation/contamination

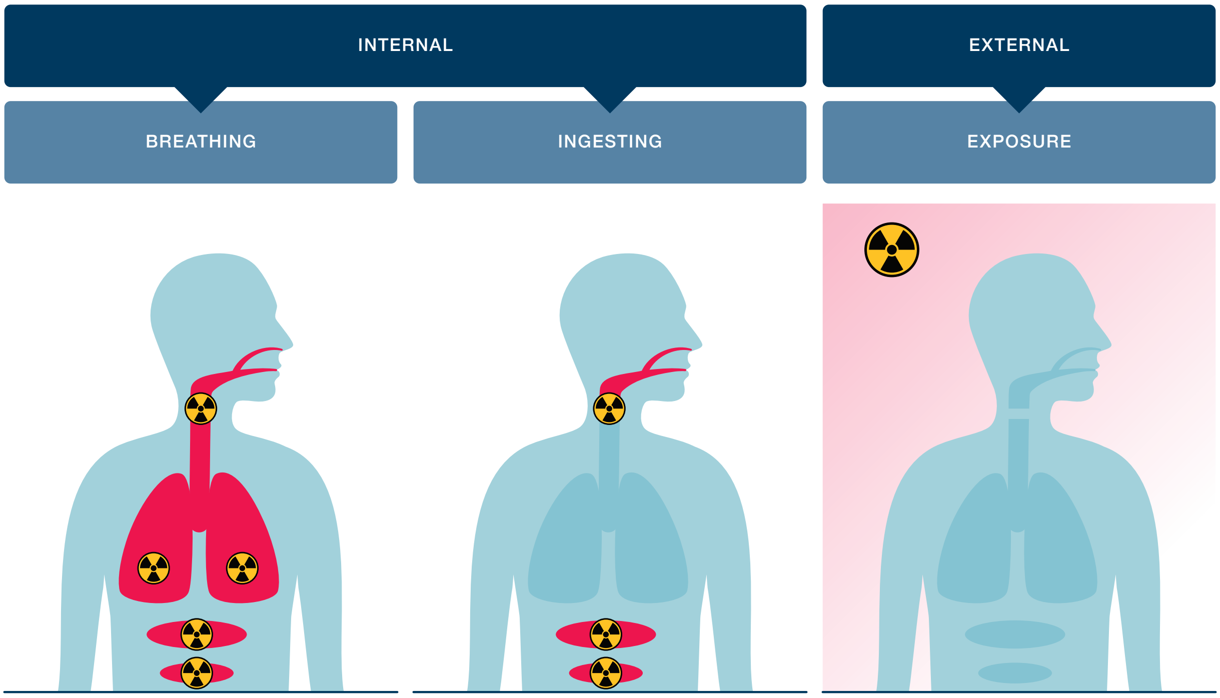


Diagram showing internal versus external radiation/contamination.

Ionisation processes in detail

When particulate and electromagnetic radiations pass through matter they deposit energy by mechanisms that depend on the type of radiation. The **primary radiation** is that which comes from the source of radiation exposure itself, for example an X-ray tube or a radionuclide source. As this radiation passes through matter it loses energy to the surrounding atoms and molecules by various processes,which can involve a change of direction (scattering) or absorption. Some of this deposited energy causes complete ejection of electrons from their original atoms, the process of **ionisation**. These ejected electrons may have considerable energy and they then become **secondary radiations**. They will be emitted in a range of directions relative to the incident radiation and can cause further ionisations until the emitted electrons lose energy and make further ionisation impossible.

Ejected electrons are not the only possible types of secondary radiation. For example, neutrons may be absorbed by a nucleus which then emits a gamma ray or charged particle which will create further ionisations, or they may cause the nucleus to recoil sufficiently to cause ionisation in surrounding atoms. High energy photons can spontaneously produce electron-positron pairs that go on to cause many additional ionisation events.

The transfer of energy to atoms and molecules via their orbital electron clouds is called **excitation**, and much of this energy can have a heating effect. A rapid increase in the temperature of tissues caused by ionising radiation, or other radiations like microwaves, can be very harmful to an organism. The mechansims by which ionising radiation deposits energy are translated into heat and chemical changes to the sensitive biological mechanisms in cells: these chemical changes are especially important when they affect cell replication.

Living organisms contain a range of molecules of varying complexity. Direct ionisation by radiation can split molecular bonds. Biological tissues also contain a substantial amount of water, but ionising radiation can split one of the oxygen-hydrogen bonds in the water molecules, creating highly reactive hydroxyl radicals. These **free radicals** last only for a very short time before typically re-combining back into water molecules, but they can also react chemically with other neighbouring molecules, potentially changing them. Those changed molecules may be detrimental to the biological functioning of the tissue.

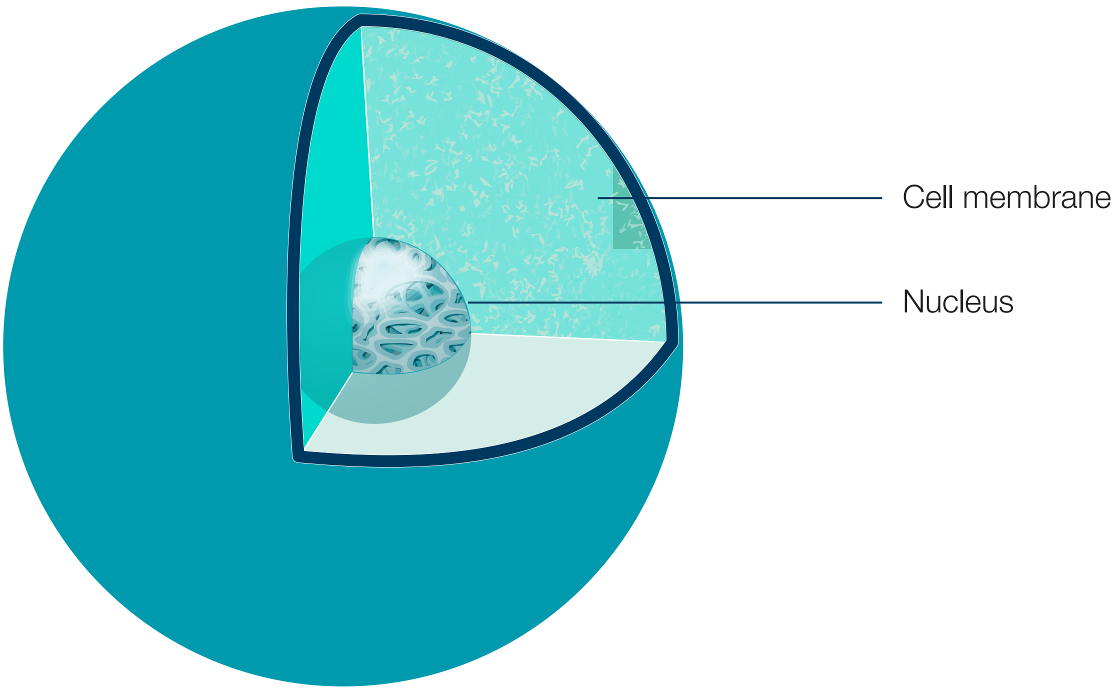
The basic unit of biological tissues is the cell. Most cells have a **cell nucleus** where many important functions of the cell are controlled, including cell replication. The nucleus of a cell is an intricate structure and must not be confused with the nucleus of an atom. Ionising radiation can affect cell replication by damaging the **deoxyribonucleic acid (DNA)** in the cell. DNA is found mainly in the nucleus of the cell, although not in all cells. It carries the **genetic code** and controls the structure and function of the cell, as well as passing on copies of itself at **cell division** (many of the cells in our bodies replicate themselves frequently). DNA molecules are large (each cell contains 1.8 metres of nuclear DNA as a fine 2 nanometre thick double helical strand) and are carried within even larger cellular structures, chromosomes. **Chromosomes**, are readily visible through a powerful microscope at certain phases of cell development. The effects of radiation on DNA will include direct radiation damage caused by ionisation of bonds within the molecule itself, but also damage caused by the action of free radicals created in the immediate vicinity. Biological systems have evolved various DNA repair mechanisms and most radiation induced damage is repaired, including most of that caused by natural background or other radiation exposures. However, some damage may not be repaired properly, which introduces errors into the DNA code. These errors can lead to harmful biological effects, including the development of cancers or inherited genetic defects, as described in more detail in Chapter 6.

Whilst all doses of ionising radiation can damage the DNA, very high doses of radiation, >1 Joule per kilogram (J/kg), also known as >1 Gy (see protection dose quantities section below), can damage or 'kill' cells by interfering rapidly with major biochemical processes. Whilst the body can cope with the loss of some cells, if too many are killed within a tissue it will no longer perform its biological function. This might lead to a failure of that organ or, in the most extreme cases, even the death of the individual. Clinically, such conditions are referred to as Acute Radiation Syndromes (ARS), or more colloquially 'radiation sickness'.

The above high dose effects are different from those at low doses because the latter will always be more a matter of chance and generally take longer to be observed as health effects

Schematic DNA molecule

A cell and its nucleus



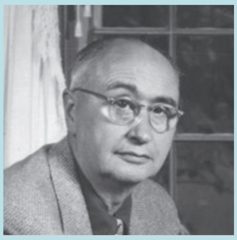
Protection Dose quantities

Unlike other radiations such as visible light and heat, ionising radiation cannot be detected directly through our senses of sight, smell, touch etc. Technological devices are needed to do this, including **photographic films, ion chambers, Geiger Muller tubes** and **scintillation counters**, as well as newer techniques using **luminescent materials** and **semiconductor detectors**.

The term radiation dose is used to describe the amount of radiation exposure received. It is known that the harmful effects of ionising radiation are related to the deposition of energy in exposed tissues and in particular the effects are proportional to the energy deposited per unit mass. This has led to the development of the basic quantity **absorbed dose**. The modern SI unit of absorbed dose is the gray (symbol Gy), named after the English physicist Harold Gray. One gray corresponds to one joule of energy deposited in one kilogram of matter. It represents a relatively large dose of radiation, so submultiples such as the milligray (mGy, thousandths of a gray) and microgray (μGy, millionths of a gray) are commonly used.

The concept of absorbed dose can be applied to both external radiation and internal radiations. In principle, the external dose received by a person can be measured by placing a radiation detector at the position of maximum exposure. Internal radiation doses cannot be measured in the same way, but if the activity (in Bq) within the body is known and it is also known where it is located, it is possible to calculate the absorbed dose delivered by the radioactive substance to individual organs within the body.

Harold Gray and Rolf Sievert



Harold Gray
1894–1968

Rolf Sievert
1896–1966

Knowing the absorbed dose alone is not sufficient to explain the relative effects of different types of ionsing radiation and their differing propensities to cause biological damage. To put all ionising radiations on the same scale with regard to their potential for causing harm, another dose quantity has been defined. An initial step in this process requires the radiosensitive tissues and organs to be identified, and then a dose quantity can be defined that relates to those tissues and organs and takes account of the different degrees of damage that different types of radition might induce. This quantity is defined by the International Commission on Radiological Protection (ICRP) and is called the **equivalent dose**, expressed in a unit called the sievert (symbol Sv) named after the Swedish physicist Rolf Sievert. This equivalent dose can subsequently be controlled to protect people by, for example, setting **dose limits**. Equivalent dose is equal to the absorbed dose in a specific tissue or organ multiplied by a **radiation weighting factor** that accounts for the way in which different radiations deposit energy in tissue and allows for relative differences in the causes of biological harm.

The primary use of radiation weighting factors (w_R) and equivalent dose is in protection against the cancer-inducing potential of ionising radiations. For gamma rays, X-rays, and beta particles, the radiation weighting factor is set at 1, so the absorbed dose and equivalent dose are numerically equal, i.e. 1 Gy → 1 Sv. For alpha particles, the factor is set at 20 (i.e. 1 Gy → 20 Sv), mainly because they produce far more dense ionisation tracks that are more likely to lead to DNA damage (and hence damage to cells) that cannot be repaired by the body. For neutrons the radiation weighting factor varies for a similar reason, in the range 2.5-20 depending on the energy of the neutron. Again, one Sievert is a relatively large radiation dose, and sub-multiples such as the millisievert (mSv) and the microsievert (μSv) are frequently used.

Radiation type	w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles	20
Fission fragments, heavy ions	20
Neutrons (energy dependent)	2.5 – 20 (maximum at about 1 MeV)

Exactly why some radiations give rise to an increased cancer risk is a complex subject. For alpha particles, the intense ionisation created along the very short track length is important in terms of understanding DNA damage. Multiple ionisations very close together are believed to be capable of causing double-strand breaks and complex damage, where multiple sites suffer changes in a short stretch of DNA in the double helix structure. These **double-strand breaks** and complex damage sites are far harder to repair than single strand breaks, where the undamaged strand provides the template to repair the damaged one. Note that the values for the radiation weighting factors described here are for applications intended to protect against the cancer risk from relatively low doses of radiation. They are not directly applicable when considering the acute effects of radiation resulting from high dose exposures, including cell killing and tissue damage such as radiation burns, although different types and energies of radiation also lead to different degrees of damage.

There are several further complications to consider in devising units for radiation dose, and in particular when setting dose limits to control the risk of late effects of ionising radiation, including cancer and potential hereditary effects. Not only do different radiations present potentially different risks per unit absorbed dose, but the same level of equivalent dose in different tissues (or organs) within the body can have a different risk. Putting that another way, some organs are known to be more **radiosensitive** than others. In addition, when considering real exposures of people, it is relatively unusual to have uniform exposures of the body. For practical purposes, including setting of legal dose limits, a single measure is needed that represents the combined risk or **index of harm** to an individual as a consequence of the exposure they have received or are receiving. The quantity that is used is the **effective dose**, which is defined as the sum of the products of the equivalent doses to the separate organs of the body, multiplied by their respective **tissue weighting factors**. The tissue weighting factors were determined primarily from analyses of the relative frequencies of excess cancers in human populations exposed to ionising radiations, especially the Japanese atomic bombing survivors, and are normalised so they add up to one. The last step means that in the hypothetical case of truly uniform exposure of all organs of the body, the numerical values of the effective dose and the equivalent dose to every part of the body are identical. The unit of effective doses is again the sievert.

Standard tissue weighting factors as currently recommended by ICRP

Tissue or Organ	w_T
Bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Breast	0.12
Gonads	0.08
Bladder	0.04
Oesophagus	0.04
Liver	0.04
Thyroid	0.04
Skin	0.01
Bone surface	0.01
Brain	0.01
Salivary gland	0.01
Remainder	0.12
Total	**1.00**

Values of the tissue weighting factors (w_T) and radiation weighting factors (w_R) are recommended by the International Commission for Radiological Protection (ICRP), and consider the total harm or **detriment** caused by the radiation exposure. The concept of detriment includes not just the risk of cancer induction but also the severity of the cancer, because some cancers are treatable or can be managed, and additionally the potential for serious hereditary damage caused by irradiation of the testes or ovaries. In this way, the concept of effective dose linked to risk factors (see Chapter 6) is central to the system of radiation protection. Again note that these standard ICRP factors are for use in protection against the late effects of ionsing radiation, and are not designed to be applicable to high dose effects that manifest shortly after exposure. Note also that the specific values of the tissue and radiation weighting factors that are recommended by ICRP have changed over time, and may change again in the future, to best reflect scientific advances and understanding in radiobiology.

The current values for w_T were recommended[3] by the ICRP in 2007 and are shown in the table on the previous page.

For the remainder of this publication where the word "dose" (in sieverts) is used it can be assumed to be effective dose; if not, this will be made clear in the text.

When considering intakes of long-lived radionuclides that are physically retained in the body for long periods, we need dose quantities that integrate the dose delivered over the time that the radioactive material is in the body. For this we have the **committed equivalent dose** for specific organs or tissues, and the **committed effective dose** for the whole body. To understand these quantities, consider first the contrasting example of an exposure to external radiation from an X-ray examination. The radiation dose is delivered immediately and can be started and stopped at any time using the equipment's controls; a limit can also be set on the annual dose that a person might be allowed to receive from such exposures, and steps may be taken easily to ensure that this limit is not breached. In contrast, if a radionuclide is taken into the body, such as plutonium-239 for example, a fraction of the original intake will be retained for many years because plutonium can accumulate in bone tissues. This will deliver radiation dose over a correspondingly long period, starting from the year of the intake. This latter timescale is important, because it presents operational difficulties when considering how to apply an annual dose limit, a calendar year being a common legal period to consider when regulating against a hazard like this. To overcome this, and to create a sound basis for considering external and internal doses within the same legal framework, the committed dose attributable to the intake is calculated for the calendar year in which the intake occured. The value of the committed dose is obtained by summing the actual doses delivered, or to be delivered, in the year of intake and during all the subsequent years up to an agreed cut-off point, which is typically 50 years from the year of intake. For children the period used is 70 years.

A further set of dose quantities exists specifically for measurement: the **operational dose quantities**. These are needed, because in radiation protection we need to measure the radiation field to which people might be exposed for two quite distinct purposes. Firstly, to check whether the radiation levels are safe for people to be exposed to, either workers or members of the public. These measurements will then be used to assess safe working practice. Secondly, to assess the doses that people were exposed to when they entered an area that has previously been assessed as safe for entry.

Assessments of the radiation field use the **quantities ambient dose** equivalent and **directional dose equivalent**. Ambient dose equivalent is used for instruments that can determine the whole body doses that people might receive, and directional dose equivalent is used to determine the risk to the skin and the eye lens. These quantities are designed to provide reasonable estimates of the effective dose that might be received and also the likely equivalent doses to the skin and eye lens. They are defined at specific depths in tissue, namely 10 mm for whole body, 3 mm for the eye lens and 0.07 mm for the skin, which leads to the symbols $H'(10)$, $H'(3)$ and $H'(0.07)$ for whole body, eye lens and skin respectively.

Doses to people are assessed using personal dosemeters, which determine the quantity **personal dose equivalent**. This quantity is required because personal dosemeters are small, light-weight devices worn on the body that are used to assess the radiation received, but they cannot estimate the effective dose received by the whole body. These assessments for workers are then entered into dose records for workers, as best estimates of effective dose. Like the ambient dose equivalent and directional dose equivalent, the personal dose equivalent is defined at different depths for protection of the whole body, eye lens and skin, leading to the symbols $H_p(10)$, $H_p(3)$ and $H_p(0.07)$.

[3] ICRP (2007). The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103 Ann. ICRP 37 (2-4).

Hierarchy of radiation quantities

Hierarchy of dose quantities

↓

Absorbed dose
Energy imparted by radiation to unit mass of tissue

↓

Equivalent dose
Absorbed dose weighted for harmfulness of different radiations

↓

Effective dose
Equivalent dose weighted for susceptibility to harm different tissues

↓

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

05

Sources of exposure to ionising radiation

Authors: Alison Jones and Samantha Watson

Everyone is exposed to a range of radiation sources throughout their lifetime. Some of these are naturally present in the environment, and some come from other sources incuding uses of radiation in medicine and industry. For each type of radiation exposure described in the following paragraphs, the percentage contribution to the total amount of exposure received on average by individuals living in the UK is given. However, there will be some variability between individuals depending on: where they live (which will affect their doses from radon and terrestrial radiation); where they work; their habits, for example how much they fly (which will affect their dose from cosmic radiation); and if they need any medical tests or treatments which result in radiation exposure. Some of these exposures are easier to control than others, and the benefits of exposure may outweigh the risk of receiving that dose. In the case of medical exposures to radiation, the health benefits of receiving a radiation exposure must outweigh the risks associated with that radiation exposure. The decision about making the exposure must be carefully considered by those involved, and efforts must be made to minimise exposures where possible.

The following paragraphs refer to effective doses (mSv) and percentage contributions to the UK average radiation dose. These values are taken from the Ionising Radiation Exposure of the UK Population: 2015 Review, and while it is recognised that these values are now over 10 years old, it is unlikely that they will have changed very much. In the case of medical uses of radiation, the total number of diagnostic procedures using ionising radiation has increased since the previous assessments. Patient doses per procedure have also changed, with technological advances and improved techniques sometimes resulting in lower levels of dose per procedure compared to the previous assessment. Until a full review of both the frequency of procedures and patient doses has been completed it is not possible to provide an accurate update on the collective dose from diagnostic medical procedures.

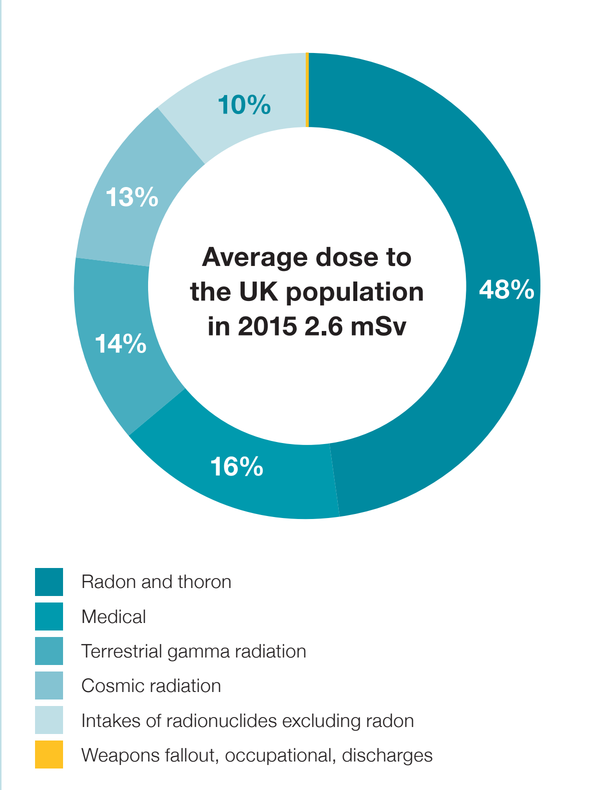
Radioactive elements (radionuclides) of **natural** origin are present in all areas of the environment, including soil, air and water. Long-lived radionuclides, called **primordial** radionuclides because some pre-date the formation of the Earth, are found in all natural environments. These include uranium, radium and thorium. On average, by far the largest source of radiation exposure is **radon gas**. Radon is a radioactive gas formed by decay of natural radioactive uranium found in the rocks that make up the earth. Radon in homes, and in buildings generally, including occupational expsoure of natural radon, contributes about 48% of the average radiation dose in the UK. Due to differences in the underlying geology the dose from radon exposure can vary considerably across the country, so that in some areas the average radon dose is almost 7 mSv a year and in some exceptional cases it can be over 100 mSv in a year. Other long-lived radionuclides in the earth's soil and rocks produce gamma radiation, known as **terrestrial radiation**, which contributes about 14% of the average radiation dose in the UK. Some natural radiation sources are also found in the Earth's upper atmosphere. This is known as **cosmic radiation**, and comes from high energy particles from deep space and some lower energy radiation from the Sun. The **cosmic radiation** arising from these radionuclides varies depending on location, and on the activity of the sun, which varies on an 11-year cycle. On average, cosmic radiation contributes about 13% of the average radiation dose in the UK. Plants and animals are also exposed to radiation in the environment, which means that plant and animal-based foodstuffs will contain sources of radiation. This can lead to exposure from ingesting **natural radionuclides in foodstuffs**. The radionuclides in food which contribute most to exposure of the UK population include potassium-40 (^{40}K), the radionuclides in the uranium and thorium decay chains, carbon-40 (^{14}C), and rubidium-87 (^{87}Rb). Intakes of natural radionuclides in foodstuffs contributes about 10% of the average radiation dose in the UK.

Human-made radiation sources in the environment include fallout from nuclear weapons testing, routine releases from both the civil nuclear industry and non-nuclear industries, and accidental releases. **Weapons fallout** refers to radionuclides arising from atmospheric nuclear weapons tests. Although such testing largely ceased by the mid-1960s, the contamination is globally widespread and persists in the environment. Weapons fallout contributes about 0.2% of the average radiation dose in the UK. Both the nuclear industry and other industries and organisations release **routine discharges (releases)** of small amounts of radionuclides. Routine discharges contribute less than 0.01% of the average radiation dose in the UK. The majority of these are released to the atmosphere but some are made to watercourses and the sea. The civil nuclear industry in the UK includes nuclear power stations, nuclear fuel cycle facilities, and research and development facilities. The UK civil nuclear industry also includes two sites involved in the manufacture of radiopharmaceuticals. Significant discharges of radiation were made in the 1960s and 1970s. While changes in regulations since then have led to substantial reductions in the amount of radiation that can be discharged, some radiation from past discharges remains in the environment and contributes to current radiation doses. The nuclear industry is not the only source of man-made radiation. Other industries that routinely release radionuclides include the oil and gas industries, coal and steel industries, the defence industry and hospitals. The contribution from non-nuclear industries is expected to be very low compared to that arising from exposure to radionuclides released by the civil nuclear industry. While the use of radiation or radioactive material is generally very well controlled and subject to many safety requirements, **accidental discharges** of radiation do occur. Examples include releases from an accident at the Windscale facility in Cumbria in 1957, the Chornobyl nuclear accident in 1986 and the accident at the Fukushima nuclear power station in Japan in 2011. Accidental discharges contribute less than 0.02% of the average radiation dose in the UK, with current exposure from accidental discharges being negligible.

As well as exposure to radiation from sources in the environment, exposures also arise through **uses of radiation**, though these exposures tend to affect a smaller number of people. By far the largest contribution from uses of radiation is exposure of patients to radiation for medical purposes, with diagnostic procedures contributing 16% of the average radiation dose in the UK when averaged over the whole population.

Occupational exposure occurs in a range of sectors. Many workers receive no radiation exposure above natural levels similar to that which they receive at home, and this exposure has been included in the contribution from radon gas. However, some groups of workers do receive radiation exposures that must be controlled. Overall, averaged over the whole population, occupational exposure contributes 0.02% of the radiation dose in the UK. There are a range of minor sources of exposure associated with the use of radioactivity in **consumer products**. For example luminous items incorporating small amounts of radioactive substances such as watches and other timepieces may give small doses to their wearers. Domestic smoke detectors contain a small radiation source that emits weak gamma rays. However, doses from these products are very small, and other than smoke detectors, the number of individuals regularly using such items is also very small.

