# Introduction to Radiation

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# 1 ATOMS, ISOTOPES AND RADIOACTIVE DECAY

All matter is made of atoms. Atoms are made up of protons and neutrons constituting a nucleus, and electrons orbiting around the nucleus. In a normal (un-ionised) atom the number of protons equals the number of electrons, and this number determines the chemical nature of that element (see Figure 1)

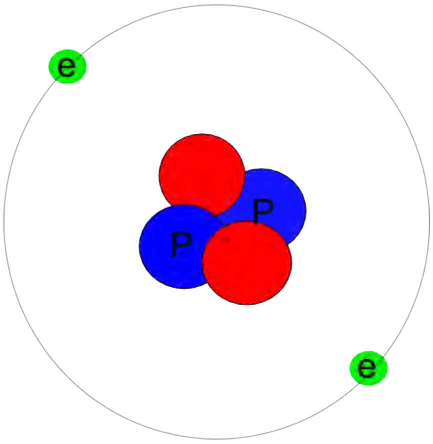


**Figure 1 A Helium atom showing nucleus of 2 protons, 2 neutrons and electrons**

Atoms of the same chemical type can have different numbers of neutrons in their nuclei. These are called isotopes of the element. Some isotopes are unstable, and will spontaneously emit radiation in the form of subatomic particles or electromagnetic energy, and form a lighter nucleus. This process is called radioactivity, and the atoms that undergo it are called radioactive. There are radioactive forms (called radioisotopes or radionuclides) of all elements. For example, lead has 27 different isotopes, 23 of which are radioactive, and four are stable (that is non-radioactive). Most radioisotopes are produced artificially, usually in nuclear reactors, but there are also many naturally occurring radioisotopes. All isotopes of elements heavier than bismuth are radioactive.

Isotopes are written with their chemical symbol and the total number of protons and neutrons in their nucleus (the mass number). Thus the most common isotope of uranium, with 92 protons and 146 neutrons, can be written as $^{238}U$ or uranium-238.

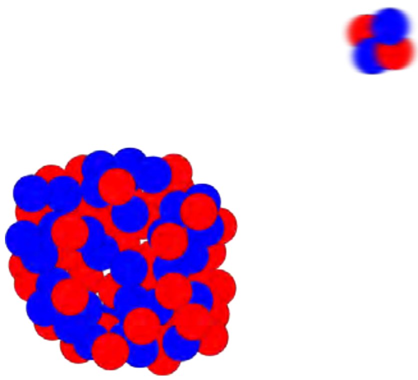

**Figure 2 Atom emitting alpha particle**

Different radioactive isotopes emit radiation at different rates. The breakdown (or decay) of radioactive atoms reduces the number remaining, so that the amount of radiation emitted continually reduces. It is convenient to describe the rate of reduction by the 'half-life'. This is the time taken for one half of the radioactive atoms to decay away, and thus also the time for the rate of radiation emission to decrease to one half of its original value. Each radioactive atom has its own half-life, which is fixed, and cannot be changed. Half lives of naturally occurring radioisotopes range from fractions of a second to billions of years. The half-life of $^{238}U$ is 4.5 billion years, one of the longest known.

The decay of a radioisotope with a half-life of 20 days is illustrated in Figure 3. An initial 1,000 atoms has been reduced to 500 atoms after 20 days, to 250 atoms after 40 days, and to 125 atoms after 60 days.