Breakdown of the dose to an average person in the UK population



06

Effects of ionising radiation

Authors: Elizabeth A. Ainsbury, Stephen Barnard, and Simon Bouffler

Ionising radiation can cause damage to the human body which can lead to health effects and illness in several different ways. The type of effects observed and the time taken for them to appear depend on the circumstances of exposure.

In practice, radiation doses of above approximately 2 Gy (refer to Chapter 4 for dose definitions) will lead to fairly immediate health effects called 'deterministic effects' or, more commonly in recent years, 'tissue reactions'. Dose is an important factor both in how quickly radiation effects occur and how severe they are. For example, an absorbed dose of 5 Gy or more to the whole body received instantaneously, would probably, without medical treatment, be lethal because of irreparable damage to the bone marrow and the gastrointestinal tract. If only part of the body was exposed, then the same dose would probably not prove fatal. Instead other early effects would be likely to occur, including radiation burns to the skin.

If a similar dose of radiation was received over a period of weeks or months, there would be more opportunity for cells and tissues to repair and there might be no early signs of radiation damage. This is why radiation given in medical radiotherapy is separated into smaller doses, to minimise unwanted damage to healthy tissues. However, other health effects may still be observed many years later. Even very low doses of radiation can cause longer term 'stochastic' effects such as an increased risk of cancer which might appear many years after exposure. There is also a risk of hereditary effects which may appear in the exposed individual's descendents. The sections below provide more information on how radiation exposure can result in immediate or short-term effects (tissue reactions / late-developing tissue reactions), longer term effects (induction of cancers) and heritable effects (inherited parent to offspring diseases).

Tissue reactions

Tissue reactions are effects of radiation that occur soon after an individual receives a large radiation exposure, above a certain 'threshold' dose of ionising radiation. These effects occur mainly because of direct, cellular or tissue damage and how serious the effects are depends on the size of the radiation dose received. If an individual receives an instantaneous ('acute') radiation exposure above approximately 2 Gy to the whole body, then they will be likely to develop Acute Radiation Syndrome (ARS). The initial symptoms of ARS can involve vomiting, diarrhea and headache. How likely someone is to develop these symptoms and how quickly the symptoms develop will also depend on how much radiation they have been exposed to. These initial symptoms will be followed by a 'prodromal' phase of ARS, where the superficial damage is starting to be repaired and the individual begins to feel better. Individuals exposed to doses lower than approximately 8 Gy may have no symptoms at all during the prodromal phase. After the prodromal phase, the individual will experience the main phase of ARS. This will involve a range of different effects that will depend on the amount of radiation the individual has been exposed to and the way in which they have come into contact with radiation, e.g. whether the exposure was to the whole of the body or part of the body. The most common effects will involve the blood and bone marrow (the 'haematopoietic' system), the stomach and intestinal tract (the gastrointestinal system) the skin, lungs, and nervous system. The effects for any individual are also dependent on factors such as their general health prior to the exposure.

If an individual has received a high enough dose of radiation to cause gastrointestinal syndrome or inflammation of the lungs (pneumonitis), it is very likely that the individual will die. If an individual receives a large dose of radiation to the testes or ovaries then this can cause infertility.

Recent advances mean that even an individual exposed to very high doses of radiation to their whole body can survive if they promptly receive the correct treatment. The availability of specialist medical care and modern treatments including bone marrow growth factors (cytokines) is likely to be critical in determining whether the individual survives. With supportive treatment in a clean facility (such as an organ transplant suite), approximately 50% of people would survive a dose of around 4 - 5 Gy.

Late-developing tissue reactions

Another category of tissue reactions is late effects that can affect people after a large dose of radiation, but which don't usually occur until months or even years after exposure. As with other tissue reaction effects, in most cases, the severity of these effects will depend on the dose of radiation an individual has been exposed to. 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. Examples include skin damage (thinning and ulceration) and cataract in the lens of the eye. Normally only high absorbed doses of several Gy cause these health effects.

However, there have been recent changes in our understanding of the risks of late developing tissue reactions, including cataracts and skin damage, as well as circulatory diseases and cognitive effects. These are discussed in more detail in the 'Emerging Issues' section below.

Induction of cancers

Unlike tissue reactions, the later developing effects of cancers and heritable effects (collectively known as 'stochastic effects') occur with a probability that increases with dose, rather than increasing severity with dose. Cancer is caused by a wide range of different factors and its development is a complex cellular process that happens in several stages over many years. Despite much research in this area, there is still a lack of understanding about why many types of cancer develop. However, it is well known that exposures to agents such as tobacco smoke, asbestos, ultraviolet radiation and ionising radiation contribute to the development of cancers. Radiation appears to contribute to the development of cancers by causing certain mutations in the DNA of normal cells. These mutations may lead cells to grow abnormally, and this can sometimes lead to the development of cancers.

In recent years, a great deal has been learnt about how radiation exposure leads to DNA damage and about how this damage is repaired or misrepaired. Along with improved knowledge in cancer biology, this information suggests that even the smallest doses of ionising radiation can lead to small increases in the risk of developing cancer. On the basis of this current scientific evidence, it is therefore assumed that an individual's risk of developing cancer increases in direct proportion to the dose of radiation that the individual has been exposed to, and this is called the 'linear no-threshold' model or assumption.

Risk factors for cancers

Risks of cancer from exposure to radiation are estimated by studying groups of people who have been exposed to known doses of radiation in their occupation, in medical settings or as a consequence of accidents. The increased risk of cancer among groups exposed to radiation is estimated by comparing the occurrence of different types of cancers in these groups with the numbers of cancers occuring in similar unexposed groups. The main source of information on the risk of cancer following exposure of the whole body to gamma radiation comes from studies on the survivors of the atomic bombs dropped at Hiroshima and Nagasaki in 1945. Other risk estimates relating to the effects of gamma radiation come from studies of radiation workers exposed to radiation during their employment, as well as research on people exposed to radiation for the treatment of cancers, and for diagnostic purposes. Information on the effects of other types of radiation comes from studies of: miners exposed to radon underground and those living in high radon areas; workers exposed to plutonium, uranium and radium-226 in luminous paint; patients treated with radium-224 for bone disease; and patients given an X-ray contrast medium containing radioactive thorium oxide.

To make sure that risk estimates are as accurate as possible, it is important to conduct studies on large groups of people. Factors such as age, sex, and time since radiation exposure are usually considered as well, as these can also be associated with the development of different types of cancers. It is also useful to predict how many additional cases of cancer will have been found by the time all the exposed individuals have died. Various mathematical methods are used for this purpose and the process introduces some uncertainty into the accuracy of the risk estimates. The risk that a cancer will occur is usually given as a risk per unit dose.

Information relating to the risk of cancer from radiation exposure is assessed periodically by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the International Commission on Radiological Protection (ICRP), the US National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation (BEIR Committee), and by UKHSA, PHS (Public Health Scotland), PHW (Public Health Wales) and PHA (Public Health Agency) in Northern Ireland. These bodies review, carry out, and collate research. Some, in particular ICRP, make formal practical recommendations for radiation protection which are then used by law makers to ensure that any use of ionising radiation in society is as safe as possible, based on the most current understanding.

ICRP is the body of experts that translates detailed research findings into recommendations for practical radiation protection. The recommendations are based on scientific research findings, and expert judgements on the health effects of radiation exposures using human and animal studies; ethical considerations and practical experience are also taken into account. ICRP uses a representative international population to estimate the radiation risk factors for different types of cancer. Values of the risk factors are averaged so that they can be applied to every person in the same way. For real individuals, the risks of developing cancer following radiation exposure depend on a large number of other factors including age, sex and other factors specific to the population group.

For instance, if a person receives a radiation dose later in life, a cancer may not have time to appear before the person dies of another cause. Also for example, the risk of breast cancer is virtually zero for men but about 1 - 2% per Sv for women.

The total risk of cancer is calculated as the relative harm for an average population, and is dependent on the tissue or organ affected, the risk of death from each type of cancer and the effect on quality of life. Overall, the life-time risk of developing cancer following radiation exposure is thought to be about 6% per Sv. The risk factor for the working population (those aged 18 to 65 years) is 4% per Sv. This is lower than for the general population because workers do not include children or young people who have more years at risk of developing cancer after radiation exposure. The risk factor for the working population is estimated separately as this group is of particular interest for radiation protection.

Hereditary disease

Apart from cancer, the other main late stochastic effect of concern is heritable disease. As with cancer, the probability of heritable disease arising from radiation exposure – but not the severity of disease – depends on the dose of radiation that an individual is exposed to. The reason that radiation can result in heritable disease is that radiation can cause genetic damage to the male and female reproductive cells (sperm and ova/egg cells respectively) in the testes and ovaries. Ionising radiation can cause mutations in these cells as a result of structural changes in DNA. It is the germ cells which carry the hereditary information in the DNA through to future generations, and may lead to heritable effects of radiation in the exposed individual's descendents. The heritable diseases that might be caused by radiation vary in severity, and can cause anything from early death and serious neurological defects to less severe skeletal abnormalities and minor metabolic disorders.

Large experimental studies using animals (mainly mice) have tested the impacts of a wide range of ionising radiation doses on heritable effects. These studies clearly demonstrate that ionising radiation does cause mutations that can result in heritable disease. The results also show how often different doses cause heritable effects.

Although mutations can appear in human beings without any apparent cause, natural radiation and other agents in the environment may also cause mutations and contribute to the occurrence of heritable disease. However, there has been no conclusive evidence that natural or artificial radiation exposure results in heritable effects in human offspring. Extensive studies of the offspring of the survivors of the atomic bombs in particular, have not shown increases in heritable effects. These negative findings help to provide an upper estimate of the risk for these effects, and when considered with the findings from animal studies, they allow estimates to be made of the impact of different doses of radiation on heritable disease in human beings.

Against this background, ICRP has assessed the risk of severe heritable disease in a general population of all ages exposed to low doses and dose rates of radiation. It estimated a risk factor of 0.2% (or 2 in 1000) per Sv for the reproductive aged population for radiation exposure resulting in heritable diseases appearing at any time in their children and grandchildren. Mutations leading to diseases that are strictly inherited, such as haemophilia and Down Syndrome, make up about half of the total: the remainder comes from a group of so-called multifactorial diseases (caused by a combination of factors) such as diabetes and asthma. This estimate of risk carries a considerable amount of uncertainty, especially for the multifactorial diseases where the relationship between genetic and environmental factors that influence the diseases is poorly understood.

In genetic terms, radiation exposure to the testes and ovaries is potentially harmful only if it occurs before or during the reproductive period of life.

Radiation exposure in pregnancy

The risks to children who are exposed to radiation while in the womb deserve special mention. If an embryo or foetus is exposed to radiation at the time when the brain and 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 to radiation before birth have indicated that mental retardation mainly follows radiation exposure during the first 8 to 15 weeks of pregnancy (which is the period during which the neurons of the brain migrate to their final positions). However, there is only a very small amount of direct human data and so the uncertainties are large. There has been debate over the relationship between dose and response. For exposures during the most sensitive 8-15 week period, ICRP assumes that the decrease in IQ depends directly on the dose, but with a small effect.

High doses of radiation to the embryo and foetus can cause death. The types of effects and how they occur depends on the time after conception that radiation exposure occurs. Radiation exposure before birth can also lead to an increased risk of cancer in childhood.

The risk of fatal cancer up to age 15 years following radiation exposure in the womb is estimated to be about three times higher than in the population as a whole.

For all of these reasons it is best to avoid diagnostic X-rays of the abdomen during pregnancy, and other medical procedures where the developing fetus may be exposed, wherever possible. Indeed for all those of reproductive age where pregnancy cannot be reasonably excluded, it may be prudent to restrict diagnostic procedures that give high doses of radiation in the pelvic area to the early part of the menstrual cycle when pregnancy is least likely. In radiation protection, there are special restrictions on the radiation dose that those who work with radiation sources and are known to be pregnant may receive.

Emerging issues

The table below summarises the above information on what is known about different types of radiation effects.

Radiation protection is a constantly evolving field and there have been a number of recent developments that may lead to changes in the way radiation protection is carried out. For instance, recent evidence suggests that cataracts might be caused by smaller doses of radiation than previously thought, although it is likely that such cataracts would take many years to develop. There is also a suggestion that very low doses of radiation below the thresholds for tissue reactions could cause non-cancer effects - in particular cardiovascular disease and neurological disorders.

Recent advances in knowledge suggest that a person's genetic constitution and their environment/lifestyle may influence their risk of developing cancer (and heritable diseases) following their exposure to radiation. At present, we can only identify rare families who may carry an increased genetic risk, but experts may in future be able to use genetic and lifestyle information to estimate an individual's risk from radiation exposure.

Research is continuing in these and other areas and UKHSA will continue to investigate and review the evidence and implications for radiation protection.

Tissue reactions (following whole body, instantaneous exposure)

Tissue	Exposure	Health effect
Lens of the eye Skin Testes/ovaries Hair	Local dose > ~ 0.5 Gy Local dose > ~2 Gy Local dose > ~3 Gy Local dose > ~4 Gy	Cataract months – many years after exposure Reddening/burn (erythema) within hours – weeks Temporary or permanent sterility Temporary hair loss within 2 – 3 weeks
Mental retardation	Foetal dose > ~ 0.1 Gy	Reduction in IQ of ~25 points per Sv
Bone marrow (blood)* Stomach and intestine** Lungs and kidney Nervous system	Whole body dose 2 – 10 Gy Whole body dose > 6 Gy Whole body dose 5 – 15 Gy Whole body dose > 10 Gy	Recovery if treated; death in 4 – 8 weeks Death in 1 – 2 weeks Death in 8 – 12 weeks Death in < 1 week

* Haemopoeitic syndrome, ** Gastrointestinal syndrome

Stochastic effects

Effect	Exposure	Outcome
Cancer	Risk at any dose	Years later – survival depends on tissue/organ affected, time of diagnosis and treatment available
Heritable effects	Assumed risk at any dose	Potential to appear in children of parents exposed to radiation, though have not been observed in studies exposed to radiation

07

The system of radiation protection

Authors: Axel MacDonald and John Moody

Around the world there is remarkable consistency on approaches to protect against ionising radiation and to a large degree this is due to the work of United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), International Commission on Radiological Protection (ICRP) and International Atomic Energy Agency (IAEA). UNSCEAR independently evaluates ionising radiation exposures and the consequent effects and risks to human health and the environment. This provides an objective and up-to-date scientific basis for radiation protection making UNSCEAR the world authority on radiation science and estimation of global levels and effects of exposure to ionising radiation. Governments and organisations throughout the world rely on the Committee's estimates as the scientific basis for evaluating radiation risk and for establishing protective measures.

In parallel, ICRP as a non-governmental international scientific organisation, references the work of UNSCEAR as the basis to lead in the area of practical radiation protection by providing recommendations and guidance on all aspects of protection against ionising radiation. The authority of ICRP derives from the scientific standing of its members and the merit of its work that are complimented by the recommendations and guidance provided by other international bodies including IAEA and European Commission under the auspices of Euratom (European Atomic Energy Community). This leads to a harmonised approach to radiological protection that ultimately results in implementation by individual countries through national regulations.

ICRP's recommendations identify three basic types of radiation exposure situation to assist in the appropriate application of its system and principles of radiation protection.

Planned exposure situations are those where human actions will add radiation exposure. Examples include exposure of workers operating a nuclear power station or medically supervised administration of radioactive substances to a patient. The first of these will give rise to exposure of workers and the public while the second involves the patient receiving the medical exposure and hospital staff and potentially the public who may be exposed to waste discharges. Some family members may also be physically close to the patient while they still have radioactive material inside them and be exposed to radiation.

Existing exposure situations include normal exposure of the public and workers to natural radiation but also exposure to legacy residues of past practices including those that have built up from historic nuclear facility discharges or created in accidents such as Chornobyl or Fukushima. Industrial processes involving materials with natural radioactivity inevitably give rise to worker exposure, while generated wastes, including direct discharges, can expose the public. Within certain levels, this is accepted as normal and treated as an existing exposure, but where processes involve a substantial concentration of natural radionuclides, it should be regarded as a planned exposure situation.

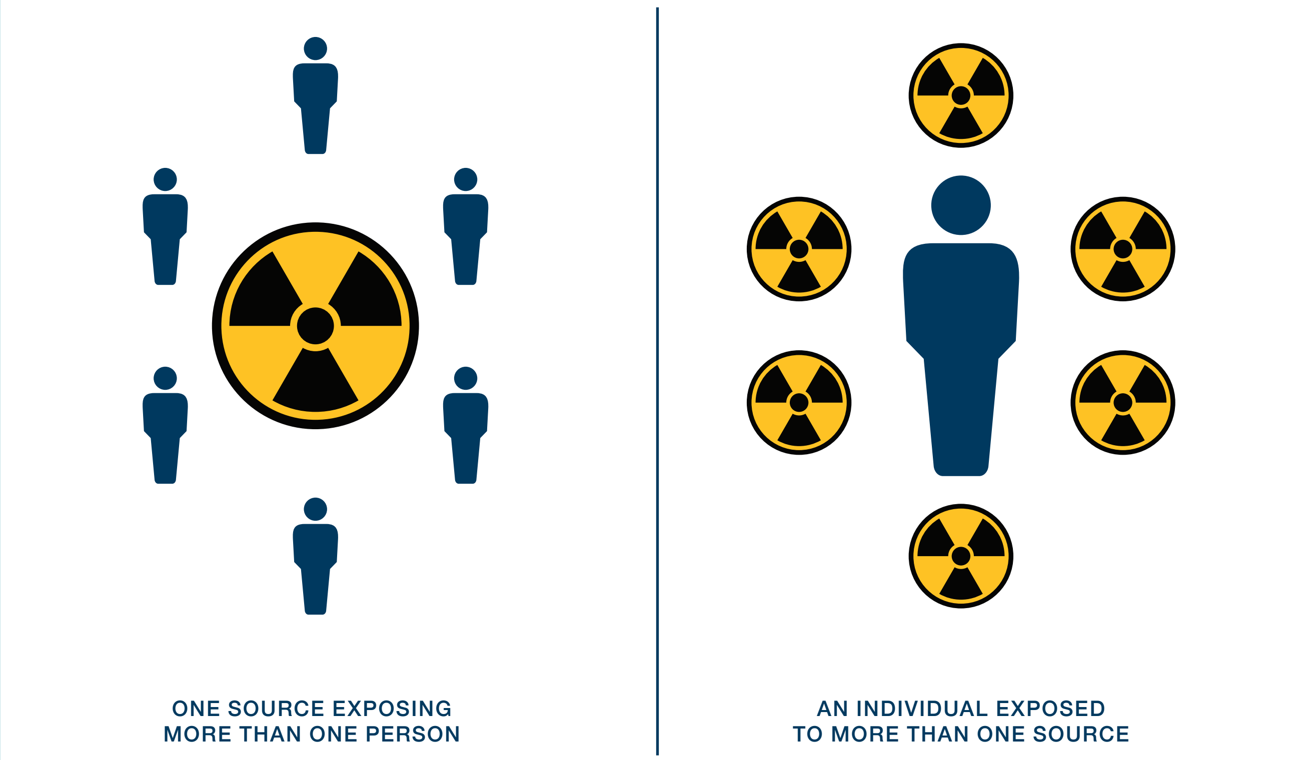
Emergency exposure situations relate to exposures that take place during the early phases of an accident involving a radiation source. In these situations, exposure of persons is either ongoing or is imminent and it will be necessary to decide quickly on urgent actions to reduce or avoid exposures and consequent doses. This includes considering actions to protect the public living nearby but also protecting those workers involved in emergency operations and response. Here it is essential to undertake planning for emergencies, including rehearsals, so that no time is lost in deciding on actions when accidents occur. Importantly the radiation protection criteria for emergency exposure situations need not be the same as for normal planned exposures.

ICRP also distinguishes between three categories of personal exposure, namely **occupational** exposure of workers, **public** exposure, and **medical** exposure, and in any or all of these categories a person may be involved in each of the three exposure situations. Finally, ICRP considers the possibility that radiation protection measures may need to be either **individual related** or **source related**, or some combination of these depending on the circumstances.

These classifications and distinctions seek to promote a consistent approach to radiation protection for all likely exposure scenarios. Nevertheless, it is recognised that attempts to apply exactly the same approach in all possible situations could be wrong and may be unacceptable to some stakeholders.

Exposure type	Examples
Planned	Working at a nuclear power station Working with a high activity industrial radioactive source Overexposure of a worker (this is a potential exposure) A medical exposure of any type Public exposure to discharges from a nuclear facility or a hospital Consumer products incorporating radioactivity
Existing	Radon Natural radioactivity in food Terrestrial gamma radiation Cosmic radiation at ground level and altitude Contamination due to historic practices or earlier accidents
Emergency	Exposure of persons living near to a nuclear facility where there has been an accident and a release of radioactive materials Exposure of the public as a result of a malicious acts including terrorism

Source related vs individual related

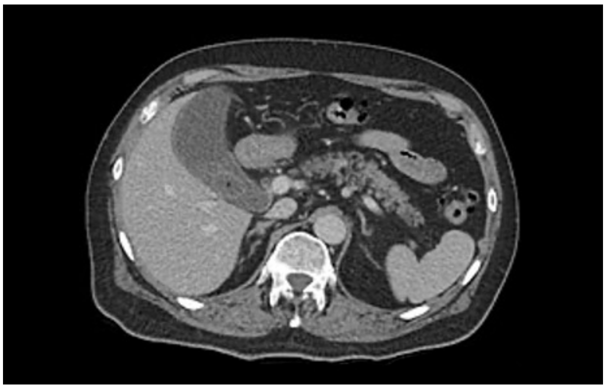


For all these scenarios, ICRP recommend that three basic radiation protection principles should be considered and applied in the order they are described, but with some variation allowed in particular situations. The first and second principles are **justification** and **optimisation** and should be applicable to all situations. The third principle is **dose limitation** and, unlike the first two, it is not recommended for all situations.

Justification

The principle of justification requires that any action involving a radiation source should give a positive net benefit. In other words it should do more good than harm. An example of its application is the use of X-rays in diagnostic medicine. Few would question this practice as the benefits in diagnosing injuries and diseases are clear, even though individual doses for some examinations and the collective doses summed over the whole population may be relatively high. In medicine, the balance here can change over time as more modern equipment allows the same diagnostic information to be obtained at lower doses than before. However, some techniques have become much more accessible, such as standard computerised tomography (CT) or the more sophsticated positron emission tomography and computed tomography (PET CT). While these technologies providing tremendous imaging capability, they do come with much higher doses than conventional X-rays, so these procedures deserve more careful justification.

Dental X-ray image and a CT scan image of the lower thorax



In medicine, screening programmes for healthy individuals (such as mammography for breast cancer) would not be justified if the risks from the radiation exposure outweighed the benefits in terms of the chance of detection of disease. Also X-rays taken for general, legal or insurance purposes are usually unwarranted since they do not benefit the health of the exposed person. However, while this approach has been adopted by the UK, there are some countries that take a less precautionary stance.

Justification can be applied at the source or individual related levels. For example, it may be applied to decisions about whether a particular type of medical examination is justified for all patients. UK law requires that whenever a CT scan is requested, the medical practitioner requiring the scan must be identified and give the reasons why it is appropriate for that patient.

There are practices that fail to satisfy the legal test of justification. For example, putting radioactive substances in toys and jewellery has been regarded as unacceptable for a number of years.

A more recent and difficult issue is the use of X-rays to scan passengers at airports for security purposes.

The principle of justification applies both for new sources of exposure s well as for actions aimed at reducing doses. For example, if there is a small release from a nuclear facility that give rises to trivial radiation exposures, there is no justification for automatically evacuating people from their homes because of the direct physical risks and psychological impact that can result.

Nuclear power plant – Sizewell B

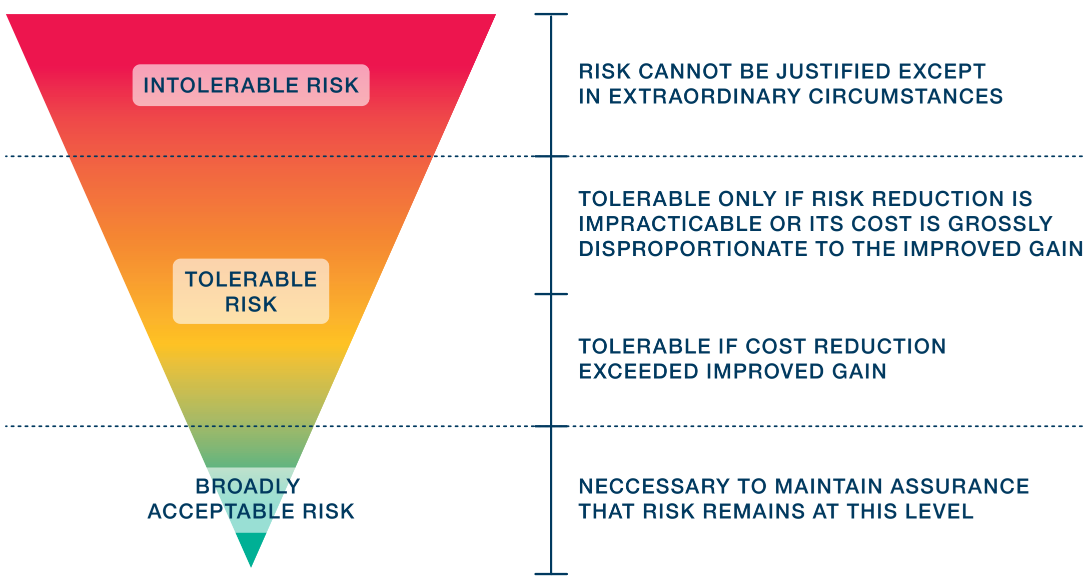
Although simple to state, the principle of justification can be remarkably difficult in its application. The harm created by a new radiation source may be hard to quantify in terms of likely doses and challenging to explain the accompanying risk. It is also controversial to describe justification in monetary terms as this new exposure situation may include non-radiological outcomes that make up part of the overall social and economic costs. Also, the benefits of the new radiation source may be uncertain to predict.

While this uncertainty might favour a straightforward decision to not use the radiation source, there may be similar uncertainties involved in predicting the implications of alternatives. Perhaps nowhere is this more contentious and difficult than with decisions about the use of nuclear power or the building of a new nuclear power station. An analysis of the radiation protection aspects may involve the assessment of future doses to workers at the power station and to the public from routine discharges. There are also doses to workers and the public arising from the mining of uranium, fuel fabrication and transport to consider, along with dealing with the spent fuel and radioactive wastes from each process. Account should also be taken of the potential for a nuclear reactor accident and accidents at industrial facilities serving the power station. All this needs to be compared with the implications of doing without the energy provided by nuclear power or from using alternative methods to produce it. For example, energy from coal, oil or gas can raise concerns about greenhouse emissions and their contribution to global warming that can have far reaching consequences for people and environment while power from hydroelectric, wind or solar sources still has an environmental impact. All these non-nuclear methods of power generation come with their own direct costs and with risks both to site workers, those who build the equipment, and to the public. The analysis would also need to consider strategic and economic factors including energy diversity, security, availability, storage and transportation, known reserves of fuel like coal, oil, and natural gas, the construction and operating costs of the various types of power station, and the expected demand for electricity. Not surprisingly these are major political decisions and radiation protection experts should aim to provide objective and independent scientific advice as an input to these difficult decisions.

Optimisation

Optimisation is the second principle of protection and often the most important in practical terms. This is because it applies to protection against individual and identifiable sources of exposure. It requires that the likelihood of exposure, the numbers of persons exposed, and the magnitude of individual doses be kept **as low as reasonably achievable**, taking into account relevant economic and social factors. This is translated into UK law as a requirement to keep doses and the risk of accidental exposures **as low as reasonably practicable (ALARP)**.

ALARP



Inherent in the optimisation principle is the acknowledgement that all doses of radiation carry some risk of harm. It is therefore not possible to specify a level of exposure below which the radiation risk can be completely ignored and by definition no safe dose of radiation can be defined. This presents a challenge when discussing and comparing risks from low radiation doses when an extremely small radiation dose presents a similarly very small risk of harm. However, there may be agreement on a level below which no further effort to reduce dose is likely to be worthwhile. In the early years of radiation protection, the optimisation principle was not so strongly emphasised and there was greater acceptance of simply keeping exposure of workers below dose limits. But from the mid-1970s onwards there was acceptance that just relying on dose limits was not appropriate, and there was increasing public concern about discharges from the nuclear industry. In the mid-1980s, ICRP formally advised that risk factors for ionising radiation needed to be increased substantially. Since then there has been widespread application of the optimisation principle, particularly in the nuclear industry, and this has led to significant reductions in average worker doses. In parallel, very large sums of money were invested to reduce discharges, particularly from the Sellafield reprocessing site in the UK. Some questioned the necessity of this given the relatively small radiation doses involved but nevertheless these reductions were implemented. It is an illustration of how social and political factors often enter into decisions on optimisation and radiation protection.

Optimisation of protection can be applied in a straightforward way to working with radiation sources, and this principle has been an important part of training of radiation workers. However, the application of the principle in decision making is more contentious. It requires a decision on the monetary value of an averted radiation dose which can be compared with the financial cost of the measures needed to avert this dose. It is then possible to compare alternative protection measures and their efficiency in terms of cost per unit of dose saved which equates to the cost of reducing the risk of harm. Assigning a monetary value to a radiation dose is problematic and contentious, but this concept is applied to other health related decisions when there are limited financial resources and competing demands. Such examples are the introduction of new technologies or prescription of novel drug treatments. For radiation, this type of analysis almost always involves groups of individuals and the concept of **collective dose** is often used. This is the sum of the individual effective doses in the group, the unit being the **person-Sievert**. Difficult judgements still have to be made when there are large numbers of people receiving very small doses, or small exposures received over extremely long time periods in the future from some radioactive waste storage/disposal scenarios.

Dose constraints and reference levels

ICRP recommends the use of **dose constraints** and **dose reference levels** in the optimisation of protection to avoid relying solely on dose limits and in situations where applying the limits is not practical. These are not new terms and the distinction between them is partly a matter of history, but there are genuine differences in their application.

Dose constraints are prospective and source related restrictions to be applied to the individual dose (or risk) to workers or the public. A dose constraint is an upper bound on the annual dose to the overall critical group, summed over all exposure pathways, from the planned operation of a controlled radiation source. For example, a dose constraint can be set when designing a new nuclear reactor with the aim to ensure that no future worker will receive a dose above the constraint during both routine operation and foreseeable maintenance work. In addition, discharges from the facility can be controlled by the application of a constraint on the allowable maximum dose to an individual living near to the facility. The emphasis is always on forward planning and the optimisation process is expected to result in a dose that is always below the constraint. This ensures that the power station will not be built unless the design is likely to ensure the worker dose constraint is met, while the regulator will not allow the discharges unless it is confident that the public dose constraint will not be exceeded.

Dose reference levels are defined for existing exposure and some aspects of emergency exposure situations as well as to medical exposures. An **emergency reference level** will be set to trigger the decision to implement a countermeasure such as evacuation of the public from the area around a nuclear site. A non-nuclear example is a **radon reference level** set within a programme to reduce domestic radon exposures, where action will be recommended if the level is found to be exceeded in a particular dwelling. **Diagnostic reference levels** have been applied to medical exposures for many years. Doses for particular procedures are compared with the reference level and if doses are above it, there is an investigation to see if it is possible and appropriate to reduce them. If new lower-dose X-ray equipment arrives at a hospital it will be assessed by comparing it with other similar equipment, and the local dose reference level may be lowered.

Dose reference levels are not dose limits, so a dose reference level optimisation should apply around the reference level doses rather than always below it. In contrast, a dose constraint is very similar to a dose limit in its application.

ICRP does not give firm recommendations on values for dose constraints and reference levels because they are usually specific to industries or medical practices. However, it does suggest ranges of dose bands from which common constraints and reference levels might be chosen.

Dose band (mSv)	Examples
> 20 to 100 mSv	Constraint for emergency exposures of workers in extreme situations and subject to very close control and management Upper emergency reference level (counter-measures almost certainly needed) for actions to protect the public in the event of release of radionuclides
> 1 to 20 mSv	Constraints on occupational exposure for new and planned situations Reference level for intervention to reduce domestic or workplace radon levels Lower emergency reference level (consider countermeasures) for actions in the event of release of radionuclides
1 mSv or lower	Maximum constraint set for public exposure in planned situations (e.g. discharges, radionuclides in consumer products). In the UK the current constraint for discharges is set at 0.3 mSv y^{-1}

Dose limits

Dose limits apply to individual exposures and are only set for certain situations. The most well known example is the annual dose limit applying to workers exposed to ionising radiations, currently set in the UK at 20 mSv, and applies to the effective dose received, including any committed doses from intakes. This and similar dose limits are clearly very important from a legal standpoint because it would be a criminal offence if they were exceeded by an employer.

The effective dose limit is set because of the risk of radiation exposure causing cancer and heritable harm. There are separate higher limits for equivalent dose to protect the eye, skin and extremities. These limits guard against tissue reactions which have dose thresholds (see Chapter 7) and they are set to guarantee this type of harm is avoided. The UK regulations in this area have lower dose limits for young persons at work. They also require that the dose to the foetus of a pregnant worker is kept below 1 mSv from the time pregnancy has been declared, at which time any appropriate extra protection measures should be put in place for that worker.

UK regulations also set dose limits for the public exposed to man-made sources. The application of these limits can be complex because there is no direct monitoring of doses to members of the public and the possibility of being exposed to multiple sources. The annual dose limit currently recommended by ICRP and specified in UK regulation is 1 mSv per year although the UK already operates a lower constraint of 0.3 mSv per year applied to doses attributable to future discharges from any single site. As direct monitoring of the public is not practicable, dose assessments should be carried out and assessed prior to the building of the site or implementation of a new practice at an establishment.

The public dose limit does not apply to radon in the home and there are no dose limits set for medical exposures of any type as it is not appropriate. In radiation emergencies, ICRP advises that the 1 mSv public and 20 mSv worker dose limits need not apply and is set out in UK regulation. Any relaxation could only ever be allowed in the UK under strict criteria.

Instead of the dose limits, ICRP recomendations and UK regulation specify an emergency reference level of 100 mSv for public and workers and only in exceptional circumstances, such as saving life, could a higher 500 mSv reference level for emergency workers be allowed. This would certainly ensure that workers would avoid receiving high or possibly fatal doses of radiation during their response to an incident. Unfortunately some workers responding to the Chornobyl nuclear reactor fire and explosion in 1986 did not have their radiation doses controlled in a similar way and died as a consequence.

The annual 20 mSv limit on effective dose for a worker is set on the basis of considering what would be the maximum tolerable level of risk, and this is also the basis for setting the public annual dose limit. The worker dose limit is set higher since higher risks are deemed more acceptable for workers because they receive a benefit from their employment. In contrast, members of the public do not receive any direct or immediate benefit from the risk imposed on them as a consequence of receiving a radiation dose so a dose limit is not usually regarded as appropriate in these circumstances.

All dose limits are subject to reviews which include considering the latest advice from ICRP. Concerns about radiation induced cataracts in the lens of the eye have led to the annual dose limit for the eye in the UK being substantially lowered from 150 to 20 mSv equivalent dose, although other dose limits are unlikely to change substantially in the forseeable future.

A main objective of radiation protection is to keep doses to the public and to workers as low as reasonably achievable. Dose limits are a way of achieving this but there is a common misconception that they mark an abrupt change in biological risk, a line of demarcation between safe and unsafe. This is certainly not the case for late effects such as cancer and dose limits are set well below the thresholds for tissue reactions like radiation burns.

Comparing risks

One way of judging the effectiveness of the system of radiological protection is to compare the residual risks of fatal cancer from radiation with the prevailing risks of death from other causes.

Workers

The risk of cancer averaged over an adult population is estimated by ICRP to be about 4% per Sievert. Therefore, if 100,000 workers were exposed for a year at 20 mSv then 80 additional cancers are predicted to be caused by the radiation exposure in this group of workers. The UK Health and Safety Executive (HSE) publish reports of reported fatal accidents at work and these show a range of rates[4]. For the UK fishing industry, well known as a higher risk occupation, there are on average 126 deaths per 100,000 workers caused by accidents, and the agricultural sector, also an occupation with a relatively high risk, recent annual rates have been about eight per 100,000 workers. Averaged over all work sectors, the fatality rate for UK workers is about twenty times lower than this at 0.4 deaths per 100,000 workers. This therefore suggests radiation exposure at the dose limit for workers corresponds to a significant level of occupational risk comparable with the most hazardous of industries such as marine fishing[5].

However, in the UK the highest annual doses to radiation workers very rarely exceed 10 mSv and the current average across all monitored sectors, including the nuclear industry, is of the order of 0.4 milliSievert per year[6]. This corresponds to a predicted two or three excess cancers per 100,000 workers which is broadly compatible with the general risks across all UK industry. However, workers in some industries are exposed to other cancinerous agents that cause 8,800 deaths per year for all industries[7], with construction experiencing the highest occupational cancer deaths of about 3,500 per year or some 130 deaths per 100,000 workers[8], mainly attributable to exposure to asbestos and silica[7] and of the same order as deaths in the fishing industry from accidents. With radiation workers also exposed to other conventional risks at work, there should be an extra incentive to reduce all risks to a minimum.

All risk comparisons need to viewed with care and they do not necessarily justify exposure to a risk. Also the predicted cancers due to exposure to ionising radiation are likely to show up later in life and not all will be fatal. In contrast, workplace fatalities appearing in accident statistics usually represent a sudden and immediate loss of life and there is often little doubt as to how it was caused.

Exposure of the general population

When considering exposure to discharges and man made sources other than medical radiation, most people derive little or no immediate direct benefit from the exposure and they would probably regard it as an involuntary risk imposed upon them. There is considerable debate as to what maximum level of risk is acceptable in such circumstances, but reviews considering wide ranges of risks have suggested that the maximum tolerable annual risk of death for members of the public should be of the order of 0.001% or one in one hundred thousand.

The risk factor for fatal and non-fatal cancers after exposure to radiation and averaged over the general population is estimated by ICRP as nearly 6% per Sievert. The ICRP annual dose limit of one milliSievert implies a corresponding risk of 0.006% per year or one in seventeen thousand. Even allowing for some cancers not being fatal, this suggests the limit may be incompatible with the maximum tolerable risk of 0.001% per year. This is part of the reason why UK regulators apply the ICRP recommended dose constraint of 0.3 mSv y^{-1} (corresponding to a risk of 0.0018%) for new sources of exposure, and insist all practicable means have been taken to reduce discharges. Given that abatement may involve significant expenditure, it is necessary to consider how far this can and should go. There is some acceptance that below an annual risk of about 0.0001% or one in a million, the situation or practice should be regarded as generally acceptable for the public and workers. This level of risk corresponds to an annual radiation dose of about twenty microSieverts (20 μSv), and this figure has been incorporated into some national and international targets for radioactive discharge reduction.

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[4] Work-related fatal injuries in Great Britain. On HSE website.

[5] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/377352/FishingVesselSafetyStudy.pdf Accident Investigation Branch Analysis of UK Fishing Vessel Safety 1992 to 2006

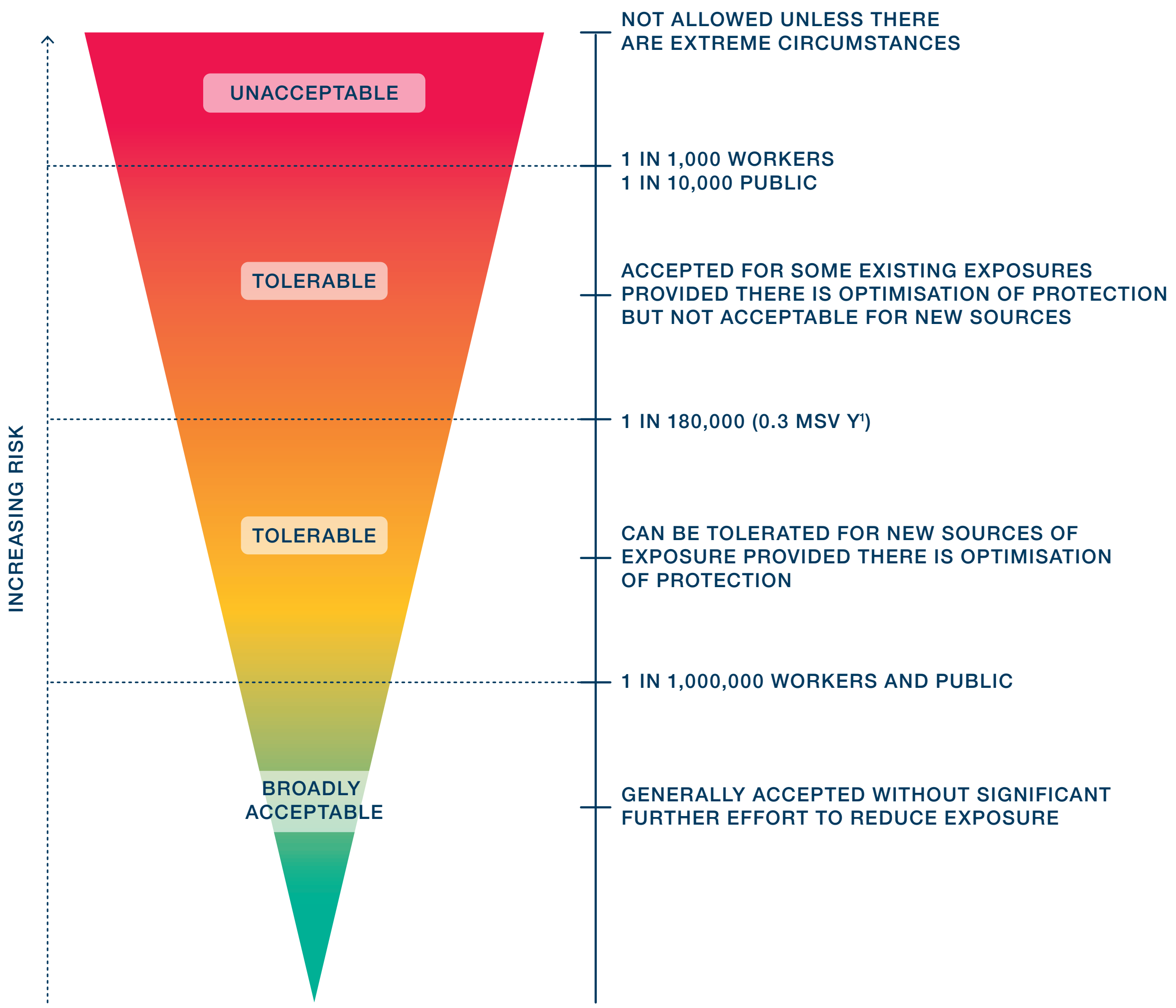
[6] https://www.hse.gov.uk/statistics/ionising-radiation/index.htm HSE data.

[7] https://www.hse.gov.uk/statistics/causdis/cancer.pdf Occupational Cancer statistics in Great Britain (2022) HSE

[8] According to the CITB, there are 2.69 million construction workers in the UK at the start of 2022

The diagram below shows how dose limits and constraints apply to limit the potential risks of planned new situations, with the value for each depending on whether it is workers or the public who are exposed.

Dose limits and constraints



Other risks

The risks from ionising radiations described previously can be usefully compared to general risks to which we are all exposed. These illustrate that the risk from exposure to ionising radiation is often very much lower than other common risks to life that are generally accepted. However, this does not necessarily justify the risk for some people, because they perceive no benefit at all from exposure to the risk.

Average annual risk of death from some common causes

Common cause	Probability	
Smoking (10 cigarettes per day)	5 10^{-3}	1 in 200
Circulatory disease	3 10^{-3}	1 in 330
All cancers	3 10^{-3}	1 in 330
All causes (40 year old)	1.2 10^{-3}	1 in 820
Exposure to natural radiation (2.3 mSv y^{-1})	1 10^{-4}	1 in 10,000
Accident in the home	6 10^{-5}	1 in 17,000
Accident on the road	3 10^{-5}	1 in 33,000
Homicide	8 10^{-6}	1 in 125,000
Exposure to nuclear discharges (0.1 mSv y^{-1})	5 10^{-6}	1 in 200,000
One (annual) chest x-ray	1 10^{-6}	1 in 1,000,000
Hit by lightning (USA)	1 10^{-7}	1 in 10,000,000

Legal controls

The system of radiological protection described here is implemented in UK law via a body of legislation that has built up since the 1940s with many developments and changes to this legislation over the years being traced back to the ongoing development of ICRP and other international recommendations.

The legislation implements what is sometimes referred to as a “graded approach” based on the levels of risk and controllability of radiation hazards. At one end of the risk spectrum is the operation of nuclear power stations with their potential for major accident hazards, and somewhere below this, other undertakings which have very high activity radioactive sources and produce significant amounts of radioactive wastes. These higher risk situations are always regulated using **permitting** and **licensing** processes operated by independent regulators which include the Office for Nuclear Regulation and the various UK environment agencies. These processes allow for close interaction with the regulators including prior approval of significant new activities, making changes to existing ones, and frequent inspection of operations. Permit and licence conditions can be changed more easily without the need for new legislation. At the lower end of the risk scale ordinary regulations are used, including the UK **Ionising Radiations Regulations (IRR)** that require users of radiation to **notify**, **register** or obtain **consent** from HSE in order to carry out that activity.

The IRRs still apply to major sites as well as the use of an X-ray source in a dental surgery or the use of low activity radioactive training sources in schools and universities. The regulations contain details such as the dose limits applied in the UK and allow regulators to make inspections and take enforcement actions. Responsibility for enforcing these particular regulations in workplaces outside of the nuclear industry in the UK falls mainly on HSE.

Several government departments and agencies related to them have important roles in radiation protection. The Department of Health and Social Care has a particular interest through its links with the Radiation, Chemical, Climate and Environmental Hazards Directorate (RCCE) within the UK Health Security Agency. RCCE, which incorporates the work of the former National Radiological Protection Board that was set up in 1970 as a direct response to the 1957 Windscale Fire, is the UK’s national centre of expertise and advice in radiation protection matters. RCCE has throughout been closely involved in the work of ICRP, UNSCEAR and IAEA as well as being a consultee on all relevant UK legislation on radiological protection.

08

Natural ionising radiation

Authors: Tony Riddell, Julie Scott, and Rick Tanner

Background levels of naturally occurring ionising radiation are encountered throughout the environment. The Earth is constantly exposed to cosmic rays from space and is itself composed of natural materials some of which are radioactive. These materials make up the rocks and soils of the Earth, but through processes such as leaching, erosion and the formation of gasses, trace amounts can also be found in water, plants, animals, and air. This radioactive material has been present since the Earth was formed billions of years ago, at which time background levels of radiation were considerably higher than today. As life has successfully developed and evolved in the presence of this background radiation, this has led to a consensus view that this level of radiation exposure does not pose a significant risk to health. However, as levels of background radiation vary according to location, there are occasional exceptions where some protection measures are considered necessary, for example employing underfloor, mechanical, or forced ventilation to reduce the amount of naturally occurring radioactive radon gas entering buildings from the ground beneath.

Cosmic Radiation

Cosmic radiation is comprised of many different electrically charged and neutral particles and electromagnetic rays, but mostly protons, electrons, alpha particles, gamma and X-rays. Much of this radiation is high energy and originates from deep space, while lower energy particles also emanate from the Sun, with this component increasing during solar flares. Most of the charged particles bathing the Earth are prevented from reaching ground level by the Earth's magnetic field and atmosphere. Particles captured by the magnetic field lines are drawn to the North and South poles where these higher concentrations of particles can interact with molecules in the atmosphere to produce the Aurora Borealis (Northern Lights) and Aurora Australis (Southern Lights).

As a result of interactions with the Earth's magnetic field and the atmosphere, the amount of cosmic radiation reaching the surface of the Earth begins to reduce below about 15 km above sea level, reducing rapidly with decreasing altitude and, to a lesser extent, with decreasing latitude, from about 55 degrees, toward the equator.

Neutrons in the cosmic radiation can interact with atmospheric nitrogen to produce the mildly radioactive isotope ^{14}C, a process relied upon by scientists for carbon dating. In a similar way a small number of other 'cosmogenic' radionuclides are produced, but none have any consequence for doses to humans.

Compared with some other parts of the World, the altitude at which people live is relatively constant across the UK and not that far above sea level, the range of latitudes encompassed is also comparatively small. There is therefore relatively little variation in annual doses from cosmic radiation in the UK as a result of where someone lives. The average annual effective dose from cosmic radiation at ground level in the UK is about 0.3 mSv.

Air travel, which can involve many hours at high altitudes, increases doses slightly, particularly routes at higher latitudes, nearer the poles. Air travel typically increases the average person's dose from cosmic radiation by around 0.03 mSv a year, bringing the total dose up to 0.26 mSv per year.

Gamma radiation

The radioactive decay of uranium, thorium and potassium isotopes found in the Earth's molten core and crust is now thought to contribute about half of the Earth's internal heat, the other half is what remains from when the Earth was formed. Together this vast amount of energy continuously remodels the Earth's crust.

Although these radioactive isotopes occur throughout the Earth their concentrations in particular rocks are determined to a large extent by the underlying geology. As uranium-238 decays to lead-206 and thorium-232 to lead-208, various gamma rays of different energies are produced that contribute to natural background radiation. As building materials are extracted from the Earth, they too are mildly radioactive, some more than others, so people are irradiated indoors as well as outdoors to some extent, depending on the structure of buildings. The average effective dose in the UK from natural gamma radiation is about 0.35 mSv a year with the range of doses being quite wide depending on location.

Although these radioactive natural isotopes are spread throughout rocks and soils at low concentrations of a few parts per million (ppm), there are locations where the local concentration may exceed 1,000 ppm in ores. In the case of uranium, this makes mining it for nuclear fuel economically viable. Likewise radioactive isotopes may also be associated with ores mined for other metals such as tin or copper.

Potassium is more abundant than either uranium or thorium and makes up 2.4% of the weight of the Earth's crust. However, only one of the naturally occurring potassium isotopes, potassium-40, is radioactive and it makes up only 0.012% of natural potassium. With a half-life of 1.25 billion years potassium-40 decays very slowly and only 10% of these decays are by gamma ray emission: it therefore makes a negligible contribution to the average effective dose to the UK population from natural gamma radiation. Consequently, it is the radioactive isotopes of uranium and thorium that are the main sources of exposure and resulting dose.

Radon inhalation

The primordial radionuclides uranium-238, uranium-235 and thorium-232 are the parents of three long decay series of radioactive elements (known as 'progeny') that include the radioactive gas radon and which ultimately decay to stable lead. Radon is the only radioactive gas that is naturally occurring.

Radon is a Noble gas, which means it is chemically inert and will readily pass-through other materials without binding to them. The thorium-232 decay product radon-220, or 'thoron', has a half-life of only 56 seconds and much of it decays before it can percolate through rocks and escape into the atmosphere. Uranium-235 decays to radon-219, or 'actinon', which has a 4 second half-life that means it can only exhale from the surface of materials. With a half-life of 3.8 days, however, radon-222, produced by uranium-238, readily escapes to air and is a significant source of exposure to natural radiation. The other radioactive decay products from the uranium and thorium decay chains are chemically reactive solids and remain in any condensed materials where they are formed. If they are formed from radon which has escaped to the air, they can be inhaled. Once in the lungs, these short half-lived radon progenies undergo radioactive decay and irradiate lung tissues, primarily with alpha particles, and this exposure has the potential to increase the risk of lung cancer.

When radon gas escapes from the ground into the atmosphere it is dispersed so concentrations outdoors tend to be low. Radon can directly enter buildings from the ground, predominantly through the floor, drawn in by the stack effect (warm air rising). This enables concentrations to build up in enclosed spaces, particularly those with poor ventilation. In UK homes, the average radon concentration is 20 Bq m^{-3} (becquerel per cubic metre of air) although with a wide range, and exceptionally over 20,000 Bq m^{-3}. In the UK, 200 Bq m^{-3} is identified as an Action Level, at or above which residents are advised that remedial action should be taken to reduce radon levels. The advice given is to reduce levels as far as reasonably possible and not just to below the 200 Bq m^{-3} Action Level, with the type of remedial action depending on the building construction and initial radon concentration.