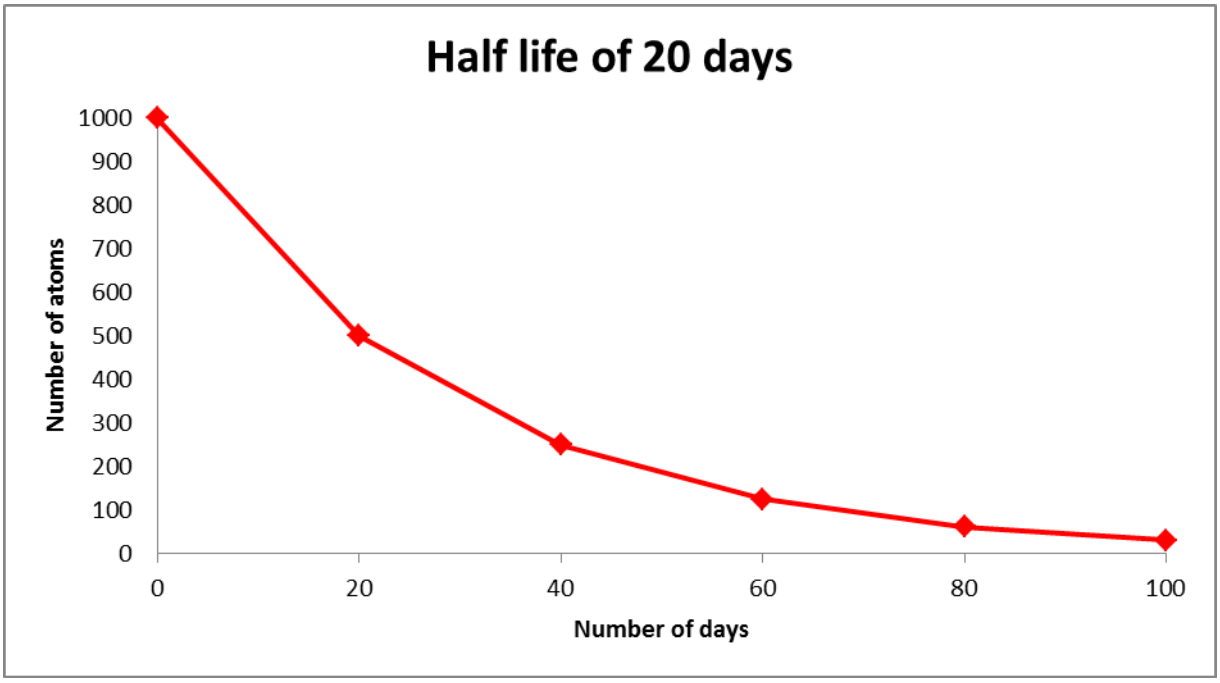


**Figure 3 Radioactive decay**

When a radioactive atom decays, the new atom formed may itself be radioactive, which might in turn decay to another radioactive atom. For example, in Figure 2 above, the $^{234}Th$ formed from the decay of $^{238}U$ is also radioactive, and subsequently decays. Such chains of radioactive decay are called 'decay series' or 'decay chains', (see Figure 4.).

## 1.1 Uranium

Uranium is a naturally occurring heavy metal. It is widespread in the earth's crust, and present in almost all normal soils with an average concentration of about three parts per million (ppm). The best known property of uranium is its radioactivity.

Like all elements, there are different isotopes of uranium that have different numbers of neutrons in their nucleus. The most common is uranium-238 ($^{238}U$) with 92 protons and 146 neutrons, and it makes up more than 99% of natural uranium (by weight). $^{235}U$, with 92 protons and 143 neutrons, is the next most abundant, with 0.07% by weight.

Uranium mined in Australia is used only in nuclear power reactors (see Section 8). The rare $^{235}U$ isotope is essential for the operation of reactors, and before uranium can be used for that purpose the concentration of $^{235}U$ must usually be increased from 0.07% to about 3%, by the process of enrichment.

The isotopes of the elements formed by the decay of $^{238}U$ are themselves radioactive, and so form a decay series, ending with the stable (non-radioactive) lead-206. There are 13 radioactive decay products in the series, which is shown in Figure 4. Uranium ore contains all of these radioisotopes and they all have different properties. The radiation emitted by all of these needs to be included when considering the radiation exposures that may occur in uranium mining and processing. Uranium-235 and its decay products are also present in the ore, but its relative abundance is so low that they make only a very small contribution to the overall radiation levels.

| Element | Radiation emitted | Half-life |
|---|---|---|
| **$U^{238}$** | $\alpha$ | **4.5 Billion yrs** |
| **$Th^{234}$** | $\beta$ | **24 days** |
| **$Pa^{234m}$** | $\beta$ | **1.2 mins** |
| **$U^{234}$** | $\alpha$ | **245000 yrs** |
| **$Th^{230}$** | $\alpha$ | **75 000 yrs** |
| **$Ra^{226}$** | $\alpha$ | **1600 yrs** |
| **$Rn^{222}$** | $\alpha$ | **3.8 days** |
| **$Po^{218}$** | $\alpha$ | **3 mins** |
| **$Pb^{214}$** | $\alpha$ | **27 mins** |
| **$Bi^{214}$** | $\beta$ | **20 mins** |
| **$Po^{214}$** | $\alpha$ | **160 $\mu$secs** |
| **$Pb^{210}$** | $\beta$ | **22 yrs** |
| **$Bi^{210}$** | $\beta$ | **5 days** |
| **$Po^{210}$** | $\alpha$ | **138 days** |
| **$Pb^{206}$** | **stable** | **stable** |

**Figure 4 Uranium decay chain**

Uranium is extracted from ore by physical and chemical processes. These processes remove only the uranium isotopes, leaving all other radioisotopes in the waste (tailings). As some of these radioisotopes have very long half-lives (for example $^{230}$Th 77,000 years) tailings will remain radioactive for hundreds of thousands of years.