UK monitoring campaigns have identified **radon Affected Areas** to focus attention on buildings with the highest radon concentrations and hence highest risk to health. These are specified as areas of the UK where at least 1% of homes exceed the 200 Bq m^{-3} Action Level. Current advice is that residents in these areas should consider having the radon concentration in their homes measured and, depending on the result, take appropriate remedial measures to reduce it. When extensions are made to existing buildings, or new buildings are constructed in high radon areas, the Building Regulations state that builders may need to incorporate protective measures against radon.

Extensive UK measurement campaigns have made it possible to estimate that the average annual effective dose to the UK population is 1.3 mSv from radon and its decay products.

In terms of predicted health consequences of exposure to radon, evidence from epidemiological studies has shown that residential exposure to radon and its decay products, either alone or in conjunction with active smoking, could be responsible for more than 1,100 lung cancer deaths in the UK per year. The annual total of lung cancer deaths from all sources including smoking tobacco is around 34,800 per year.

The Ionising Radiations Regulations 2017 require action to protect employees if the average annual radon gas concentration exceeds 300 Bq m^{-3}.

In all cases, the radon concentration can easily be measured in buildings using passive radon detectors at low cost.

Internal radiation exposure

Internal irradiation hazards are considered separately from other radiation hazards because they pose different risks even when the same type of radiation is involved. For example, alpha radiation emitters pose little or no risk when they are external to the body, as this type of radiation cannot penetrate the outer dead layer of cells which protects normal skin. However, if an alpha particle emitter is ingested in food or drink or inhaled, it may pass into the bloodstream and end up in living cells within organs and tissues. While an alpha particle will typically be halted within one cell when it is emitted, it will cause substantially more damage to that cell than an equal quantity of beta, gamma or X-ray radiation would. Consequently, a weighting factor to adjust for this effect is applied when alpha radiation doses from internal irradiation are calculated. Furthermore, the way in which a radiation emitter interacts with normal biological processes which move chemicals around the body and also remove them from it, has a considerable impact on resulting doses.

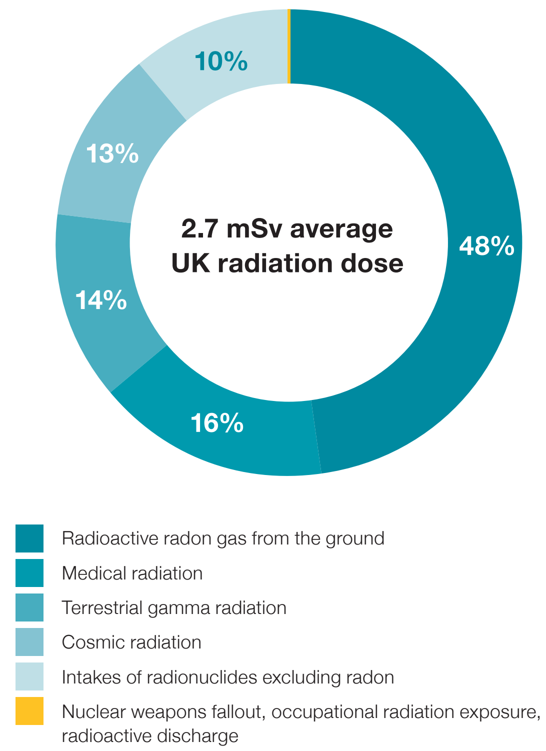
Uranium and thorium together with their radioactive decay products are present in small amounts in the soil, water and to a lesser extent air, which leads to them also being found in food and drink. As a result, when a person eats or drinks, radioisotopes will enter the body and irradiate it internally. A notable example of this is Brazil nuts. The trees that produce them seem to be particularly effective in concentrating environmental radium-226 and radium-228, so while an individual nut only has a mass of about 4 g, consuming one can result in a dose of 0.2 µSv (0.0002 mSv). Most people don't eat a lot of Brazil nuts in a year and the dose from them is not a significant part of their total dose, but for the minority who eat 2 or more nuts per day, it will be. Together with ^{14}C formed in the atmosphere, the uranium and thorium decay series contribute 0.15 mSv to the average annual effective dose in the UK.

Potassium is a very important element for life and is found in natural foodstuffs. Consequently, all living things contain potassium, of which a small proportion is radioactive potassium-40, for example, bananas are rich in potassium and eating a single banana could potentially result in a dose of 0.1 µSv (0.0001 mSv). However, unlike Brazil nuts, eating things that are rich in potassium, like bananas, will not significantly increase an individual's dose due to internal irradiation. Although there is some variability between people, various biological processes and functions control the total amount of potassium, and hence potassium-40, in the body. Potassium retention in the body is primarily associated with muscle mass and as a result, very fit people can have twice the amount of potassium found in people with lower levels of fitness. In the UK potassium-40 contributes about 0.17 mSv/year to the annual effective dose to the population.

Total doses

The total average effective dose from natural radiation is about 2.2 mSv in a year for the UK population. Differences in average doses from one locality to another frequently exceed 10 mSv per year and differences in individual doses may exceed 100 mSv per year, due to homes with particularly high levels of radon and its decay products.

Breakdown of the dose to an average person in the UK population



09

Medical uses of radiation

Authors: Una Findlay and Louise Fraser

Introduction

Radiation has many uses in medicine today. Ionising radiation in the form of X-rays, gamma rays, electrons, neutrons, and protons are used to diagnose, monitor and to treat a wide range of medical conditions. There are also opportunities to use non-ionising (less energetic, not directly damaging) radiation, such as ultrasound and Magnetic Resonance Imaging (MRI) for diagnosis, treatment and to guide further treatment (for example to assist with biopsies). Justification for medical procedures involving radiation is a legal requirement in the UK and clinicians need to identify the most appropriate test to provide or confirm a diagnosis and to aid the clinical management of the patient. In making this decision, clinicians must balance the expected benefit of diagnosis or treatment against any potential risk associated with radiation. In imaging, the technique used (e.g., fluoroscopy or CT scanning) will depend on the part of the body being imaged and reason for the investigation.

General Radiography

In general radiography such as a chest X-ray, a beam of X-rays is passed through a part of the body onto an electronic detector. An image produced in which the internal structures such as bone, lung and other soft tissues can be seen.

Due to the structures of the body having differing X-ray absorption characteristics, the amount of energy passing through those structures to the detector varies. In the resulting X-ray image, bone (high absorption of X-rays) appears white with soft tissue tending to be differing shades of grey and areas containing air (minimal absorption of X-rays) looking black.

It is not possible to become radioactive from an X-ray. Following an X-ray examination, the radiation has gone as soon as the exposure is completed in a similar way that the light from a light bulb vanishes when the switch is turned off.

Mammography

Mammography is a type of general radiography. X-rays are passed through breast tissue onto a detector to produce detailed images of the breast tissue. This aids the early detection and diagnosis of breast diseases.

In the UK all women within a defined age range are offered a mammogram every three years as part of a national screening programme to detect early breast cancer where no obvious symptoms are evident.

Individuals experiencing symptoms such as lumps or pain are referred to ‘fast track’ symptomatic breast clinics where access to specialist clinicians and diagnostic tests are available.

Fluoroscopy

Fluoroscopy uses X-rays passing through the body onto a detector to produce real time, moving images and allows snapshots of relevant findings to be captured. Fluoroscopy is often used to visualise the structure and movement of the oesophagus, stomach, and bowel. The patient may be asked to drink a liquid which coats the walls of the gastro-intestinal tract and enhances detail within the X-ray images.

Fluoroscopy is also used to assess other internal structures such as blood vessels, the heart and urinary tract. A contrast medium, which helps make the image clearer, may be injected into a vein or artery to show the circulatory system and organs.

Fluoroscopy can also be used during the treatment of some medical conditions. An example is using a stent or balloon during interventional radiology to restore blood supply or repair of partially blocked blood vessels caused by coronary heart disease. The whole procedure is conducted using fluoroscopy for visual guidance and to confirm satisfactory results.

First X-ray of a hand

Modern X-ray of a hand

Computed Tomography (CT)

CT scanning is a digital imaging system using X-rays, which produces a detailed cross-sectional image (slice) of the patient's anatomy. To acquire this image the X-ray tube and detectors rotate around the patient whilst the bed moves through the scanner. The amount of radiation absorbed by different tissues is measured and a computer program processes the large volume of data collected to create a set of images through the body. This provides detailed images of the anatomy of the individual, making diagnosis easier.

Technological advances over the years have enabled additional information including 3D reconstructions and images in different planes. Advances in speed of scanning and improved image quality have enabled the development of applications such as cardiac CT where moving arteries in the heart can be imaged.

CT plays a significant role in detecting abnormalities, tracking the response to drugs or surgical treatment, diagnosing issues with blood vessels, and providing additional information in orthopaedics, or in trauma and injury. CT is also used to guide treatment such as microwave ablation of certain cancers and to ensure the precision of biopsies (taking a sample of tissue).

Magnetic Resonance Imaging (MRI)

Unlike X-ray examinations and CT scanning, MRI does not use ionising radiation. Instead, MRI uses powerful magnetic fields and radio waves to produce highly detailed images of anatomy and the physiological processes of the body in very fine detail. These images can be reconstructed in any direction.

Body tissue contains water and when inside the powerful magnetic field of an MRI scanner, many of the hydrogen protons in the water molecules become aligned in one direction. A radiofrequency pulse is applied to the area of the body being examined. Some of the hydrogen protons absorb the radiofrequency energy and flip to point in another direction. After the radiofrequency pulse is switched off, the protons relax back to their original position generating a radiofrequency signal which is measured. This process is repeated many times a second and the resultant signal is used to generate the image.

MRI scan images provide high resolution detailed images to detect or assess a variety of conditions in many areas of the body. For example, an MRI scan of the brain and spinal cord can reveal evidence of brain injury, stroke, blood vessel damage and spinal cord injuries.

Advances in technology have developed a sophisticated type of MR scan, functional MRI (fMRI). This scanning technique can demonstrate, for example, which parts of the brain are active when certain tasks are carried out such as language, memory, and movement. It is particularly helpful when planning brain surgery.

It may not be possible for everyone to have an MRI scan. Some heart pacemakers, artificial heart valves, metal clips on blood vessels, ear implants or metal fragments imbedded in the body mean it may not be safe to go into a strong magnetic field. Safety checks are completed on all individuals about to undergo an MRI scan and any metal or implants are checked to ensure they are safe to enter the scanner. Staff working in and around MRI units will also undergo similar safety checks.

Ultrasound

Ultrasound imaging does not use ionising radiation. It uses sound waves and the measurement of their reflection from tissue to produce an image. Ultrasound is a high frequency sound that is beyond the hearing range of the human ear and is generated and detected by special probes.

Ultrasound is used in many clinical situations and travels freely through fluid and soft tissues. When the ultrasound is emitted from the probe positioned on the patient's skin, it hits structures inside the body of different density, reflecting echoes of varying strength. This echo is detected by the probe and used to create an image. The way the ultrasound reflects from different tissues can determine the size, shape and structure of soft tissues.

Since sound waves are used rather than radiation, ultrasound is considered more appropriate to use routinely in pregnancy to help to monitor the growth of an unborn child and check for abnormalities. Ultrasound scans can also be used to detect heart problems (an ultrasound scan of the heart is called an echocardiogram), examine other parts of the body such as the liver, kidneys and abdomen, or help to guide some types of biopsies (taking samples of tissue).

Doppler ultrasound

A Doppler ultrasound is an ultrasound scan which records sound waves reflecting off moving substances, such as blood cells, to measure their speed and aspects of how they flow through the body. If the structure is moving then the echo comes back at a slightly different frequency (called the Doppler effect), the difference in frequency can be used to measure the speed of movement.

The sound waves may be amplified through speakers or converted to colour images on a monitor (colour Doppler). Blood flow through arteries or veins can be heard, seen, or displayed on a graph showing changes in the speed and direction of flow.

Doppler ultrasound is also used for listening to the heartbeat of an unborn baby (foetus) during pregnancy. It can be used for examining blood flow in arteries or veins following injuries, and to establish the presence or absence of deep vein thrombosis (blood clots) or peripheral vascular disease.

Nuclear Medicine

Nuclear medicine uses small amounts of radioactive pharmaceuticals (radiopharmaceuticals) to diagnose, monitor or treat disease. Radiopharmaceuticals may be administered to patients by injection into a vein or skin, ingested in tablet or liquid form, or by inhalation. After administration, the radiopharmaceutical temporarily collects in the tissue or organ under investigation. For the majority of diagnostic nuclear medicine examinations, the amount of radiopharmaceutical within the body reduces to undetectable levels within 24 hours.

Diagnostic nuclear medicine imaging

In diagnostic nuclear medicine imaging, the radiation emitted from the patient's body after the administration of a radiopharmaceutical is detected by a detector called a 'Gamma camera'. The camera produces an image by tracing where the radiopharmaceuticals are in the body. Nuclear medicine imaging provides clinicians with both structural and functional information about organs. Diagnostic nuclear medicine can often identify abnormalities at a very early stage of disease.

Technetium-99m (99mTc) is used extensively in diagnostic nuclear medicine imaging in the UK and around the world. 99mTc emits gamma rays and has a half-life of 6 hours, which means that the intensity of the radiation is halved every 6 hours. These physical properties and the fact that it can be conveniently labelled to a range of different pharmaceuticals and prepared in the hospital, make 99mTc an ideal radionuclide for diagnostic nuclear medicine imaging.

PET CT imaging

Positron Emission Tomography (PET) uses short-lived radiopharmaceuticals to image cells that are more metabolically active than normal. PET CT is most commonly used to diagnose or stage cancer and to show response to treatment. Cancer cells metabolise glucose about ten times faster than normal cells so they can be identified, even in small numbers. PET images are often combined with CT images – both scans are taken at the same time – to give accurate localisation of increased cell metabolism. Combining PET and CT images allows clinicians to give a more accurate diagnosis than using PET or CT images alone.

Fluorine-18 (^{18}F) is the most commonly used radionuclide in PET CT imaging. It has a half-life of 110 minutes. It can be attached to a molecule, flurodeoxyglucose, that mimics glucose metabolism.

Therapeutic nuclear medicine

In nuclear medicine therapy, radiopharmaceuticals that emit beta particles are often used because they are absorbed locally within the target tissue or organ. Nuclear medicine therapies are used to treat a range of cancers and some non-cancerous conditions.

The treatment of an overactive thyroid gland – hyperthyroidism – is the most common example of a therapeutic nuclear medicine procedure. It uses radioactive iodine 131 (^{131}I). ^{131}I is accumulated in the thyroid where the radiation is absorbed, gradually returning the thyroid function to normal levels.

After some nuclear medicine treatments, patients are required to follow a few simple precautions to restrict the radiation exposure to cohabiting family and friends. As discussed in Chapter 7, the UK uses dose limits and dose constraints as part of the wider system of radiation protection. The purpose of these precautions is to ensure that any exposure received is below the dose constraints and to minimise the risks to acceptable levels. Advice tailored to each individual patient is provided by the hospital staff administering the treatment.

Radiotherapy

Radiotherapy is the use of high-energy ionising radiation such as X-rays, gamma rays, electrons, neutrons, protons and other sources to cure, reduce the risk of recurrence, or relieve symptoms of disease, usually cancer. Radiotherapy is also indicated in the treatment of some non-cancerous conditions, such as thyroid disease and some blood disorders. Approximately 50% of cancer patients will undergo some form of radiotherapy. This may be given as a stand-alone treatment or in conjunction with other treatments such as surgery, chemotherapy (chemical treatment for cancer) or hormone therapy.

Radiotherapy can be administered from outside of the body (external beam) or internally by inserting radioactive materials inside the body, close to or inside the cancer (brachytherapy). The type of radiotherapy selected depends on the cancer and the area of the body to be treated.

Radiotherapy works by depositing energy within the cancerous cells causing damage to the cell's DNA. This damage renders them incapable of dividing. Normal cells can also be damaged but are usually able to repair themselves.

Radiotherapy treatments are designed to maximise the damage to the cancer whilst minimising the dose to the normal healthy tissue, this is called the therapeutic ratio. In order to ensure the best possible therapeutic ratio, each patient treatment is individually planned, dose calculated and independently checked before delivery. This is particularly important as the radiation doses from radiotherapy are significantly higher than the other procedures discussed in this chapter.

Diagnostic imaging tools allow better cancer visualisation and sophisticated radiotherapy treatment delivery allows further optimisation of the therapeutic ratio, increasing accuracy in targeting the tumour cancer and safely delivering higher doses to the cancer cells whilst reducing dose to surrounding tissues. A CT or MRI scan will be undertaken to inform the planning process and enable a personalised plan to be produced based on the type and location of the cancer. Additional imaging will be undertaken during treatment to verify the treatment and enable any required adjustments to be made. Most frequently treatments are delivered by a machine called a linear accelerator, which aims a radiation beam at the cancer.

Different tumour types respond to radiotherapy in different ways, some being more or less sensitive. A range of treatment doses and schedules are used, varying from one up to 30 or more treatments. Side effects of radiotherapy can be short term or long term and are localised to the area that is treated. These are discussed prior to treatment and help provided if required to manage them.

Minimising ionising radiation in the medical setting

Ionising radiation in medicine is widely and increasingly used. It is therefore important to ensure that it is used wisely and appropriately. Unnecessary examinations should be avoided and the use of alternative examinations using non-ionising radiation considered.

Several key pieces of legislation are in place in the medical setting to protect the patient from the potential hazards of radiation. Where the use of ionising radiation in medical techniques is justified, radiation doses must be kept to a level which achieves the required image quality or the desired therapeutic effect with the lowest possible radiation dose. The decision whether to justify an examination using ionising radiation is a matter of clinical judgement made in the best interests of the patient.

Children and young people are more radiosensitive than adults, so special attention is given to examinations involving ionising radiation in these patients. If a patient is or could be pregnant, the potential radiation dose to the foetus is also considered when deciding which is the most appropriate examination to used to answer the clinical question. Doses from the same X-ray examination may vary from patient to patient because of differences in their size and shape, but they should generally fall below an agreed value for a given size patient. This is called a reference dose, and a set have been recommended in the UK and issued by the UKHSA as national Diagnostic Reference Levels (DRLs) for the more common X-ray examinations. This enables a radiology department to compare their own doses with these national DRLs to examine, and where needed refine, their own practice. Paying close attention to DRLs has led to a downward trend in doses for each examination throughout the country in the last couple of decades.

Other methods of minimising doses include using well maintained, optimised equipment, operated by trained staff and having a full programme of quality assurance in departments using ionising radiation such as Radiology, Nuclear Medicine and Radiotherapy departments.

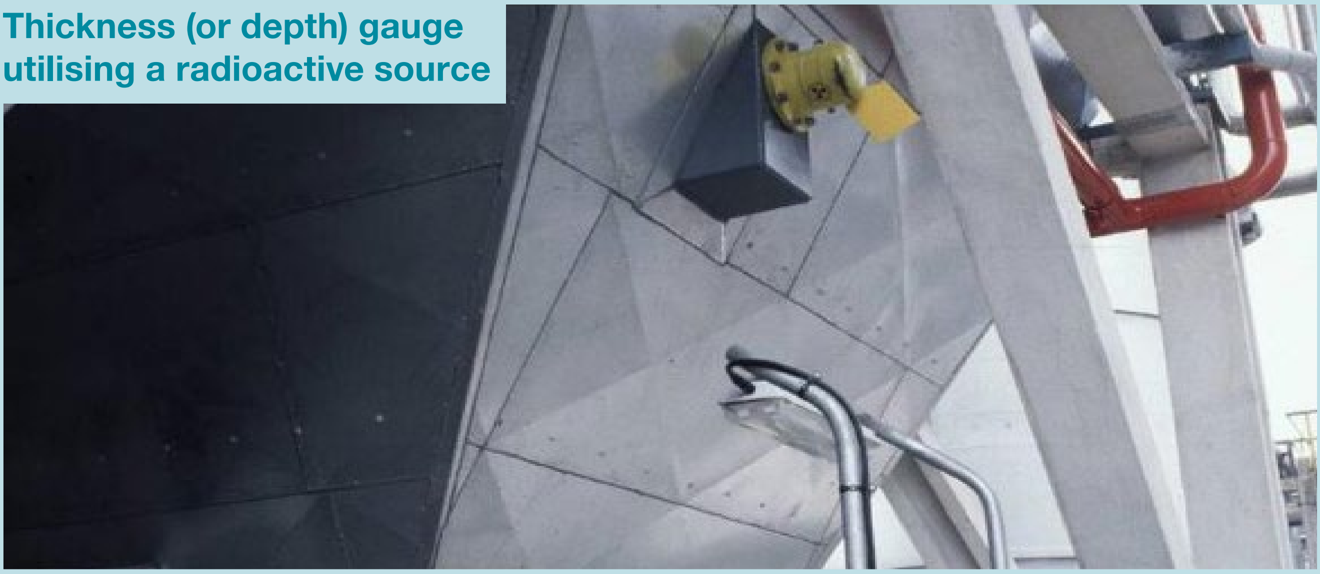
10

Occupational exposure to ionising radiation

Authors: Simon Jakes and Axel MacDonald

Workers are exposed to ionising radiation in a wide range of situations, perhaps most obviously those who work in the nuclear power industry. X-rays or artificially produced radionuclides are also commonly used in the manufacturing and service industries, in areas of defence, in research institutions, veterianry care, for security purposes and in universities and other educational establishements. Naturally occurring sources for instance radon or enhanced naturally occurring radioactive materials (NORM) may also lead to higher worker exposures. Also, as described in Chapter 9 radioactive sources are extensively used in medicine, leading to exposure of medical workers and dentists.

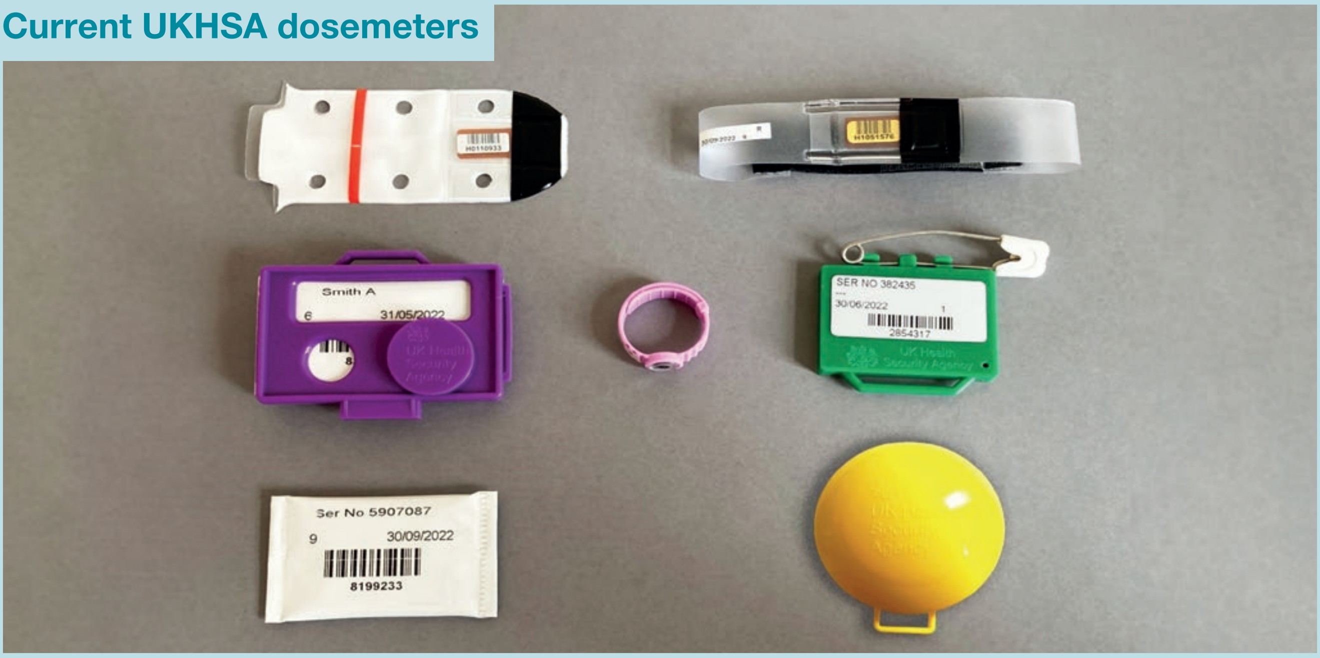
Thickness (or depth) gauge utilising a radioactive source



Level gauges used to determine minimum and maximum levels within the vessel (gamma radiation detectors fitted on the other side)

Many people who work with radiation sources wear dosemeters, for instance thermoluminescent dosemeters (TLDs), which superceded older dosemeters based on photographic film. These dosemeters measure the radiation incident on the body from external sources and record an estimate of the dose to the worker. Millions of these dosemeters are used in the UK each year, issued and processed by dosimetry services including UKHSA.

Current UKHSA dosemeters



Monitoring of internal radiation exposure of workers is more complex. It can be undertaken using sampling of airborne activity in the workplace to estimate what the worker has inhaled, by measuring radioactivity in excreta, or by measuring gamma emitting activity in the body directly using sensitive detectors.

Special calculations are needed to convert these measurements into estimated internal doses for comparison with dose limits. Monitoring for intakes of radionuclides may be undertaken as part of a routine monitoring programme or as a result of an incident.

The whole body monitor

Picture of the UKSHA whole body monitor used to measure gamma emissions from the body to estimate internal dose

Periodic reviews of occupational doses are undertaken by UKHSA using data provided by the Health and Safety Executive (HSE), other dosimetry providers and some individual employers. The table below shows data for individually monitored workers for the year 2010. The numbers of workers indicated does not include all those who might work with radiation sources, only those where there is more accessible data including those that are designated as classified persons under the UK Ionising Radiations Regulations.