# 2 IONISING RADIATION

The type of radiation emitted by radioactive material, including uranium and its decay products, is called ionising radiation because it is able to ionise material through which it passes. That is; it will produce charged particles called ions as it passes through matter. Ionising radiation is distinguished from non-ionising radiation, which does not have sufficient energy to produce such ions. Examples of non-ionising radiation include microwaves, ultra-violet radiation, infra-red radiation, lasers and radio waves, including those from mobile phones. Non-ionising radiation is different from ionising radiation, arises from different sources, and any health effects it may produce arise from entirely different mechanisms. This section is concerned only with ionising radiation, and wherever the term radiation is used, it means ionising radiation.

## 2.1 Types of radiation

There are three major types of ionsing radiation emitted by naturally occurring radioisotopes: alpha, beta and gamma radiation (see Figure 5, and Figure 6).

### 2.1.1 Alpha

Alpha radiation consists of streams of alpha particles, which consist of two protons and two neutrons bound together. Alpha particles are relatively heavy and slow moving. Their range in air is only a few centimetres and they are not able to penetrate matter to any significant extent. For example, they cannot penetrate a sheet of paper or, importantly, the outer layer of the skin. Inside their range they ionise very heavily, (i.e. they produce a dense trail of ionisation) when they pass through matter. To be a health hazard, alpha emitters need to be inside the human body to irradiate sensitive cells.

### 2.1.2 Beta

Beta radiation consists of high-energy electrons. They have moderate penetration, typically (for $^{238}$U decay products) about one metre in air and a few millimetres in water or tissue. Because of their relatively short range, most of the ionisation from external beta radiation occurs in the skin cells. However, irradiation of internal cells can occur if the source is within the body.

### 2.1.3 Gamma

Gamma radiation is not a particle but an electromagnetic wave similar to light and x-rays but of much higher energy. Gamma rays associated with uranium mining are generally able to penetrate up to several centimetres of metal or 10 cm of concrete, and can pass through the human body. Gamma radiation has a much lower ionizing ability when compared to that of an alpha particle.

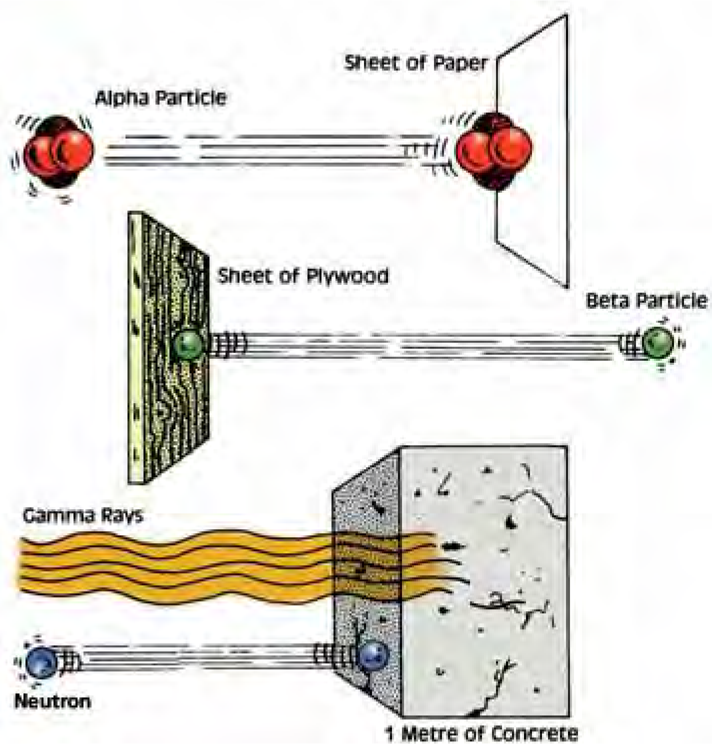


**Figure 5 Penetrating power of radiation**

## 2.2 Radiation exposure pathways

Radiation exposure can only occur when there is a pathway or exposure route between the radioactive material and the person exposed. There are two general types of exposure, external and internal.

### 2.2.1 External radiation

External exposure occurs when the source of radiation is outside the body. Examples include exposure received during a medical x-ray examination, or gamma radiation received by standing near radioactive ore. In uranium mining and processing, gamma radiation is the dominant form of external radiation. Because alpha radiation cannot penetrate the skin, it is not a source of external radiation.

### 2.2.2 Internal radiation

Internal exposure arises from radioactive material inside the body. The most common ways that radioactive material enters the body are by inhalation or ingestion (swallowing), with less common ways of entry through wounds and skin absorption. Once inside the body (e.g. the lung or the gut), the radioactive material may be absorbed into the bloodstream and transported around the body. Some radionuclides are quickly excreted, but others may be absorbed by various organs and retained for long periods, so that internal radiation exposure can continue long after the initial intake. In contrast, external exposure ceases as soon as the source is removed.

Some of the pathways between the source and the person exposed may be complex. For example, radioactive dust may be deposited on grasses or plants that are then eaten by cows, the radionuclides may be excreted in milk, which may subsequently be consumed by people.

# 3 RADIATION MEASUREMENT AND UNITS

Two types of radiation quantities are used widely in radiation protection. One refers to the amount of "radioactive material" in a sample . The other refers to the amount of "radiation" received at a point and is measured as a dose. They are quite different and there is no simple relationship between them.

## 3.1 Activity

Activity is the measure of the amount of radioactive material. Its unit is the *becquerel* (Bq), which is defined as the quantityof radioactive material that produces one radioactive decay per second. It may be applied to either a single radionuclide, or to a mixture. The activity concentration is the amount of radioactivity in a unit mass (or volume) of material and is measured in becquerels per gram (Bq/g) (or Bq/L).

As an example, the total activity (all $^{238}U$ series radionuclides) in 1 g of typical Kintyre ore is about 800 Bq, of which 60 Bq is from $^{238}U$. In comparison, the activity concentration of $^{238}U$ in normal soil is about 0.03 Bq/g.

## 3.2 Dose

Dose refers to the amount of radiation received at a point or to a person. The two main measures of radiation dose are called absorbed dose and effective dose.

Absorbed dose refers to the physical amount of ionisation produced in matter by the radiation, as might be directly measured by an instrument such as a Geiger counter. The unit of absorbed dose is the *gray* (Gy). Absorbed dose may refer to the dose to an object, a person, or parts of a person (organs or tissues).

Effective dose includes factors that take account of the biological effects of radiation on a person. These factors include the type of radiation (alpha, beta or gamma) and the different sensitivities of organs or tissues to radiation. The unit of "effective dose" is the *sievert* (Sv). For "whole body" gamma radiation the absorbed dose (in Gy) equals the effective dose (in Sv). The sievert is quite a large unit of measure, and doses are usually expressed in millisieverts (mSv - thousandths of a sievert).

The effective dose (mSv) gives a measure of the effect (or "detriment") of radiation on the human body, One mSv has the same detriment no matter if it is for example 1 mSv of gamma radiation to the whole body, or 1 mSv to the lung only, or any combination.. The limits on dose (to people), that are most relevant in uranium mining are expressed in terms of effective dose, and where the term “dose” is used alone, “effective dose” is usually meant. Dose can refer to either internal or external exposure, or a combination of both.

As an example, typical natural background radiation in Australia results in an annual (effective) dose of about two millisieverts (2 mSv).

# 4 NATURAL BACKGROUND RADIATION

Radiation is very common in nature and everyone is exposed to natural radiation throughout their life (see Figure 7). This radiation comes from the rocks and, soil of the earth, the air we breathe, water and food we consume, and from space. Exposure to this radiation is from both external and internal sources.