Sector	Number of workers	Collective dose	Average dose
		man-Sv	mSv
Nuclear industry	20,600	10.5	0.51
Defence related	10,600	1.8	0.17
Medical sector	36,000	4.9	0.14
General industry	4,200	1.1	0.26
Research and education	4,300	0.23	0.05

Average doses to workers are well below the legal 20 mSv annual whole body dose limit. Of the approximately 75,000 workers covered in these data, only 0.2% received doses above 6 mSv in a year. Doses have declined markedly over time, especially in the nuclear sector, with better standards of radiation protection being applied but also changes to patterns of work and levels of activity in each work sector. Further substantial reductions may be unlikely and there remain some areas of concern. For example, some clinical procedures with diagnostic radiology require a physician to be close to the patient and at risk of repeated exposures. Doses to industrial radiographers using X-ray and high activity gamma ray sources can also be significant but the use of suitable shielded enclosures and following safe working practices reduces the risk of high exposures.

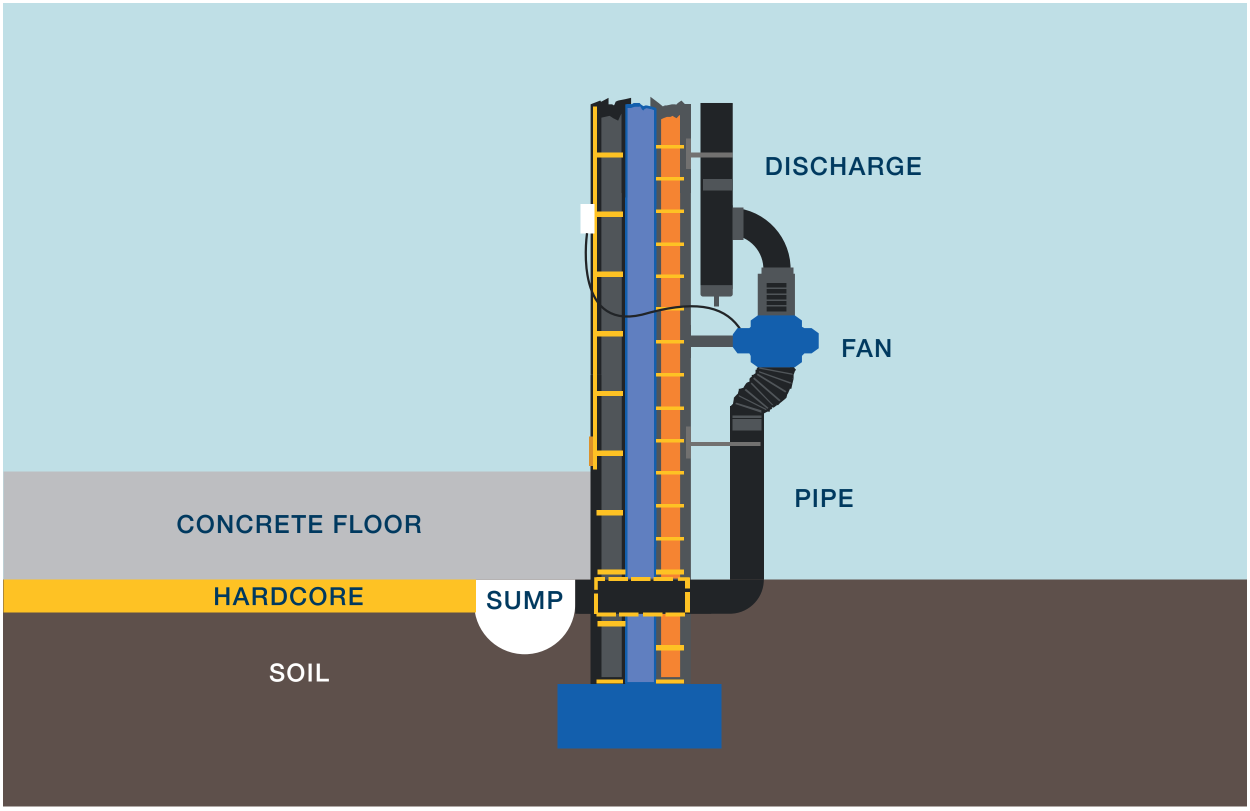
Radiation monitor

The table shows only exposure to artifical radiation sources. All workers are exposed to natural radiation in their workplaces as they are in their homes. Even when employee exposure is due to nauturally occurring radiation, the employer has a duty to ensure these expsoures are ALARP[9] and control must be implemented to reduce exposure. For example, workplaces with high radon levels including mines and also industries such as oil and gas production, where elevated concentrations of natural radionuclides can be encountered (radium scale in pipework). There is considerable uncertainty about levels of exposure to natural radioactivity including radon because few workers are directly monitored. There is some data for a very small number of regularly monitored miners who have a higher average annual dose of about 6 mSv due to radon, and large numbers of workers exposed to radon at lower levels. In some situations, this may be high enough for controls to be applied in the workplace but not so high as to require individual monitoring.

[9] ALARP – As low as reasonably practicable

Depending on the underlying geology, there is a risk that some other workers may still be exposed to radon at very high levels. Usually such areas can be readily identified using a post code check followed by radon monitoring. Considerable efforts have been made by UKHSA working with HSE and local authorities to identify such workplaces. Once a radon issue has been identified from monitoring results, remediation can be applied to reduce the radon levels. The collective workplace exposure to radon can be estimated from the UK average individual dose which is about 0.19 mSv per year.

An active radon sump



Another group or workers who receive higher than the UK average dose from their work are aircrew who are exposed to elevated levels of cosmic rays at flying altitudes. In 2010 there were about forty thousand people working for UK registered airlines each flying for an average of about six hundred hours per year. Their average individual dose was estimated to be 2.4 mSv and some airline crew could receive even higher doses from long haul flights.

This shows how significant natural radiation is as a source of exposure for some workers as well as the public.

11

Environmental pollution

Authors: Antony Bexon and Kelly Jones

We have seen in Chapter 8 that natural radionuclides are present in our environment. Artificial radionuclides have also been widely dispersed by events such as tests of nuclear weapons in the atmosphere, the Chornobyl and Fukushima accidents and by the discharge of radioactive wastes from nuclear and other installations. These radionuclides find their way from air and water on to the ground and into foodstuffs and can deliver radiation doses in various ways to human beings.

Radioactive discharges

Artificial radionuclides are discharged to the environment by the nuclear power industry, defence establishments, research organisations, hospitals and general industry. Discharges of any significance are subject to statutory control and they must be both authorised and monitored. Owners or operators of the facilities from which more significant quantities of radionuclides are discharged carry out monitoring programmes as do regulatory agencies.

This section focuses on the nuclear power industry as this discharges the most activity, although doses to the public remain low. 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.

During fuel preparation, when the uranium is enriched and the fuel elements are fabricated, discharges mainly contain uranium and thorium with the associated decay products. Annual doses to the most exposed group of people near the facilities is about 0.2 mSv mainly due to direct irradiation from the site. For the general UK population, the annual dose from fuel fabrications operations is much lower at less than 1/1000th of a mSv.

For operating reactor, airborne discharges to the atmosphere give rise to an estimated dose to the most exposed person of less than 0.005 mSv per year, principally from hydrogen-3, carbon-14 and sulphur-35. Typically liquid discharges from nuclear power plants result in individual doses of 0.005 mSv for the most exposed members of the public. Some individuals living near the site receive doses up to 0.03 mSv due to external exposure from contamination in intertidal or shoreline areas The typical annual dose for the UK population from consuming radionuclides in seafood, due to these discharges to coastal waters, is around 25 thousand times smaller.

In the vicinity of the Sellafield nuclear site in Cumbria where fuel reprocessing (this stopped in 2022), decommissioning and clean-up of redundant facilities as well as waste treatment and storage are carried out, individual doses to the most exposed persons is around 0.2 mSv per year. The doses at this location are however dominated by historical discharges of naturally occurring radioactive material from the former phosphate processing plant near Whitehaven. Doses to the most exposed group in this location is around 0.02 mSv from artificial radionuclides resulting from Sellafield discharges and 0.2 mSv from the historical industrial discharges.Doses to the typical person in the UK for both liquid and gasous discharges from such waste management facilities are less than 1/1000th of a mSv.

Discharges of radionuclides to the Irish Sea from the facilities at Sellafield have been greatly reduced since the peak in discharges which occurred in the 1970s.

Table of annual doses due to discharges from the nuclear fuel cycle in the UK

* includes direct radiation

	Type of effluent	Most exposed people (mSv)
Fuel fabrication	Airborne*	0.2
	Liquid	0.03
Reactor operations	Airborne	0.018
	Liquid	0.03
Fuel reprocessing / waste management	Airborne	<0.005
	Liquid	0.21

Nuclear accidents

Fukushima

The most recent significant accident involving a nuclear power plant took place in Fukushima, Japan in the days following a tsunami caused by the Great East-Japan Earthquake in March 2011. The tsunami resulted in damage to the electrical supply to the facility as well as destruction of safety infrastructure on the Fukushima site. This resulted in loss of cooling to three operating reactor units which subsequently overheated resulting in melting of the nuclear fuel and damage to the containment vessels. In addition, hydrogen was released into the reactor buildings which resulted in explosions. Releases of radioactive material to both the atmosphere and the sea occurred. In terms of the comparison, releases of iodine-131 were around 10 percent and caesium-137 around 20 percent of those from the Chornobyl accident (see below).

In terms of doses to people, the most significant exposure routes were from (i) external irradiation from material in the plume which deposited on the ground; (ii) internal exposure of the thyroid gland from iodine-131, and (iii) internal exposure to other organs and tissues from intake of caesium-134 and caesium-137. Very low levels of radioactive iodine were detected at two monitoring stations in the UK but any doses received from inhaling air with the measured levels was miniscule and much lower than the annual background radiation dose. Below is a photo of a high volume air sampler.

High volume air sampler

Chernobyl

An explosion in a nuclear reactor at the Chornobyl 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 and reached the UK within a week. As the contaminated air spread over the UK, local weather conditions largely determined where the radionuclides were to fall: heavy rain in the northwest caused more to be deposited there.

In terms of doses to people, the most significant radionuclides were iodine-131, caesium-134 and caesium-137. Almost all of the doses were caused by external irradiation from radionuclides on the ground and by internal irradiation from radionuclides in foodstuffs. Since 1986 the level of radioactivity in the environment due to the Chornobyl accident has declined and the dose to the UK population from the accident is indistinguishable from other sources of exposure.

Weapons tests

When nuclear weapons are tested above ground, a practice now banned, they release a variety of radionuclides from hydrogen-3 (tritium) to plutonium-241 into the upper atmosphere. From there, these radionuclides transfer slowly to the lower atmosphere and then to ground level. About 50% of particles fall close to the test site, but others travel further and some can spread globally. Around 500 atmospheric explosions were conducted before the Limited Test Ban Treaty in 1963, with a few more tests occuring until 1980. Today, the concentrations of radionuclides in air, rain and human diet are much lower than the peak values in the early 1960s. Between 1963 and 1996 nuclear tests were carried out underground, releasing significantly less radioactivity into the atmosphere. In 1996 the Russian Federation, the UK, the USA, France and China also stopped underground testing.

Currently the most important radionuclides in terms of human exposure are ^{14}C, caesium-137 and strontium-90. The routes of exposure are split broadly equally between ingested residual radioactivity associated with food and drink and external exposure to residual activity on the ground. Internal and external irradiation contribute about equally to the average effective dose of about 0.005 mSv in a year in the UK: this compares with a peak of 0.1 mSv in 1963.

Disposal at sea

Low-level radioactive waste was disposed of at sea in the North-East Atlantic between 1949 and 1982. The majority of the disposal was at depths of between 3,000 and 5,000 metres. The disposal at sea was stopped in 1983 with the adoption of initially a voluntary moratorium under the London Convention followed by a global ban in 1993. A report produced in 1995 to assess the impacts of the disposed activity estimated doses to the most exposed members of the public are less than 1/1000th of a mSv.

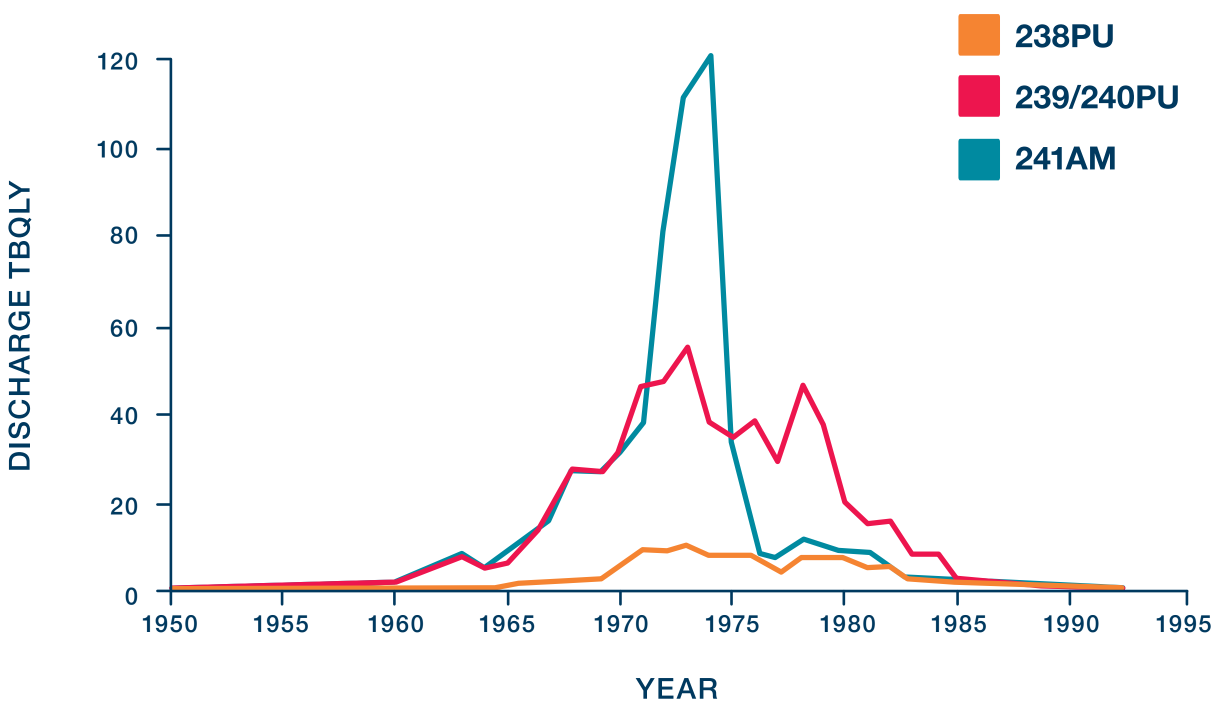
Contaminated land

In some parts of the UK, land has been contaminated with radioactivity, mainly from historical industrial activities. Radionuclides are naturally present in a range of materials and some industrial processes can inadvertently concentrate those radionuclides in wastes. For example, radionuclides naturally present in coal concentrate in ash produced through burning. Other industries made use of radioactivity and any wastes they produced may contain radioactive material. For example, during the mid-twentieth century, paint containing radioactive radium was added to watches and aircraft instrument dials so they could be seen in the dark. Prior to 1963, industrial waste, including that containing radioactivity, was disposed of in any convenient piece of land. As some radionuclides have very long half-lives, even wastes containing radioactivity which were disposed of over a century ago may still pose a hazard today.

The most common radionuclides likely to be present in land contaminated with radioactivity are radium-226, lead-210 and polonium-210, which all emit radiation primarily in the form of alpha particles. Other radionuclides include caesium-137, bismuth-214, lead-214 and bismuth-210, all emit radiation in the form of both beta particles and gamma rays.

To manage the risks posed by such land, the UK government introduced legislation in 2006, known as the Radioactive Contaminated Land Regime, to provide a system for the identification and remediation of land where levels of radioactivity in that land, above that which is present naturally, is causing unacceptable risks.

Discharge of principal alpha emitters to sea from Sellafield (1952 – 1992)



12

Nuclear power

Authors: Antony Bexon and Kelly Jones

Nuclear reactors have been producing electricity in the UK since the 1950s. The UK currently has nine operational nuclear reactors across five sites, which produce about 15% of the electric power generated in the country. Currently, fourteen other power or research reactor sites are being decommissioned and there are plans to build more nuclear power stations (including the consideration of Small Modular Reactors and Advanced Modular Reactors) in the future as they are a source of low-carbon energy.

Nuclear reactors

Nuclear reactors depend on a reaction between neutrons and the atomic nuclei of the fuel for their operation. Uranium, the fuel for reactors in the UK, consists principally of two isotopes, uranium-235 and uranium-238. In natural uranium, the fuel for early reactors, those isotopes are in the proportion by weight of 0.7% and 99.3%, respectively. The enriched uranium for later reactors contains between 3 - 5% of uranium-235.

Energy is released when a uranium-235 nucleus absorbs a neutron and undergoes nuclear fission, that is, it splits into two smaller nuclei, releasing energy and two or more neutrons. The neutrons are slowed in the reactor so that they induce further fissions in the uranium-235. 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 the neutrons so the nuclear fission process operates in a controlled manner.

A coolant, usually water or gas, conducts heat away from the fuel and then passes through heat exchangers to turn water into steam. This steam then drives turbine generators to make electricity.

The majority of the reactors used in the UK use graphite as a moderator and pressurised carbon dioxide gas as the coolant: the early types are called Magnox reactors which have now all entered decommissioning and the later types Advanced Gas Cooled Reactors (AGR). Another common design is the Pressurised Water Reactor (PWR) where water acts both as the moderator and the coolant: the Sizewell B reactor in Suffolk is currently the UK's only PWR.

To ensure a high degree of safety in the design of nuclear power plants, a concept of defence-in-depth is used which involves multiple layers of safety systems as an intrinsic part of the design and operation. As an example of this, the fuel is sealed in metal containers and the core is contained within a pressure vessel. Massive concrete shielding helps to absorb the intense radiation emitted by the core during and after operation. The reactor building further contains the reactors.

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 in the fuel; this means that an accident at the reactor could release significant amounts of radioactive materials. After removal from the reactor, the spent fuel remains hot and must be cooled as well as shielded to prevent melting and reduce human exposure.

Waste management

In Chapter 11 the discharge of effluents from the nuclear fuel cycle was described, but there are also other radioactive wastes. They fall into three broad categories according to activity: low level waste, intermediate level waste and high level waste. The radioactivity in the waste will typically result from fission products and from actinides (those elements with atomic numbers from 89 (actinium) to 103 (lawrencium) notably including thorium, uranium and plutonium.

Low 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 contami¬nated soil and building materials. Intermediate level wastes exceeds the limits of activity set for low level waste but do not generate significant amounts of heat. These include materials used in the treatment of gaseous and liquid effluents before they are discharged to the environment, the sludges that accumulate in the cooling ponds where spent fuel is stored, and components of nuclear reactors. High level waste refers to waste where the temperature may rise significantly due to the radioactivity. Highly active liquid is produced when spent fuel is reprocessed. If not reprocessed, spent nuclear fuel itself is regarded as high level waste.

The aims of waste management is to process the wastes in such a way as to make them suitable for storage and disposal and to dispose of them so that there are no unaccept¬able 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. For some of the disposal routes, potential exposures to future generations may not occur for many hundreds or thousands of years. There is uncertainty over the likely behaviours and ways of life of such future generations but the principle is to consider their exposure as we do for current generations.

Low level waste does not generally need processing: it can be packaged, sometimes after compaction, and disposed of directly to an authorised landfil site. Most waste in this category from the nuclear fuel cycle is disposed of at the Low Level Waste Repository in Cumbria. Very low levels of radioactivity may also be disposed of in suitably authorised landfill sites alongside commerical and domestic wastes. Other forms of disposal may also be used such as through authorised metal recycling facilities or through appropriately authorised incineration.

Most intermediate level waste does not occur in a form suitable for direct disposal; it must be mixed into an inert material such as concrete, bitumen or resin. In the past, some of these wastes were dumped at sea, but this is no longer allowed so all intermediate level waste is stored in interim stores awaiting the construction of a long-term management facility. The preferred option in England and Wales is a geological disposal facility and the preferred option in Scotland is near-surface disposal; sites have yet to be identified.

High level waste in the UK is typically in liquid form generated as a by-product of spent fuel reprocessing. Liquid high level waste is mixed with molten glass at Sellafield in a process called vitrification and stored in stainless steel canisters. The canisters are planned to be stored for 50 years or more to allow for radioactivity to decay and for the waste to cool before eventual disposal. The preferred option for disposal of high level waste is geological disposal where the packaged radioactive waste will be placed in an engineered facility located in suitable geology to prevent any releases of radioactive material.

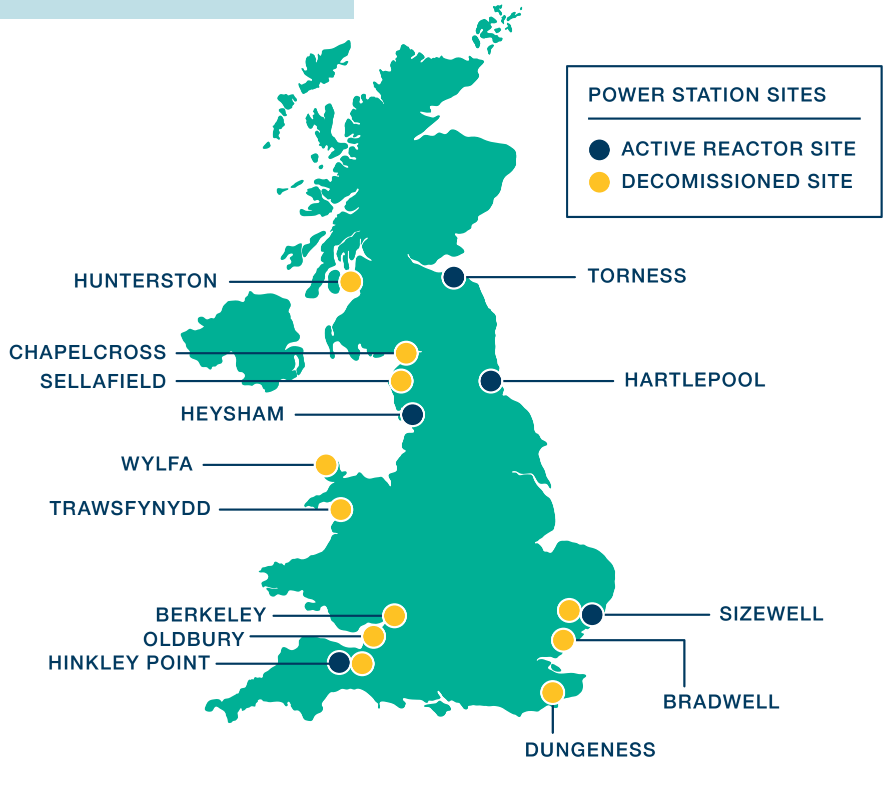
Decommissioning

Once nuclear reactors and other nuclear facilities reach the end of their operational life, they require a phase of management to reduce the hazards from the facilities and to reach a agreed end-state in terms of any risk from future use for the site. This process, called decommissioning, may involve the removal of hazards such as spent fuel or contaminated equipment, decontamination of the facility and the potential dismantling of buildings.

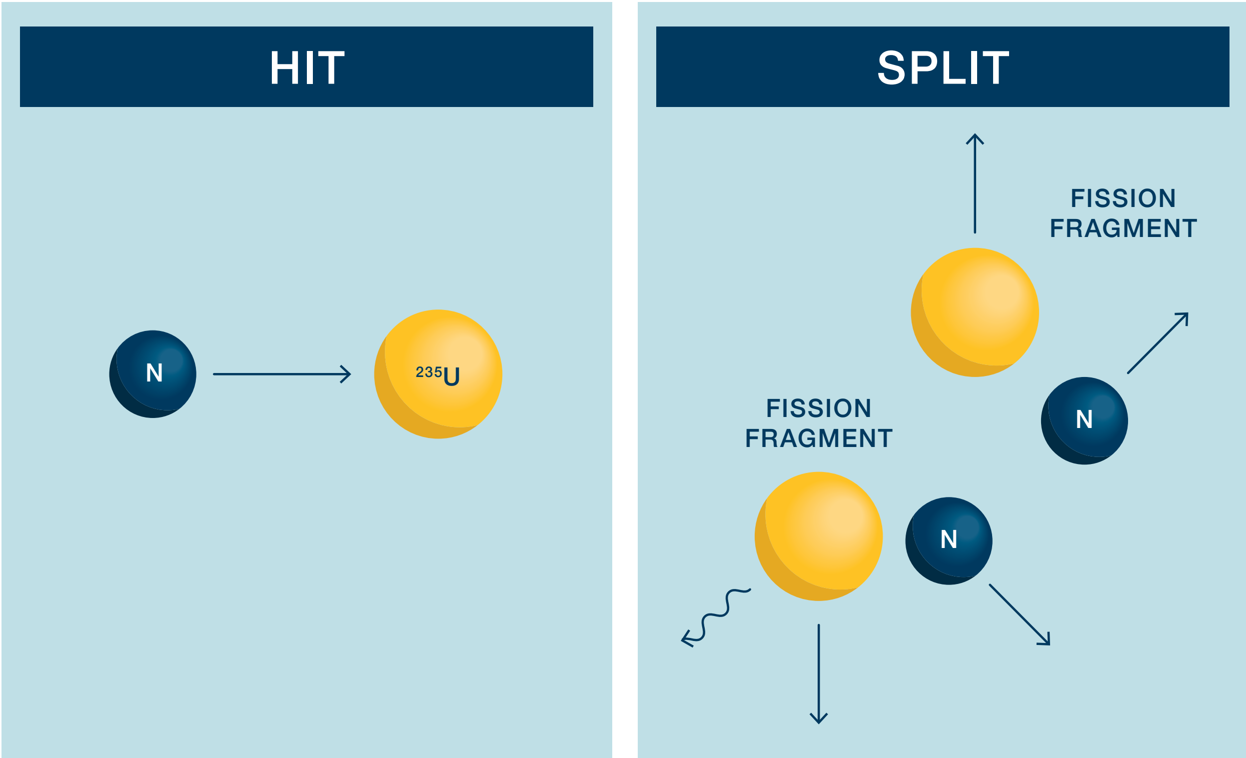
Decommissioning of the most radioactive parts of a reactor requires strict control of operations. Complicated techniques to remotely handle radioactive material are being used to optimise the protection of workers and the public. Decomissioning activities can generate large volumes of low and intermediate level radioactive waste.

Decommissioning is currently well underway at several nuclear sites but none have completely achieved progress to the agreed Site End State as the process may not be achieved for several decades due to the need to allow for radioactive decay to ensure that workers and the public are protected. The UK has developed considerable experience in decommissioning such sites.

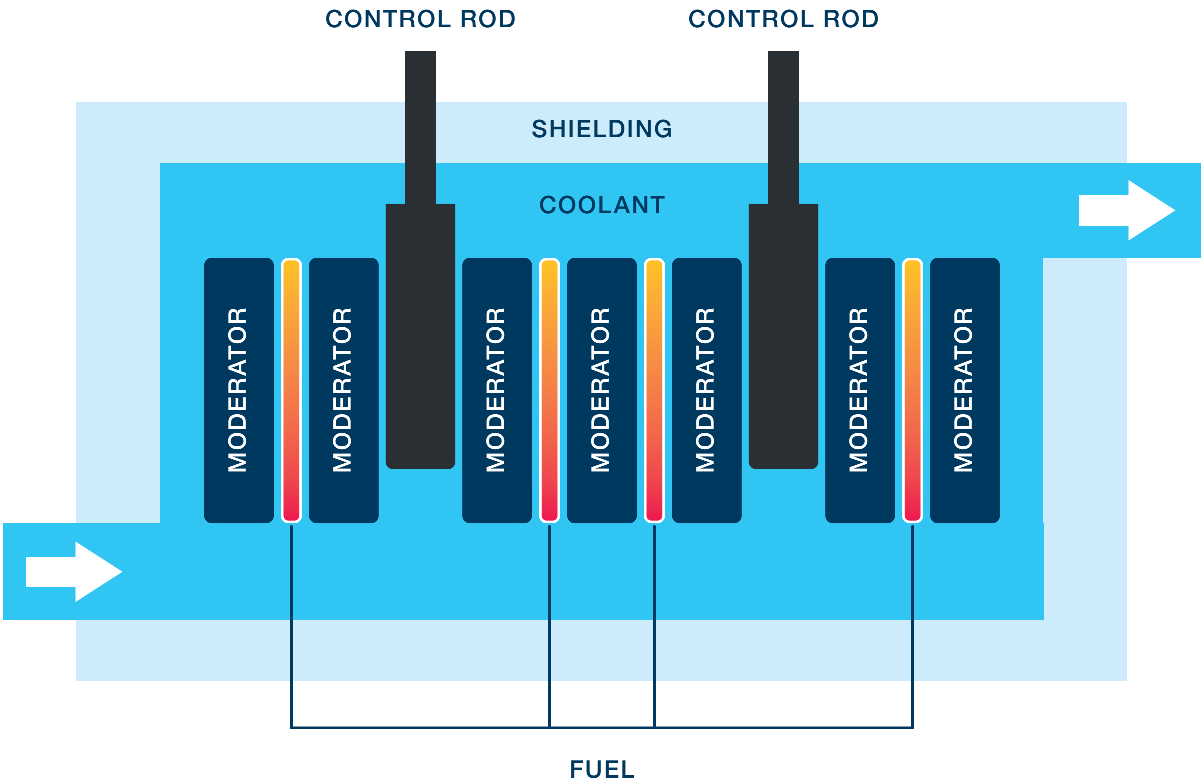
Nuclear sites in the UK



Uranium-235 fission



Nuclear reactor



Waste categories

Low level wastes

Contain various radionuclides in general refuse and rubble. Low activity, high bulk

↓

Intermediate level wastes

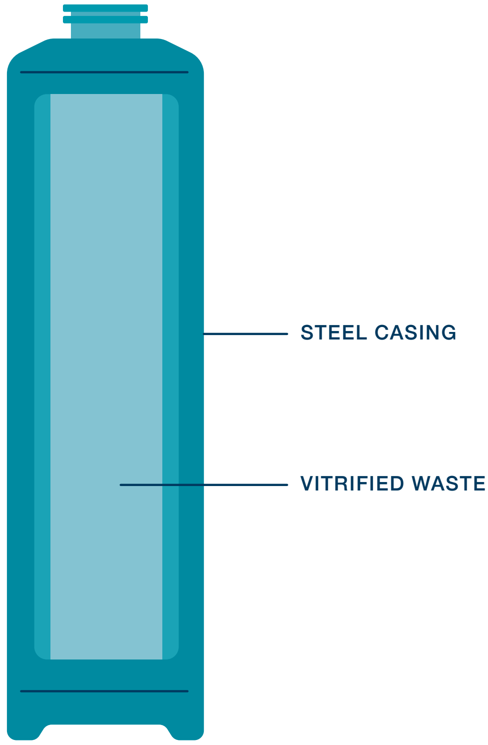
Contain larger quantities of fission products and actinides with long half-lives. Low heat creation, high bulk

↓

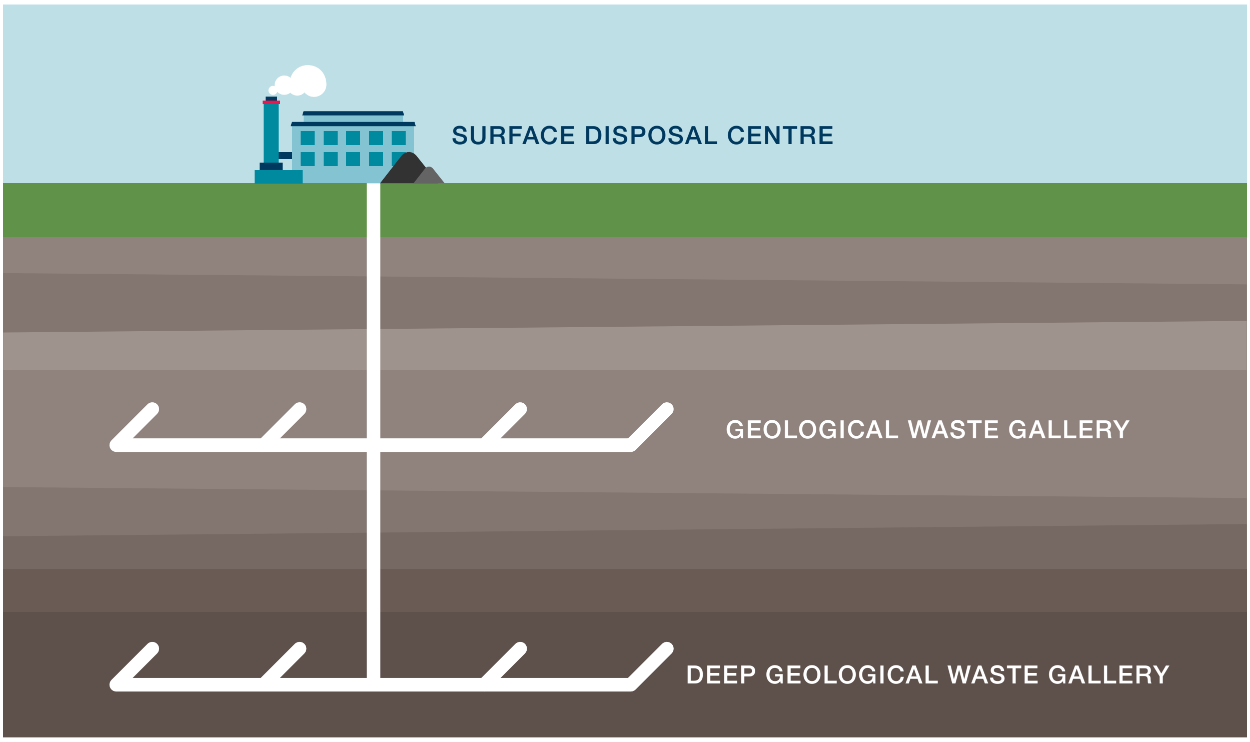
High level wastes

Contain most of the fission products and actinides from fuel cycle. High heat creation, low bulk

Vitrified high level radioactive waste



Underground repository for radioactive waste



13

Radiation emergencies

Authors: Duncan Cox and Connaugh Fallon

Emergency arrangements

The UK has a long history of using radioactive materials and established the world's first civilian nuclear energy programme in 1952 with the opening of the Calder Hall reactor. Since then, there have been many advancements in radiation science, with applications spanning many different disciplines, including energy, research and development, medicine, and industry.

The potential hazards and biological effects of radiation mean that activities involving radiological or nuclear materials must be regulated and controlled to protect workers the public, and the environment. The UK has a robust legislative and regulatory framework that ensures safe practices are in place for radiological and nuclear safety, including the requirement to prepare for emergencies.

The Civil Contingencies Act 2004 (CCA) forms the legal basis for emergency preparedness in the UK and outlines the duties of organisations that are responsible for emergency preparedness and response at the local level. In the CCA, responders are defined as Category 1 (those organisations with a core response role that are subject to the full set of duties) or Category 2 (organisations with a requirement to co-operate and share information).

Regulations also exist that specifically relate to radiation emergencies, including but not limited to:

Great Britain	Northern Ireland
Radiation (Emergency Preparedness and Public Information) Regulations 2019 (REPPIR)	Radiation (Emergency Preparedness and Public Information) Regulations Northern Ireland 2019 (REPPIRNI)
Ionising Radiation Regulations 2017 (IRR)	Ionising Radiation Regulations Northern Ireland 2017 (IRR)
The Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2009	The Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations Northern Ireland 2010
The Nuclear Installations Act 1965	

Under these regulations, licenced sites, such as nuclear reactors, are required to maintain safe practices to prevent an accident occurring, assess the potential hazards that could arise in the event of an emergency, and ensure a plan is in place to effectively respond to that scenario. CCA category 1 responders are required to fulfil their duties under these plans in accordance with regulation.

Radiation emergency plans are based on reasonably foreseeable worst-case scenarios, termed reference accidents. However, there are also arrangements in place for 'extendibility' should an accident occur that deviates from the anticipated accident sequence. For emergencies with radiological consequences off-site, the local authority is responsible for establishing a radiation emergency plan; whereas on-site emergency plans are the responsibility of the site Operator. The Office for Nuclear Regulation, as the UK licensing authority for nuclear installations, is the responsible body for inspecting facilities and assessing the adequacy of radiation emergency arrangements.

In the event of a radiation emergency, the Central Government's Concept of Operations (CONOPS) will form the basis of the UK response arrangements. Under the CONOPS, the local response will be led by the Strategic Co-ordinating Group (SCG), which will likely be chaired by the police.

The UK implements a Lead Government Department (LGD) model for coordination across central government in the event of an emergency. The appointed LGDs are responsible for ensuring all phases of an emergency are planned for, including risk assessment, preparedness, response and recovery. Risk identification and assessment for the UK is performed by the Cabinet Office. Identified risks are owned by a LGD or arms-length body to ensure clear lines of responsibility and response co-ordination should the risk materialise. The National Risk Register (NRR) provides a publicly available summary the most serious risks facing the UK.

The LGDs for radiological or nuclear events vary based on the scenario being considered and the phase of the emergency. Other departments are expected to support the LGD by preparing for, and leading a response to, any downstream impacts or disruption to their own sectors.

The UK is committed to aligning its radiological and nuclear emergency arrangements with international standards and guidance, such as those produced by the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP) (*-***see footnotes).

Protective actions

In the event of a radiological accident, it may be necessary to introduce one or more protective actions to reduce radiation doses to people living or working near the site. Should an accident occur at a reactor for example, various radionuclides in gaseous, volatile, or particulate form could be expelled into the atmosphere. They would then be borne away in a plume by the wind and dispersed and diluted, with some deposited on the ground and other surfaces. The concentration of radionuclides in the air would decrease rapidly downwind from the site as would the associated hazard; however, appreciable activity could be deposited on the ground at considerable distances depending on weather conditions. Accidents occurring overseas generally would have less radiological impact on the UK due to the greater distance that any released contaminants must travel.

Protective actions may be applied in the initial phase, sometimes known as urgent protective actions, or in the longer term.

If radioactivity is released into the atmosphere, advice to people to simply stay indoors with windows and doors closed, known as sheltering, can be very effective in the initial phase. Sheltering will provide shielding from direct irradiation and limit the amount of material that is likely to be inhaled, thereby reducing internal doses. When the plume has blown over or the release stopped, particularly in situations when doses are expected to be low, the overall health impact can be very low. In extreme situations where the expected doses are higher or the release prolonged, it may be necessary to temporarily evacuate people and relocate them further away.

A nuclear reactor accident can release some radionuclides that can give potentially high doses to people in the early stages. Radioactive iodine isotopes are an example, particularly iodine-131.

Naturally occurring iodine is present in food in trace quantities and is accumulated by the thyroid to make specific hormones. Radioactive iodine-131 is a beta emitter and can deliver a radiation dose directly to the thyroid if it is accumulated. This is a potentially serious problem because the thyroid has been shown to be sensitive to radiation, especially in younger people. To overcome this, stable iodine tablets (in the form of potassium iodide) can be given to the public to reduce the harmful effects of iodine-131. The stable iodine within the tablets saturates the thyroid and so blocks the accumulation of radioactive iodine. Excess iodine is then excreted from the body within a couple of days. Emergency plans may include measures to pre-distribute iodide tablets to homes or public buildings. Stable iodine should only be taken when instructed to do so, as the efficacy varies depending on the time of ingestion relative to the time of exposure to radioactive iodine. Stable iodine is most effective if taken between 24 hours before and 2 hours after exposure to radioactive iodine. The effectiveness of stable iodine reduces the longer the time between exposure to radioactive iodine and taking the tablets, as radioactive iodine will already have been taken up by the thyroid gland, but it can still be useful up to 8 hours after exposure.

The UK Health Security Agency (UKHSA) has recommended Emergency Reference Levels (ERL) of dose for the introduction of protective actions to protect the public in the early stage after an accident. UKHSA specifies a range of averted doses, bounded by an upper and a lower ERL for each of these protective actions. If the predicted level of averted dose is below the lower ERL level, the protective action is unlikely to be worth implementing, as only a small dose is avoided. Above the second level, however, the protective action would be worth implementing in most circumstances, as the dose avoided by those taking the action would be more significant. If the dose averted by taking the protective actions falls between the upper and lower ERLs, the decision about whether to implement the action depends on the individual circumstances.

As radionuclides can deposit on the ground and vegetation, it may be necessary to restrict distribution and consumption of crops and milk. Such food restrictions may be implemented in the initial stage after an accident, or longer term. Other protective actions that may be considered after the initial response could be hosing roads, paths or roofs, cutting back and removing vegetation or burying surface contamination by ploughing.

Depending on the accident scenario, it may be necessary to introduce long lasting protective actions to protect the public from residual radioactivity. For example, radioactivity deposited on the UK a few days after the Chornobyl accident (April 1986) led to movement restrictions imposed on sheep farms in certain areas of the country. This was due to the radionuclide caesium-137 being recycled in grass in certain soil conditions – normally it becomes fixed in soils and does not enter the food chain. These restrictions were finally lifted in June 2012, some twenty-six years after the accident.

Emergency controls may also be implemented to prevent contaminated or unsafe products from entering the food chain. Maximum Permitted Levels of radioactivity in foodstuffs is controlled under legislation and monitored by the Food Standards Agency and Food Standards Scotland.

Radiological Impact

The potential consequences and long-term impact of a radiation emergency are assessed by national monitoring and other local monitoring capabilities, as well as expert scientific advice. The UK Government maintains the Radiological Response and Emergency Management System (RREMS), consisting of fixed and mobile gamma dose rate monitors spread nationally across the UK. This system operates continuously and would be an important source of information after any nuclear or radiation accident in the UK. The UK also subscribes to the European Radiological Data Exchange Platform (EURDEP).

The UK Government also has a Joint Agency Modelling (JAM) capability, which estimates, forecasts and provides advice on radiation emergencies from incidents within the UK and overseas. JAM uses enhanced dispersion modelling to map areas where thresholds for various impacts such as health, food restrictions and environmental contamination may be exceeded.

The plume maps and accompanying expert narrative from across the multi-agency partnership provide the Government's Scientific Advisory Group for Emergencies (SAGE) with a single, coherent output to support decision making.

Minor incidents

For minor incidents where no formal contingency plans exist, the police are able to activate the National Arrangements for Incidents involving Radioactivity (NAIR). This voluntary scheme is coordinated by UKHSA and draws upon the services of expert responders from industry, institutions, and hospitals around Great Britain to provide advice and assistance to the police when requested. A similar scheme operates in Northern Ireland.

The parallel RADSAFE scheme offers mutual assistance in the event of a transport accident involving radioactive materials belonging to members of the scheme. RADSAFE covers all the nuclear industry to provide a response, expert advice, and support to the emergency services in the event of such an incident.

Incidents involving military equipment are supported by a dedicated response force with the Nuclear Accident Response Organisation (NARO) and Military Co-ordinating Authority (MCA) liaising with government departments as well as national and local organisations.

Further Information

For further information on appropriate actions to take in the unlikely event of a radiological or nuclear emergency from UKHSA, search 'What to do in a radiation emergency'****.

Guidance documents:

*Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy: How we regulate radiological and civil nuclear safety in the UK (webpage)

**Cabinet Office: The Roles of Lead Government Departments, Devolved Administrations and Other Public Bodies (html)

***Cabinet Office: National Risk Register 2025

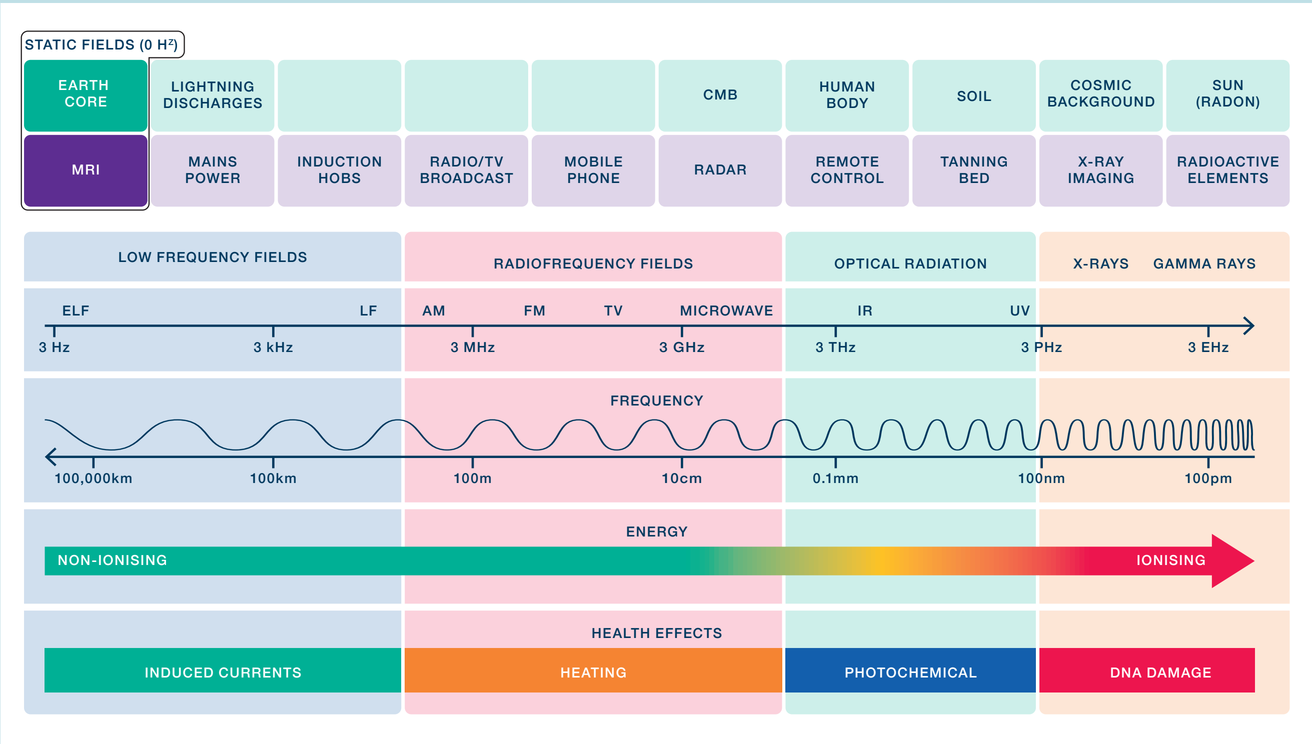
****UK Health Security Agency: What to do in a radiation emergency

14 Electromagnetic fields

Authors: Azadeh Peyman, Carolina Calderon, and Darren Addison

Electric and magnetic fields (together known as 'electromagnetic' fields) are produced by the generation and use of electricity. Electric fields are measured in volts per metre ($V\ m^{-1}$). Magnetic fields are usually measured in units of tesla (T); however, a tesla is a very large unit and the fields that people are usually exposed to, are measured in microtesla (μT, millionths of a Tesla). When the strength of a field changes with time, as with alternating current (AC) supplies of electricity, it is said to be time-varying. Time-varying fields are described by their frequency (number of wave cycles per second), or by their wavelength, which is inversely related to frequency, meaning the lower the frequency the longer the wavelength and vice versa (as shown in the diagram below). The unit of wavelength is the metre, and the unit of frequency is Hertz (Hz). Static fields are not time-varying and thus have a frequency of 0 Hz.

The electromagnetic spectrum showing representative sources of exposure



This chapter is about electromagnetic fields with frequencies less than 300 GHz where the wavelength in air is greater than 1 millimetre. It includes, for example, the electricity mains frequency of 50 Hz with a wavelength of 6,000 km, and the mobile phone frequency range of 700 – 3,800 MHz with a wavelength of 43 cm to 8 cm respectively. Here, low frequency fields are defined as having frequencies up to 100 kHz, and high frequency fields as having frequencies between 100 kHz and 300 GHz.

At low frequencies, the electric and magnetic components of the electromagnetic field are independent from each other, and act as separate sources of exposure. However, at high frequencies, the two fields are mainly coupled to each other and form one source of exposure.

Electromagnetic fields have photon energies that are many orders of magnitude below that at which ionisation occurs or chemical bonds in cells are disrupted. Photons in the optical radiation part of the spectrum have higher photon energies but these are still below the ionisation threshold. Because of this, electromagnetic fields and optical radiation together are often termed as "non-ionising radiation".

Sources of exposure

We are all exposed to electromagnetic fields from a variety of natural and artificial sources (see diagram on previous page), and exposures from manmade sources are generally much greater than natural sources.

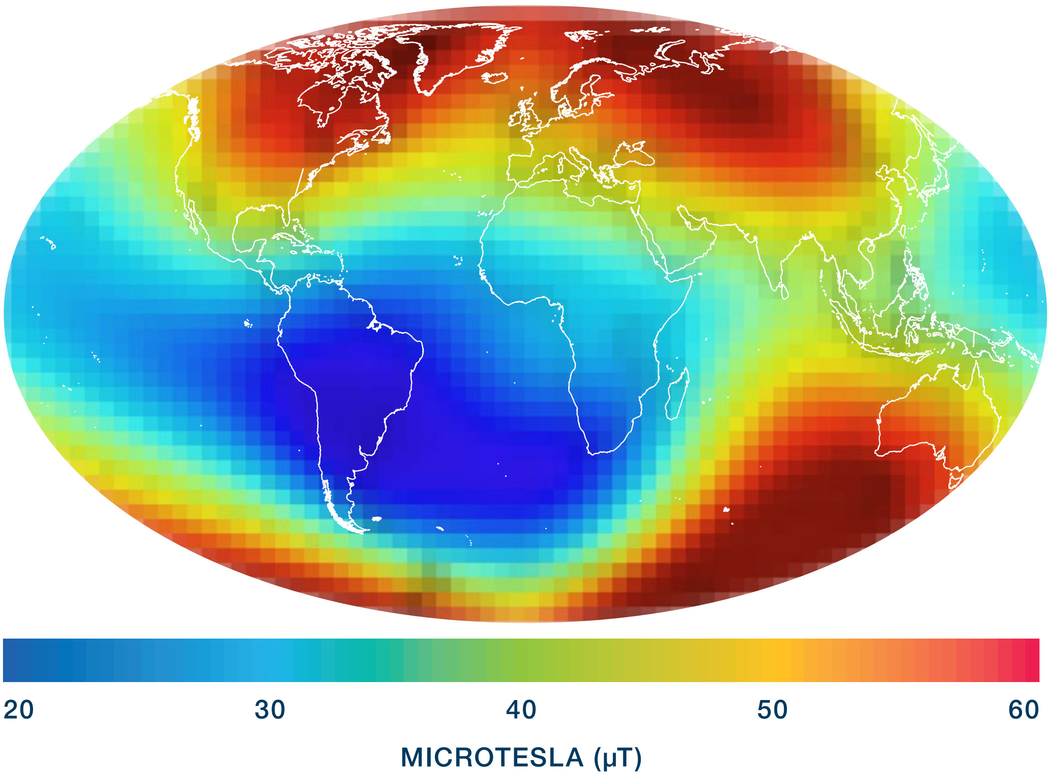
Static fields

Static electric and magnetic fields include the natural fields that occur in the atmosphere, as well as man-made fields produced by direct current (DC) electricity and permanent magnets.

Natural fields include Earth's magnetic field and static electric fields arising as consequence of thunderstorms and other atmospheric conditions. Friction can also generate strong static fields. The intensity of Earth's magnetic field varies from 25-65 µT (as seen in diagram below); in the UK, this field is about 50 µT.

Greater exposures may arise from manmade static fields produced from the operation of electrical equipment and distribution of DC electricity such as trains and trams or from permanent magnets such as those used in magnetic resonance imaging (MRI).