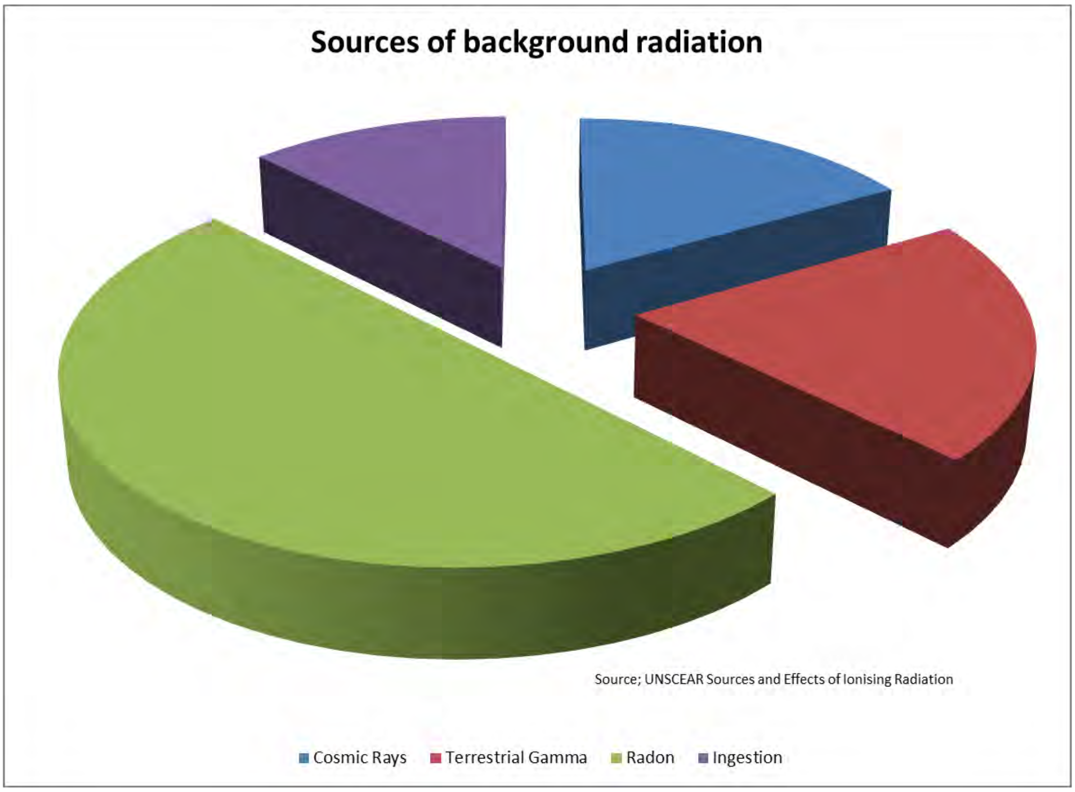


**Figure 6 Sources of natural background radiation**

## 4.1 External radiation pathways

The two main sources of external background radiation are cosmic rays and gamma radiation from soil.

Cosmic radiation is a form of ionising radiation that comes from outer space. The atmosphere provides shielding against cosmic rays, and consequently cosmic ray exposure is higher at higher altitudes. Aircrew who regularly fly at high altitudes can receive significant radiation doses from cosmic radiation.

Almost all normal soils naturally contain uranium, thorium and potassium. The average uranium and thorium soil concentrations are approximately 3 ppm and 10 ppm respectively. Both of these have gamma-emitting radionuclides in their decay series, and so contribute to external radiation levels. In addition, one of the isotopes of potassium, K-40, is radioactive, emitting both gamma and beta radiation, and this also contributes to the external dose rate.

In several parts of the world, soils naturally contain much higher concentrations of radionuclides. This is particularly so of thorium, and some parts of Brazil and southern India have quite high natural external dose rates for this reason (UNSCEAR 2000)

## 4.2 Internal radiation pathways

Naturally occurring radionuclides can enter the human body through inhalation and ingestion.

The largest internal natural background dose generally comes from the inhalation of radon decay products. Radon is a member of the uranium decay series, being formed directly from the decay of radium in the soil. Being a gas, the radon can diffuse from the soil and enter the atmosphere, but normal atmospheric mixing keeps concentrations quite low. However if radon diffuses into an enclosed space, such as a house, from the soil below it, it may be trapped and build up to high levels. This is particularly so if there are cracks in floors or foundations, allowing easy access for the radon, and where houses are tightly sealed against the cold, thus retaining the radon.

The dose from inhaling radon itself is quite small, but radon decays to radon decay products (formerly called radon daughters) and if these are inhaled they may lodge in the lung, resulting in quite significant doses. Some houses in North America and Northern Europe have been found with radon decay product concentrations that are higher than would be permitted in modern uranium mines (International Commission on Radiological Protection 1994).