Variation in total intensity of Earth's static magnetic field in 2014

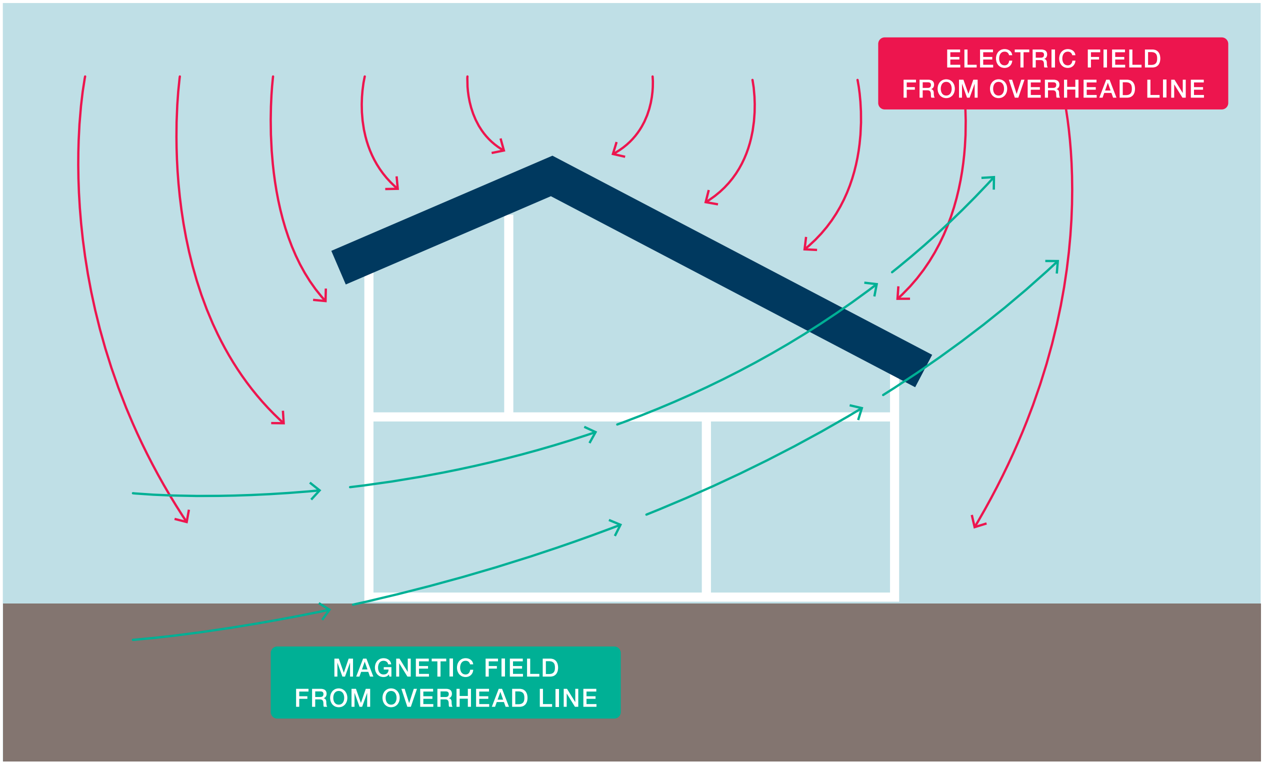


Low frequency fields

Low frequency electric and magnetic fields are associated with the generation, distribution and use of electricity. Electric fields come from the voltage that is used to make the electric current flow, and they get bigger as voltage increases, whereas magnetic fields are produced by electricity flowing as the electric current, and they get bigger as the current increases. Electric fields will be produced whenever anything is connected to the mains, while magnetic fields will only be produced when the device is in actual use. In the UK, electricity is generated at 50 Hz, so these fields are also produced at 50 Hz and are often termed power frequency fields.

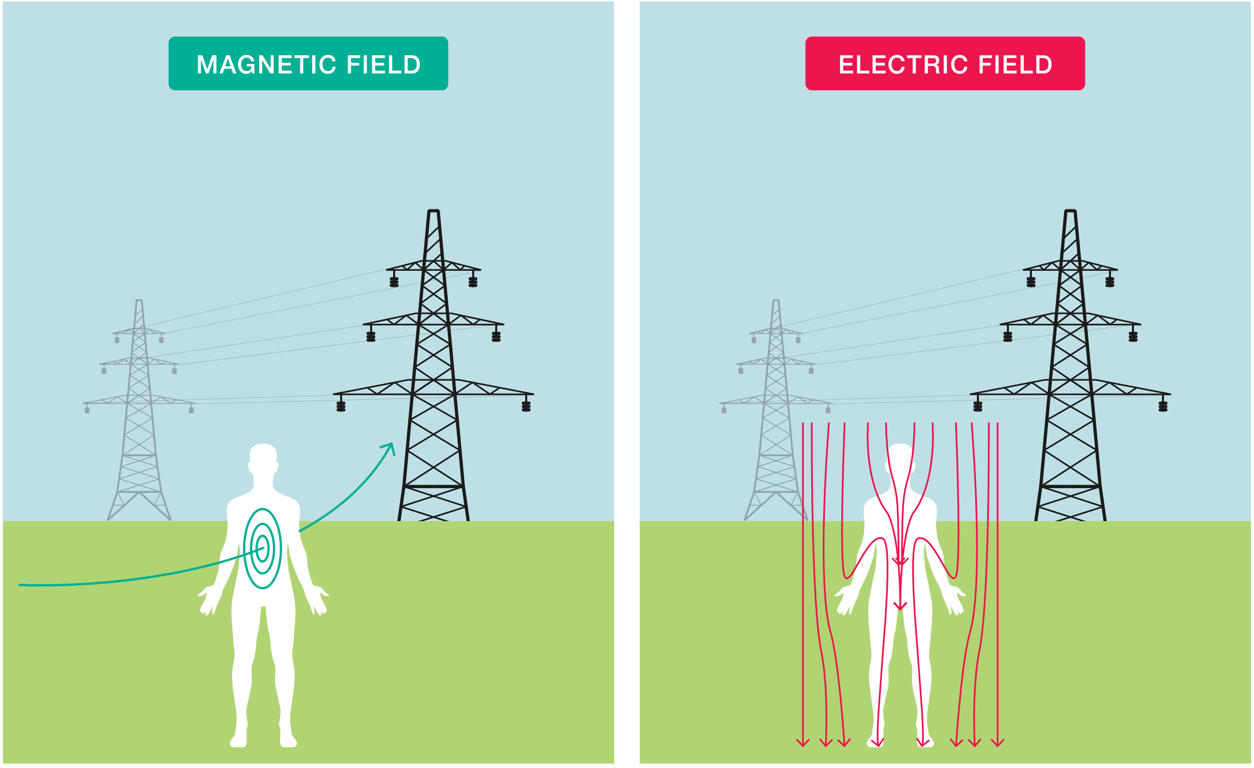
Electric and magnetic fields are produced in our homes and workplaces by the electrical appliances we use, the cables carrying electricity into buildings, the household electrical wiring, and by overhead power lines and substations outside the home. They are also produced by electric transportation systems. The largest overhead power lines across the UK operate at 275 or 400 thousand volts (kilovolts or kV) while smaller local lines operate at between 11 and 132 kV; the domestic power supply operates at 230 V. The typical background range for electric fields in UK homes is 1–20 V m^{-1} and this may increase to a few hundred V m^{-1} very close to appliances and power cables, and up to a few thousand V m^{-1} outdoors under large overhead power lines. Most building materials are very effective at shielding electric fields, so strong electric fields outside a building do not cause strong fields inside it (as seen in diagram below).

Walls will attenuate and perturb electric fields but not magnetic fields



The background level for magnetic fields measured away from appliances usually comes from the local electricity distribution cables which supply the house. The typical background magnetic field level in homes is usually in the range 0.01 – 0.2 μT. Magnetic fields of up to a few tens of μT can occur very close to appliances and close to the electrical wiring, even if it is inside the walls. In homes within a few tens of metres of large overhead power lines, magnetic field levels are typically a few μT, although the fields under the largest lines may sometimes reach up to a few tens of μT.

Electric and magnetic fields from power lines



High frequency fields

High frequency fields are used in broadcasting and telecommunications (and are often termed radiofrequency fields or simply radio waves). Microwaves ovens, Wi-Fi devices, as well as cordless and mobile phones all operate using high frequency fields. They are also used in industry in many applications to heat, weld and cure objects and materials. There can be a low level of exposure to high frequency fields everywhere that radio, television, or mobile phone signals are received. Higher exposures can arise when mobile phones are used for voice calls and close to the head.

Measures to reduce exposure

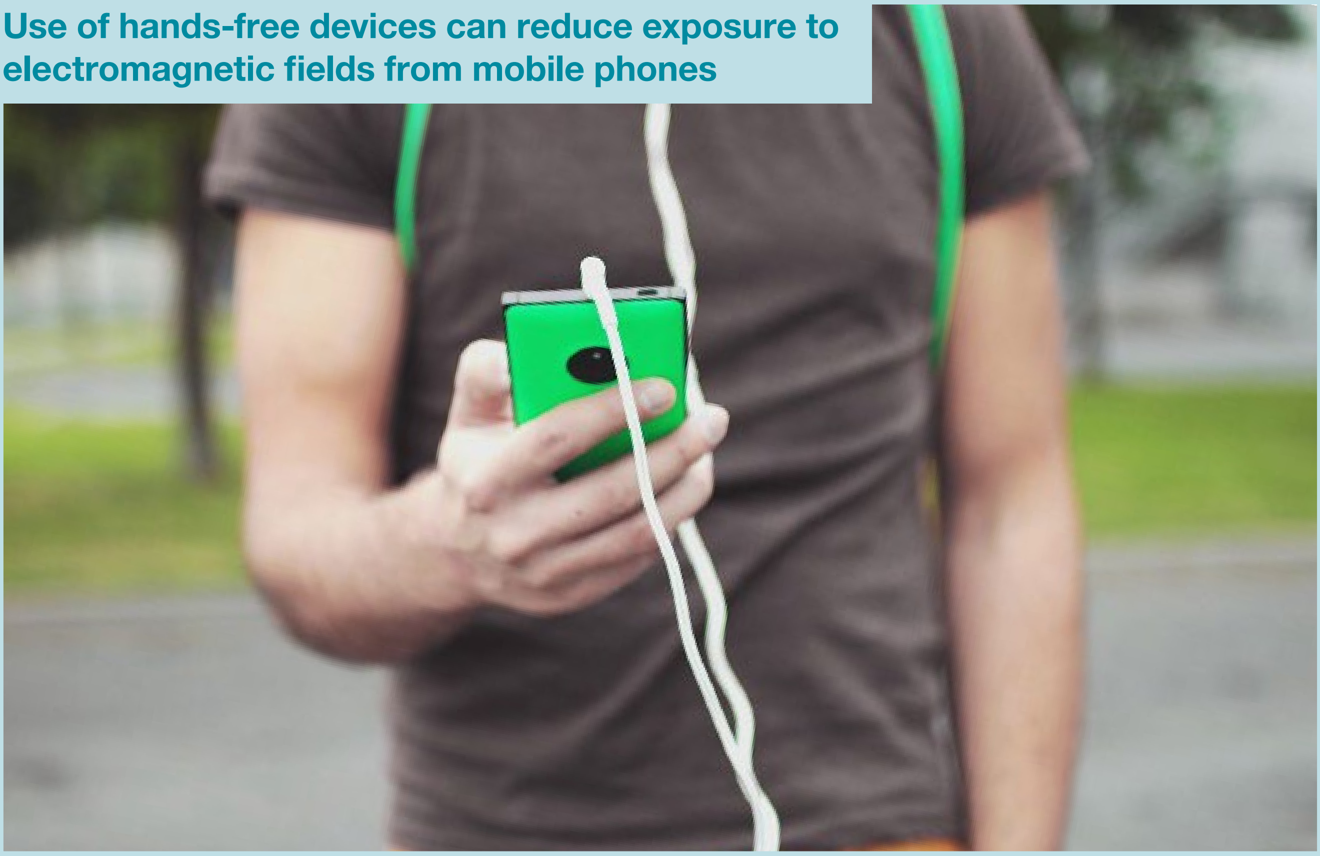
The degree of personal exposure to both low and high frequency fields amongst others, depend mainly on the strength of the source and the person's distance from it. For all sources, the field strength decreases rapidly with distance.

Exposures in our homes to low frequency fields from various appliances are usually much lower than the safety guideline levels, which provide adequate protection. People can further reduce their exposure, if they wish, by turning appliances off when not in use and when it is safe to do so, moving further away from appliances in use and reducing the time spent near to, or using appliances.

Similarly for high frequency fields, for example when using mobile phones, people can decrease their exposure levels by moving the phone away from the body, as when messaging and browsing, using a hands-free kit, keeping calls short, making calls where the network signals are strong and choosing a phone with a low specific energy absorption rate (SAR) value quoted by the manufacturer.

Exposures from other high frequency devices that are held further away from the body such as wireless-enabled laptop computers, and transmitter masts in the community are very much lower than those from mobile phones.

Use of hands-free devices can reduce exposure to electromagnetic fields from mobile phones



Effects of electromagnetic fields on human body

The interaction mechanism of electromagnetic fields with humans, and any effects they may cause, depend on the frequency of the field. The magnitude of an effect in turn depends mainly on the intensity of the field and the electrical properties of various body tissues.

Acute effects

Static electric fields induce electric charges on the surface of an exposed human, resulting in movement of the hairs on the head and body. For most people the threshold for perception is around 20 kV m^{-1}, and this becomes annoying above 25 kV m^{-1}. A person in an electric field may also receive a microshock (spark discharge) if they touch a grounded object: this is similar to the static discharges commonly experienced in dry atmospheric conditions after walking across a nylon carpet. Static magnetic fields do not produce discernible effects on people, although rapid movement in a static magnetic field will induce low frequency electric fields inside the body. In fields above 2 T these can produce transient sensations such as vertigo, nausea and a metallic taste in the mouth.

Low frequency electric and magnetic fields induce electric fields and currents within the body which can affect nerve and muscle function, if sufficiently intense. Laboratory experiments have shown that exposure can cause elusive, flickering sensations in the periphery of vision, called phosphenes, which are caused by effects on the cells in the retina. At higher field strengths, exposure may stimulate nerves and even cause muscle contractions. None of these phenomena would be expected at field intensities normally experienced in everyday life.

The main biological effect of exposure to high frequency fields is heating. This results primarily from the alignment and relaxation of electrically polarised molecules, mostly water, in the body. Such heating is not uniform, as living tissues with a high-water content, such as muscle, absorb power more than tissues with a low water content such as fat. Local blood flow through the tissues will also influence the final temperature reached.

At frequencies from about 100 kHz to 10 MHz, exposure can also induce (radiofrequency) currents to flow within the body which result in induction heating. Under these conditions, any increases in temperature are much more likely to occur in narrow parts of the body such as the ankles or wrists.

At frequencies above 10 GHz, heating is largely confined to the surface of the body, as the fields penetrate less into the body as the frequency rises. In addition, pulsed fields of sufficient intensity between 200 MHz and 6 GHz can be sensed as a buzzing or clicking noise. This is thought to be caused by a small but rapid increase in temperature in the tissues in the head when the energy is absorbed. This generates a sound wave that stimulates the cochlea and may be annoying if prolonged, although there is no evidence that this effect is harmful.

Finally, touching conducting objects in fields below 300 MHz can give rise to (radiofrequency) burns. These are caused by the flow of current to the body through a small area of contact, such as a fingertip. Usually, members of the public are not exposed to fields with such strength that they experience these effects.

Long-term effects

The possibility that electromagnetic fields might increase the risk of cancer in children or adults has been the subject of much scientific debate and public concern. As a result, programmes of epidemiological and biological research have been pursued by UKHSA and other scientific organisations around the world.

In 2002, the International Agency for Research on Cancer (IARC) concluded that static electric fields, static magnetic fields, and low frequency time-varying electric fields were "not classifiable as to their carcinogenicity in humans". This conclusion remains valid.

A considerable number of epidemiological studies have investigated if residential exposure to low frequency magnetic fields is associated with an increased risk of childhood cancers. Taken together these studies suggest that elevated levels of exposure in the home (with average values above 0.3 – 0.4 μT) are associated with a two-fold excess in the risk of childhood leukaemia. In absolute terms, it suggests that 2 to 5 cases per year on a total burden of 500 in the UK may be attributable to magnetic field exposures from powerlines. For all other childhood cancers and for all adult cancers the evidence is inadequate to form an opinion. Based on the evidence at the time (2002), IARC concluded that magnetic fields were "possibly carcinogenic to humans" (Group 2b). See figure below on IARC classification. More recent epidemiological studies do not contradict that assessment.

The epidemiological studies that form the basis of this IARC classification face many difficulties. Childhood leukaemia is a rare disease, so even national studies tend to include few cases, and this limits their ability to provide clear-cut answers. Obtaining a valid measure of exposure to magnetic fields over extended periods is also difficult. IARC and other expert groups that have reviewed these data agree that it is possible that a combination of bias in the selection of participants, the presence of confounding factors that may confuse findings, and chance could explain these results.

Importantly, despite much research, there is no mechanism or supporting biological evidence from laboratory studies with animals or cells to explain how these effects might happen, and there is no evidence that magnetic fields can damage DNA directly.

Other studies have investigated whether exposure to magnetic fields is linked to illnesses such as Alzheimer's disease. Although some studies suggest a link may exist, the overall balance of evidence is much weaker than that for childhood leukaemia and is closer to being no effect.

Box showing examples of agents classified by IARC regarding their carcinogenicity to humans

Category	Definition	Number of agents	Examples of agents
Group 1	Carcinogenic to humans	122	Alcoholic beverages, consumption of processed meat, diesel engine exhaust, arsenic, benzene, ionising radiation (all types), ultraviolet radiation (UVR) and outdoor air pollution
Group 2a	Probably carcinogenic to humans	93	Consumption of red meat, shift working that involves circadian disruption, and drinking very hot beverages (>65°C), creosotes
Group 2b	Probably carcinogenic to humans	319	Pickled vegetables (traditional Asian), talc-based body powder (perineal use), ginkgo biloba extract, petrol engine exhaust, whole leaf extract of aloe vera, and bracken fern, occupational activities such as printing, carpentry and joinery, low frequency magnetic fields, high frequency fields
Group 3	Not classifiable as to its carcinogenicity to humans	501	Acrylic fibres, caffeine, chloral hydrate, fluorescent lighting, tea, low frequency electric fields, static electric fields, static magnetic fields

Concerns about high frequency fields have largely focussed on whether using a mobile phone increases the risk of brain tumours. After reviewing the available evidence, in 2011 an IARC Working Group classified high frequency fields as "possibly carcinogenic to humans" (Group 2b). This was based primarily on epidemiology studies reporting increased risks for brain or nervous system tumours in the head and neck in the highest users of mobile and cordless phones. However, other expert groups that have reviewed the evidence, including the International Commission for Non-Ionizing Radiation Protection (ICNIRP), the UK independent Advisory Group on Non-ionising Radiation, and the EU Scientific Committee on Emerging and Newly Identified Health Risks disagree with this assessment. These groups point out the inconsistencies between studies, and an absence of an increase in brain cancer incidence rates in time-trend data suggests the evidence is increasingly against the possibility that mobile phone use for periods of up to 15 years can cause brain tumours, although there remains some uncertainty.

Although there has been less research into diseases other than cancer, the available evidence does not suggest that everyday exposures to high frequency electromagnetic fields can cause adverse effects in adults or children.

Electrical hypersensitivity

Some people consider themselves to be especially sensitive to electromagnetic fields, and even everyday exposures can trigger unpleasant subjective symptoms, or more serious conditions, which affect their health and well-being. The symptoms most reported include headaches, fatigue and nausea, but the condition is very heterogeneous, and sufferers differ in terms of the type of symptom they report, and the types of fields that are problematic.

Many laboratory studies have been carried out, particularly using high frequency fields associated with mobile phones, reflecting the importance ascribed to understanding this condition and making appropriate help available to sufferers. Taken together, these studies indicate that short-term exposures do not cause symptoms, nor can the presence of the fields be reliably detected, even by those who consider themselves sensitive. Electrical hypersensitivity has no clear diagnostic criteria and there is no scientific basis to link symptoms to exposure to electromagnetic fields. Such a conclusion does not undermine the importance of the symptoms that are experienced, but it does suggest causes other than those directly related to electromagnetic fields should be considered.

The World Health Organization (WHO) advises that treatment of affected individuals should focus on the health symptoms and the clinical picture, and not on the person's perceived need for reducing or eliminating electromagnetic fields in the workplace or home.

Exposure guidelines

Although low frequency magnetic fields and high frequency fields have both been classified by IARC as possible human carcinogens, the scientific evidence is not strong enough in either case to justify a firm conclusion that such fields cause cancer. The most robust effects relate to acute biological responses from exposure to intense fields. Therefore, guidelines are based on restricting exposure below the thresholds for acute physiological effects.

For both low and high frequency fields, UKHSA recommends the use of exposure guidelines from ICNIRP which has identified the critical biological effects that occur with exposure and has recommended a set of basic restrictions to limit exposure across the frequency range. The restrictions at low frequencies are intended to prevent the stimulation of nerves and contraction of muscles, while at high frequencies they are provided to prevent whole-body heat stress and excessive localised heating of tissues.

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Optical radiation

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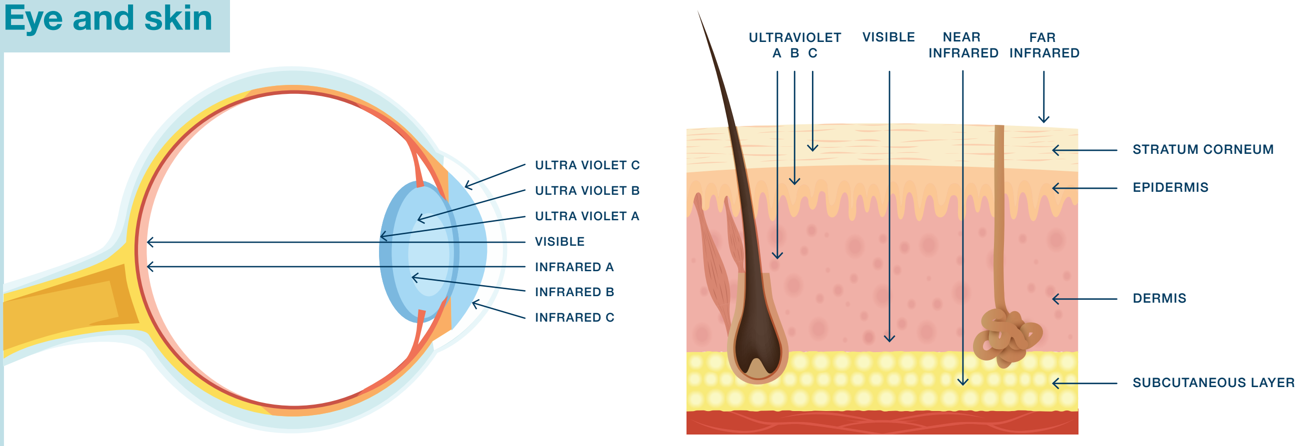
Optical radiation includes the most familiar forms of radiation to which we are all exposed – ultraviolet, visible light and infrared. The constituents of optical radiation are three adjacent regions of the electromagnetic spectrum: the ultraviolet region with wavelengths from 100 to 400 nm, the visible region from 400 to 780 nm, and the infrared region with wavelengths from 780 nm to 1 mm. These boundaries are defined for convenience rather than representing abrupt changes in the visibility of the radiation. Similarly, ultraviolet subregions (UV-A, UV-B, UV-C) and infrared subregions (IR-A, IR-B, IR C) are also defined, which approximately relate to differences in their biological effects. Although ultraviolet wavelengths range from 100 to 400 nm, the sun's ultraviolet radiation reaching the surface of the earth only extends upwards from around 290 nm because the shorter wavelengths are attenuated by the atmosphere.

Optical radiation is mostly absorbed by the skin, but exposures of the eyes and skin are natural triggers for broader systemic effects that encompass the whole body, such as circadian entrainment or synthesis of vitamin D.

Eye and skin



Some, but not all, of the direct effects on the eyes or skin are harmful. Ultraviolet, visible light and infrared are arguably the only types of radiation for which insufficient exposure may be an intrinsic health risk. However, the interactions between exposure and health are complex.

The effects of optical radiation on the eyes and skin may be subdivided into two main categories, photochemical and thermal. Photochemical effects are associated mainly with the ultraviolet and shorter-wavelength visible regions of the spectrum, whereas thermal effects are linked to the infrared and visible regions.

Photochemical effects result from chemical reactions in the body initiated by the absorption of photons and not all of them are harmful: some photochemical reactions are essential for humans, for instance, in vision or the synthesis of vitamin D. For each reaction, there is a photon energy – the threshold – below which it will not occur; this translates into a threshold frequency or upper wavelength limit. An example of photochemical harm is photokeratitis or snow blindness (arc eye).

Harmful photochemical effects on the eyes and skin may be divided into acute and chronic categories. Among the possible acute injuries to the eye are photokeratitis and laser damage, and among the chronic injuries is cataract formation. Erythema or sunburn is the most common acute injury to the skin, whilst skin cancers are the most serious effect of chronic exposure that may also be linked to short bursts of high exposure.

At longer wavelengths, individual photons do not have enough energy to initiate the photochemical reactions; thermal effects, which lead to injury when the molecular bonds of proteins and enzymes are disrupted, become dominant in the infrared region. How much disruption and damage occurs depends on how large the tissue temperature rise is and how long it lasts.

Guidance for safe exposure to optical radiation is provided by International Committee on Non-Ionizing Radiation Protection (ICNIRP). These limits support the assessment of occupational exposure to optical radiation in the UK through the Control of Artificial Optical Radiation At Work Regulations 2010.

Ultraviolet radiation and sun exposure

The sun is a natural source of optical radiation and humankind evolved under sunlight. A balanced approach to sunlight exposure is necessary. Historically, skin cancers, sunburn (erythema) and premature skin aging due to over-exposure to the sun were the main focus for policies and public health interventions. However, insufficient sunlight exposure also has many broad health consequences and may result in a greater burden on health and health services. The UV component in sunlight increases vitamin D status and promotes healthy bones; it may improve cardiovascular and metabolic health and reduce risk of some cancers. Sunlight is essential for supporting the circadian system, which itself includes melatonin regulation, sleep and daytime alertness, insulin metabolism and serotonin regulation for improved mental health. Amongst other factors, insufficient exposure to daylight due to reducing time spent outdoors has been linked to the fast-growing prevalence of myopia or short-sightedness in schoolchildren and young adults which World Health Organisation (WHO) recently recognised as emerging global health risk.

Depending on skin type and colour, sun exposure is followed by an increased production of melanin and increased pigmentation, but a suntan offers minimal protection against further exposure to ultraviolet radiation and is not an indication of good health.

The WHO recognises ultraviolet radiation as carcinogenic to humans. For most people, the sun is the main source of exposure to ultraviolet radiation, but there is also some risk to those who may be exposed to artificial sources at work where the exposures should be minimised by appropriate control measures.

Melanoma is currently the fifth most common cancer in the UK. Malignant melanoma of the skin in the UK has increased from around 6,500 new cases in 2001 to about 16,700 cases per year in 2016-2018. Although five-year survival is 89% for men and 93% for women, there are around 2,300 deaths from malignant melanoma each year in England.

The risks are higher for people with large numbers of naevi (flat mole uniform in colour) or moles, those with several unusual moles, those with fair skin, red or blond hair, those with a tendency to freckle, to sunburn and not to tan and those who are immunocompromised. Both acute sunburn and high intermittent exposures are likely contributors to the risk of malignant melanoma. It's also been suggested that excessive sun exposure in childhood increases the melanoma risk later in life, although the precise nature of this relationship is uncertain.

Non-melanoma skin cancers, basal cell, and squamous cell carcinomas can be related to cumulative exposure and occur most frequently on parts of the body exposed to the sun, such as the ears, face, head and hands, and become more common with increasing age. Between 2006-2008 and 2016-2018, non-melanoma skin cancer incidence rates increased by 42%. In 2016-2018, there were on average nearly 430 new non-melanoma skin cancers in the UK every day, or around 156,000 each year. There were also around 920 deaths each year from non-melanoma skin cancer in the UK, accounting for less than 1% of all cancer deaths, and approximately 0.15% of deaths from all causes in 2018-2019.

Overexposure of the eyes to ultraviolet radiation can cause photokeratitis and photoconjunctivitis, meaning inflammation of the cornea and conjunctiva, respectively. Repeated exposure is considered to be a major cause of non-malignant changes such as pterygium, an overgrowth of the conjunctiva on to the cornea. Epidemiological data suggest that cumulative exposure to ultraviolet radiation may be an important factor in the development of cataracts; however, the degree to which sunlight exposure contributes to cataracts is currently unclear.

For the communication of risks associated with sun exposure and to provide guidance on protection measures, the Global Solar UV Index was developed by the WHO jointly with the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO) and ICNIRP. The UV Index is reported on a scale of 1 (or “Low”) to 11 or higher (or “Extreme”). The higher the index value, the greater the potential for damage to the skin and eyes, and the less time it takes for harm to occur. The UV Index is an important tool to provide an estimate of the maximum sun exposure that should be experienced so that an individual can make an informed decision over their protection. On a clear day the maximum UV Index is at solar noon when the sun is highest in the sky.

In the UK, it is rare that the UV Index exceeds 8 (or “Very high”). However, for destinations where some of the UK population may spend one or more weeks of holiday/recreation per year, the UV Index may exceed 11 (Extreme).

UK Health Security Agency (UKHSA) has an extensive environmental monitoring and research programme on health impacts of optical radiation. Continuously measured data of visible radiation, UV-A and UV Index across the UK are useful for examining the effects of sunlight on health and the influence of climate change on exposures at ground level. The UV Index data are available to the public together with information on when sun protection is needed (**https://uk-air.defra.gov.uk/data/uv-index-graphs**).

Forecast UV levels are also widely available as part of regular weather forecasts. The SunSmart Global UV app (**https://www.sunsmart.com.au/resources/sunsmart-app**) provides five-day UV and weather forecasts at searchable locations. It highlights time periods when sun protection is required helping people around the world know when to use sun protection in an effort to reduce the global burden of skin cancers and UV-related eye damage. Advice includes adequate clothing, hats, use of sunscreens, wearing sunglasses and seeking shade especially for the four-hour period around solar noon.

Visible light from the sun is also important for health, but because of complex interactions with our lifestyles and the human body’s circadian system, those effects are best considered together with artificial lighting in the final section on other sources of optical radiation.

Other sources of optical radiation

Although the sun is the main source of optical radiation, artificial sources are also important. Sources of visible light include artificial lighting, computer screens, mobile phones, lasers and many others. Other products using optical radiation range from germicidal lamps and sunbeds which emit radiation in the ultraviolet region, to halogen cooker hobs and heaters emitting in the infrared region.

The table below gives some examples of applications using sources of optical radiation in different spectral regions. Whilst the responses of the retina and other human tissues are sometimes intended, exposure of the eye and skin to all optical radiation sources should be within safe limits.

Spectral region	Intended for retina	Intended for skin (etc.)	Other sources
UV-C			Germicidal sterilisation Fluorescence (laboratory) Photolithography
UV-B		Sunbeds Phototherapy	Fluorescence (laboratory) Photolithography
UV-A		Sunbeds Phototherapy Lighting (fluorescent)	Fluorescence (laboratory, non-destructive testing) Fluorescence (property marking, forgery / crime detection, entertainment) Photolithography Ink curing Insect traps
Visible	Phototherapy (seasonal, amblyopia) Screens (phones, TV, computers, projectors, entertainment, adverts, transportation, standby indicators etc.)	Sunbeds Phototherapy (skin repair, hyperbilirubinemia) Lighting (transportation, entertainment, area and task lighting)	Photolithography Ink curing Insect traps Photocopiers Lighting (transportation, entertainment, area and task lighting)
IR-A		Surveillance illumination Hair / thread vein removal Heating	Heating Drying Remote communications
IR-B		Heating	Heating Drying Remote communications
IR-C		Heating	Heating Drying

Sunbeds

The International Agency for Research on Cancer (IARC) classified sunbeds as carcinogenic in 2009 and ICNIRP has recommended not to use UV tanning equipment for non-medical purposes. At the same time, despite educational and legislative efforts to reduce sunbed use, according to the Committee on Medical Aspects of Radiation in the Environment (COMARE) 2009 report, around 25% of UK adults were still engaged in indoor tanning. In 2010, the Sunbed (Regulation) Act was introduced in England and Wales that prohibited use, sale or hire of sunbeds to under 18-year-olds. Similar acts were introduced in Scotland in 2008 and in Northern Ireland in 2011.

Lamps for disinfection

Ultraviolet radiation, UV-C and UV-B has been used for disinfection of air, water, surfaces and food for decades. UV-C is recognized by the WHO as a means for tuberculosis infection prevention and control. However, the rapid proliferation of UV-C disinfection technology raised concerns that some devices may pose a risk to human health if used incorrectly and/or produce insufficient inactivation of viruses and other pathogens. WHO and International Commission on Illumination (CIE) warned against the use of UV disinfection lamps on hands or any other area of skin unless clinically justified. Some UV-C lamps may also generate ozone, that when breathed in may irritate the airway, and the radiation emitted can degrade certain materials, such as plastic.

Lasers and intense light sources

People are adapted to the visible radiation from the sun. Eyes are normally protected from acute injury by bright light through involuntary aversion responses like blinking and a compulsion to look away. These actions may often protect the retina from visible and UV-A radiation that would otherwise be focused on it. However, some modern sources can have significant potential for injury, which may happen faster than the reflex time for aversion and this is particularly important for lasers.

Anterior parts of the eye, and specifically the lens, may be damaged by IR-A radiation. Infrared radiation can also produce cataracts by thermal processes and burn the cornea, but such injuries should be prevented by appropriate control measures.

Lasers usually emit optical radiation at one wavelength, or sometimes at a few discrete wavelengths, throughout most of the optical spectrum. Lasers are widely used in industry, research, commerce, medicine, entertainment and in the home.

A laser differs from other sources of optical radiation in that the beam is usually intense and has a small beam area. The degree of harm that the beam causes is related to the irradiance, that is, the power per unit area. For other sources, this quantity decreases steeply with distance, but not necessarily with a laser source. A laser beam in the visible or IR-A region entering the eye may be focused nearly to a point; the result is that the irradiance at the surface of the eye will be increased by a factor of 100,000 or so at the retina.

The smallest value of irradiance likely to cause harm in the visible region, allowing for an aversion response of 0.25 s, corresponds to a laser power of 1 mW. In the visible region, the potential harm is a thermal lesion of the retina, this can be a problem in children due to the accessibility of laser pointers that exceed the safe level.

A classification scheme has been devised by international and national standards for laser products which takes into account not only the laser output, but also human access to the laser emission. Lasers are grouped into eight classes: the higher the class, the greater the potential to cause harm. The risk could be greatly reduced by additional protective measures, including engineering controls such as enclosures. Class 1 lasers are considered safe, including long-term direct intrabeam viewing. Examples of Class 1 lasers include remote controls, mobile phones or devices where the laser beam is enclosed, such as games consoles or digital video disc (DVD) players. At the other end are Class 4 lasers for which direct viewing and skin exposure is hazardous and even diffuse reflections may be hazardous. These lasers also often represent a fire hazard.

UKHSA advice is that consumer products containing Class 1 or Class 2 lasers would be unlikely to cause eye or skin injuries. However, consumer laser products that are child-appealing must not exceed Class 1. Class 1M, Class 2M and Class 3R laser products may be acceptable for use by consumers where the manufacturer has assessed that the risk of eye injury is very low when used as intended for a particular application. Class 3B and Class 4 lasers are not suitable for general use by consumers.

In 2018, the Laser Misuse (Vehicles) Act introduced tough penalties for people who target trains, planes, air traffic facilities, cars or boats with lasers.

Indoor lighting and importance of sunlight

Visible light forms the small central part of the spectrum of electromagnetic radiation. This visible type of radiation is very important because it enables us to see the world; in fact, when it comes to living with radiation, light is the most familiar exposure we all have.

From the very first days and weeks of human life, the timing of light exposure at the eyes is important for health; it has a significant role in the orchestration of the functions of the body throughout each person's life. The light outdoors, that we evolved under, follows a daily rhythm – the light/dark cycles of day and night. The corresponding internal body cycles are collectively known as circadian rhythms: literally this term means changes that repeat approximately every 24 hours. The changing natural light around us was once what determined sleep timing and it still has an important impact on daytime body functions.

Compared to the light received indoors, the light outdoors for most of the year is much brighter during the day and gets darker sooner. With more time spent indoors, our exposure to daytime light has reduced and we often have a shorter period of darkness at night. Through unavoidable social pressures and lack of awareness, our lifestyle decisions can be detrimental to many aspects of our long-term health.This is especially true for shift workers and in places where we spend our weekdays indoors, both notable examples in terms of health consequences. Rotating shifts and night work put workers at increased risks of long-term health impairments including diabetes, heart problems and some cancers. Lack of time outdoors in school children is associated with an increasing risk of becoming short-sighted. Skin exposure to sunlight is also thought to help reduce hypertension or long-term high blood-pressure, which is also a risk for heart disease.

The modern world continues to introduce new changes to our immediate environment. Mobile phones and other electronic displays emit light – causing us to avoid daylight and to be exposed to more light at night – adding to the above problems. LED lighting, if not supplied with an appropriate electronic driver, can produce a light which flashes too rapidly to be seen directly, but that can interfere with visual tasks and produce headaches. Very few people would think that the benefits of artificial light, mobile phones, LEDs, alarm clocks and buildings aren't enough to justify their use. It's just that we should moderate the effects these innovations in our environment have on the evolutionary needs of our body for sufficient regular daily exposure to bright light and plenty of darkness at night.

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Absorbed dose
Quantity of energy imparted by ionising radiation to unit mass of matter such as tissue. 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
Attribute of an amount of a radionuclide. Describes the rate at which transformations occur in it.
Unit becquerel, symbol Bq.
1 Bq = 1 transformation per second.

Advanced Gas Cooled Reactor
A development of the Magnox reactor, using enriched uranium oxide fuel in stainless steel cladding.

AGR
Advanced gas cooled reactor.

ALARP
"As Low As Reasonably Practicable" The principle that radiation exposures must be reduced to the lowest level that can reasonably be achieved.

Alpha radiation
The emission of an alpha particle from an atom.
Alpha Particle = 2 protons and 2 neutrons.

Approved Dosimetry Service (ADS)
A dosimetry service that is approved by the Health and Safety Executive under the Ionising Radiations Regulations 2017 for assessing and/ or recording the doses to classified persons.

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

Atomic bomb
See nuclear weapon.

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.

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

Becquerel
Becquerel, (symbol Bq). Is the SI derived unit of radioactivity. One Bq is defined as the activity of a quantity of radioactive material in which one nucleus decays per second.

Beta radiation
An electron emitted by the nucleus of a radionuclide. The electric charge may be positive, in which case the beta particle is called a positron.

Brachytherapy
Term applied to the use of radiation sources in or on the body for treating certain types of cancer.

Bremsstrahlung
X-rays generated when high energy electrons such as beta particles are slowed down in a medium.

Classified Person
Person who is designated as classified under the Ionising Radiations Regulations, 2017, on the basis of the dose they are likely to receive. Must have their dose properly assessed, e.g., by personal dosimetry, doses recorded in long-term dose records, and have an appropriate health record.

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

Chromosome aberration
Changes in chromosome number (gains and losses) and changes in structure (deletions, inversions, and exchanges).

CMB
Cosmic Microwave Background is the oldest light in the universe, a faint afterglow of the Big Bang.

Collective dose
Frequently used for collective effective dose.

Collective effective dose
The quantity obtained by multiplying the average effective dose by the number of people exposed to a given source of ionising radiation. Unit man sievert, symbol man Sv. Frequently abbreviated to collective dose.

Consumer products
Personal and household goods such as timepieces, smoke alarms, and gas mantles that contain radioactive material for functional reasons.

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Contamination
Loose, unsealed radioactive material.

Controlled area
Area designated in accordance with the Ionising Radiations Regulations, 2017. Must be physically demarcated, have access restricted and be described in the Local Rules. Entry into controlled areas allowed for classified persons, and non-classified persons who are working under written arrangements.

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

Current density
The electric current or flow of electric charge through a conducting medium, such as tissue, per unit cross-sectional area. Unit ampere per square metre, symbol A m^2.

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

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

Decommissioning
The process of closing down a nuclear reactor, removing the spent fuel, dismantling some of the other components, and preparing them for disposal. Term may also be applied to other major nuclear facilities.

Deterministic Effects
See Tissue Reactions

Diagnostic radiology
Term usually applied to the use of X-rays in medicine for identifying disease or injury in patients.

Dicentric
Chromosome with two centromeres; an unstable chromosomal aberration caused chiefly by ionising radiation and used for biological dosimetry.

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

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

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

Dosimetry Service
A service that systematically measures and/or records workers' radiation doses, usually by means of personal dosemeters.

Effective dose
The quantity obtained by multiplying the equivalent dose to various tissues and organs by a weighting factor appropriate to each to represent their sensitivity to radiation and summing the products. Unit sievert, symbol Sv. Frequently abbreviated to dose.

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

Electric field strength
A measure of the intensity of an electric field. Unit volt per metre, symbol V m^{-1}.

Electromagnetic field
The region in which electromagnetic radiation from a source exerts an influence on another object with or without there being contact between them.

Electromagnetic radiation
Electromagnetic radiation is a form of radiation with both electric and magnetic field components, which can be described as waves propagating at the speed of light. Under some circumstances electromagnetic radiation can be considered to exist as particles called photons. Examples are gamma rays, X-rays, ultraviolet radiation, light, infrared radiation and radio frequency radiation.

Electromagnetic spectrum
The electromagnetic spectrum is the range of all possible frequencies of electromagnetic radiation. The spectrum ranges from short wavelengths such as x-rays, through visible radiation to longer wavelength radiations of microwaves, television and radio waves.

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Electromagnetic wave
See electromagnetic radiation.

Electron
An elementary particle with low mass, 1/1,836 that of a proton, and unit negative electric charge. Positively charged electrons, called positrons, also exist. See also beta particle.

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 x 10^{-19} joule approximately.

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

Emergency reference level
One of a dual set of doses likely to be averted by the introduction of countermeasures to protect the public from ionising radiation after a nuclear or other serious accident.

EMF
Electromagnetic field. Not to be confused with the initials for electromotive force.

Engineering Control
Safety measures of a deliberate engineering design which should be used as the fundamental method of reducing exposure to radiation. A physical means of preventing access to radiation.

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

Entrainment
The process in which the human body synchronises its internal timing with the external world. The primary environmental information on time-of-day is provided by the natural pattern of light and dark as the sun changes position due to the earth's rotation.

Epidemiology
Studies of the distribution, causes and prevention of disease and health risks in a population.

Epigenetic
The study of changes in gene expression that occur without alterations to the DNA sequence. How environmental and lifestyle factors can influence how genes are turned on or off, ultimately affecting an individual's phenotype.

Equivalent dose
The quantity obtained by multiplying the absorbed dose by a factor to allow for the different effectiveness of the various ionising radiations in causing harm to tissue. Unit sievert, symbol Sv.

ERL
See emergency reference level of dose.

Erythema
Reddening of the skin caused by dilation of blood vessels.

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

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

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

Fast reactors
See nuclear reactor.

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

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

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

Frequency
The number of complete cycles of an electromagnetic wave in a second. Unit hertz, symbol Hz.
1 Hz = 1 cycle per second.

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

Glossary

Gamma-H2AX
A marker of DNA damage response within cells, that is used for biological dosimetry.

Gamma ray
A discrete quantity of electromagnetic energy without mass or charge. Emitted by a radionuclide. Cf X-ray.

Gastrointestinal system
The stomach and intestines.

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

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

Gray
See absorbed dose.

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

Health and Safety Executive (HSE)
The (HSE) is a non-departmental public body in the United Kingdom responsible for the encouragement, regulation and enforcement of workplace health, safety and welfare, and for research into occupational risks.

Hematopoietic system
The process of blood cell production.

Heritable
Characteristic or trait that could be passed from a parent to offspring through genes.

IAEA
International Atomic Energy Agency. International organization that seeks to promote the peaceful use of nuclear energy, and to inhibit its use for any military purpose, including nuclear weapons.

ICNIRP
See International Commission on Non-Ionising Radiation Protection.

ICRP
International Commission on Radiological Protection. International body of experts which makes recommendations on radiation protection standards.

Infrared radiation
Electromagnetic radiation capable of producing the sensation of heat and found between light and radiofrequency radiations in the electromagnetic spectrum. Has subregions IR-A, IR-B, IR-C.

International Commission on Non-Ionising Radiation Protection (ICNIRP)
A body of independent scientific experts that aims to disseminate information and advice on the potential health hazards of exposure to non-ionizing radiation.

Ion
Electrically charged atom or grouping of atoms.

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

Ionising radiation
Radiation that produces ionisation in matter. Examples are alpha particles, gamma rays, X-rays and neutrons. When these radiations pass through the tissues of the body, they have sufficient energy to damage DNA.

International Commission on Illumination (CIE)
Devoted to worldwide cooperation and the exchange of information on all matters relating to the science and art of light and lighting, colour and vision, photobiology and image technology (French: Commission Internationale d'Eclairage)

IR
See Infrared radiation.

Irradiance
The power per unit area of optical radiation.
Unit watt per square metre, symbol W/m^2.

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

Laser
An acronym which describes a device which produces monochromatic light of high coherence.
Light Amplification by Stimulated Emission of Radiation.

Laser Classification
A scheme by which lasers are classified according to their laser radiation hazard. Defined in BS EN 60825-1.

Glossary

Laser Protection Supervisor
A person who provides local supervision of laser use within the healthcare and aesthetic environments. Fulfils some of the roles of the Laser Safety Officer.

Laser Safety Officer
A person who is knowledgeable in the evaluation and control of laser hazards and has responsibility for the oversight of such.

Light
Electromagnetic radiation capable of producing the sensation of vision and found between ultraviolet and infrared radiations in the electromagnetic spectrum.

Local Rules
Set of working procedures written in accordance with the Ionising Radiations Regulations, 2017, to enable work with ionising radiations to proceed safely, and in accordance with the Health and Safety at Work Act, 1974.

LoD
Limit of Detection (normally refers to sensitivity of analytical measurements).

LSA scale
Low Specific Activity scale.

Magnetic flux density
A measure of the magnetic effect induced in a medium by an external field. Unit tesla, symbol T.

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

Man sievert
See collective effective dose**.**

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

Maximum permissible exposure (MPE)
The irradiance likely to cause detectable damage to the human eye or skin from exposure to optical radiation. Unit watt per square metre, symbol W m^2.

Melanoma
Type or skin cancer that develops in the skin's melanin-producing cells.

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

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

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

Neutron
An elementary particle with approximately 1 atomic mass units and no electrical charge.

Non-ionising radiation
Radiation that does not posses sufficient energy to cause ionisation in biological materials, including DNA. Examples are ultraviolet radiation, light, infrared radiation and radio frequency radiation.

NORM
Naturally Occurring Radioactive Material

Nuclear fuel cycle
The stages in which the fuel for nuclear reactors is first prepared, then used, and later reprocessed for possible use again. Waste management is also considered part of the cycle.

Nuclear medicine
Term usually applied to the use of radionuclides for diagnosing or treating disease in patients.

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

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

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

Glossary

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

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

Nucleus of a cell
The controlling centre of the basic unit of tissue. Contains the important material DNA.

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

Optically stimulated luminescence
A physical retrospective method of dosimetry being developed for routine or emergency radiation dosimetry of individuals.

Optical radiation
Electromagnetic radiation comprising ultraviolet, visible and infrared radiations.

Order of magnitude
Quantity given to the nearest power of ten. A factor of ten or so.

Overexposure
A radiation exposure to a member of the public or a radiation worker which is higher than the individual should normally receive on a day to day basis.

Ozone
A form of oxygen gas which occurs naturally in very small quantities in air. Most of the ozone is in the stratosphere where it forms the ozone layer.

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

Photokeratitis
Painful eye condition caused by ultraviolet radiation.

Photon
A quantum of electromagnetic radiation.

Pneumonitis
Swelling and irritation, also called inflammation, of lung tissue.

Poly-allyl-diglycol-carbonate (PADC)
A type of plastic that can be used as a radiation dosemeter for radon and neutron radiations.

Positron
See beta particle.

Power density
The power per unit cross sectional area in an electromagnetic field. Unit watt per square metre, symbol W/m^2.

Pressurised water reactor
A thermal reactor using water as both a moderator and coolant. Uses enriched uranium oxide fuel.

Probability
The mathematical chance that a given event will occur.

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

PWR
Pressurised water reactor.

Radiation
The process of emitting energy as waves or particles. The energy thus radiated. Frequently used for ionising radiation in the text except when it is necessary to avoid confusion with non-ionising radiation.

Radiation Risk Assessment
Defined in the Ionising Radiations Regulations 2017, an assessment made by the employer to determine whether he should take any further steps to restrict radiation exposures.

Radioactive
Possessing the property of radioactivity.

Radioactive waste
Useless material containing radionuclides. Frequently categorised in the nuclear power industry according to activity and other criteria given in Chapter 10, as low level, intermediate level, and high level waste.

Radioactivity
The property of radionuclides of spontaneously emitting ionising radiation.

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

Glossary

Radiofrequency radiation
Electromagnetic radiation used for telecommunications and found in the electromagnetic spectrum at longer wavelengths than infrared radiation.

RF
See radio frequency radiation.

Radiological protection
The science and practice of limiting the harm to human beings from radiation.

Radiation Protection Adviser
Person deemed to be competent to give radiation protection advice, under one of the schemes recognised by HSE.

Radiation Protection Adviser Body
A body recognised by HSE as having the requisite collective experience and quality assurance systems to provide sound radiation protection advice.

Radionuclide
An unstable nuclide that emits ionising radiation.

Radiotherapy
Term applied to the use of radiation beams for treating disease, usually cancers, in patients.

Radon
Radon is colourless, odourless radioactive gas. It is formed by the radioactive decay of the small amounts of uranium that occur naturally in all rocks and soils.

Radon Affected Area
A Radon Affected Area is classed as an area where at least 1% of current or future homes are expected to be at or above the Radon Action Level of 200 Bq m^{-3}.

Reasonably Foreseeable Event
The occurrence of an event which under given circumstances can be predicted fairly accurately, and the occurrence probability or frequency of which is not low or very low.

Reference accident
One of a range of accidents at a nuclear reactor or other nuclear installation that can reasonably be foreseen in safety analysis as giving rise to the most significant release of radionuclides from the site.

REPPIR
Radiation (Emergency Preparedness and Public Information) Regulations 2019.

Risk
The probability of injury, harm or damage.

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

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

Sievert
See effective dose.

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

Specific energy absorption rate
The rate at which energy is absorbed by unit mass of tissue in an electromagnetic field.
Unit watt per kilogram, symbol W kg^{-1}.

Stochastic Effect
Health effect whose probability of occurrence depends on the dose received. Occurrence is usually many years after the exposure, and there is believed to be no threshold level of dose below which no effect will occur.

SAR
See specific energy absorption rate.

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

Thermal reactor
See nuclear reactor.

Thermoluminescent material
Material which, having been irradiated, releases light in proportion to the ionising radiation absorbed when it is subsequently heated.

Glossary

Tissue Reaction
Radiation can cause various reactions in tissues, both early and late, depending on the dose and type of radiation exposure. These reactions are classified as deterministic or stochastic. Deterministic effects, also known as tissue reactions, occur when the number of damaged cells reaches a threshold, leading to observable tissue injury. Stochastic effects, on the other hand, are probabilistic and occur at random, with the risk increasing with dose, such as cancer.

Translocation
Transfer of DNA material from one chromosome to another; a chromosomal aberration formed in response to ionising radiation and several other factors, which is detected by FISH and used for biological dosimetry.

Ultraviolet radiation
Electromagnetic radiation found between X-rays and light in the electromagnetic spectrum. Has subregions UV-A, UV-B, UV-C.

UVR
See ultraviolet radiation.

Visible radiation
See light.

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

Wavelength
The distance between successive crests of an electromagnetic wave passing through a given material. Unit metre, symbol m.

X-ray
A discrete quantity of electromagnetic energy without mass or charge. Emitted by an X-ray machine. Cf gamma ray.