The other main pathway is ingestion, or swallowing of radioactive material that is present in food or drink. Plants will take up some radionuclides from the soil in which they grow. These radionuclides may then enter our food chain either directly, by eating the plants, or indirectly, by eating animals that have grazed on them. Similarly almost all surface and ground waters contain natural radionuclides derived from the surrounding soil. Consuming such food or water will result in an internal radiation dose. The largest contribution to internal dose from ingestion is usually from potassium-40 ($^{40}K$). Potassium is an essential part of the body, and the body will extract its requirements from food. As the body cannot distinguish between the radioactive potassium ($^{40}K$) and non-radioactive potassium isotopes, the body will always contain some $^{40}K$. Other natural radionuclides, including uranium and thorium decay series isotopes will also be consumed with food and water and hence will be present in the body, and irradiate it.

The world average natural background dose from all sources is about 2.4 mSv per year (UNSCEAR 2000). Doses in Australia are less (2 mSv/y), largely because the dose from radon decay products is much lower because the climate and open-air lifestyle leads to better ventilation of houses, reducing the build-up of radon concentrations (Langroo 1991).

The average contribution of the different components is shown in Figure 7 (from (United Nations Scientific Committee on the Effects of Atomic Radiation 2000)). As noted above, natural background can vary considerably in different places in the world. While the world average is 2.4mSv/y, the typical range is quoted as 1-10mSv/y (United Nations Scientific Committee on the Effects of Atomic Radiation 2000).

### 4.3 Medical radiation

Another major source of radiation exposure to the general public is medical exposure. Radiation is used extensively for diagnosis and treatment of disease. The average annual radiation dose from diagnostic medical procedures in developed countries is approximately 1.2 mSv/y (UNSCEAR 2000).

## 5 HEALTH EFFECTS OF RADIATION

The health effects of radiation exposure (both internal and external) are well known. At high doses (several sieverts) significant numbers of cells in sensitive organs or tissues may be killed, leading to the breakdown of the organ or tissue, and possibly resulting in death. Other high dose effects include a reduction in the immune system and temporary sterility (in males). The doses required for these effects are similar to those received by fire fighters who attended the Chernobyl incident. Doses received during uranium mining and milling can not approach these levels (and are generally more than 100 times less) so these high dose effects will not occur.

At lower doses health effects may arise from cells that are damaged by the radiation but not killed. There are cellular mechanisms that are capable of repairing this damage and there are other mechanisms that eliminate such damaged cells, but it is possible that damaged cells may develop the ability to proliferate without being subject to the normal controls on cell reproduction. This may be the initiating event for development of a cancer. Development of cancer is a multi-stage process, and some of the stages may take years to complete, so a cancer would not be expected to appear for some years after initiation. An individual cell that is damaged in this way has an extremely small chance that it may pass through all the different stages, and eventually develop into a cancer. Increasing the exposure and thus increasing the number of damaged cells leads to an increase in the chance of developing a cancer.

Alternatively, the damaged cells may be part of the reproductive line (egg cells, sperm or sperm generating cells. Again repair mechanisms exist and the damaged cells may not survive, however if they do, there is the chance that such damage may be carried over to the next generation and appear as hereditary disorders in the offspring.

A number of studies have found an increased risk of cancer among people exposed to moderate doses of radiation. The best known are the studies of the Japanese atomic bomb survivors, who have now been followed for 50 years. These studies have been able to determine the effects of a large range of doses on a large population over a long period (Preston 2007). Other studies have included an international study of radiation workers who were generally exposed to low levels of radiation over a long period (Cardis et al 2005).

The studies of miners exposed to radon decay products are of particular relevance to uranium mining. Early mines were often poorly ventilated, and as a result miners were often exposed to very high levels of radon decay products. Several groups have been studied, including both uranium and non-uranium miners (Lubin et al 1995).

Both groups of studies show that there is a risk of increased cancer among those exposed to elevated levels of radiation, and that this risk increases as the radiation dose increases. The overall increase is approximately linear, that is doubling the dose doubles the risk (Brenner and al 2003).

In general none of the studies has been able to measure increases in cancer risk from exposures to low doses of radiation (below about 50mSv). In this range, which includes the annual doses expected to be received by workers at Kintyre, any increase in cancer risk has been too low to be detectable. However, it is still assumed that there is an increased risk, and the risk factors derived at higher doses are assumed to apply in this range.

There have also been studies looking for an increased rate of hereditary disorders in the offspring of parents exposed to radiation. No increased risk of hereditary disorders has been found in human studies, including those of the Japanese atomic bomb survivors. However increases have been found in animal studies (UNSCEAR 2000), and it is assumed that there are risks to humans of a similar magnitude to those found in animals. These risks are less than 5% of the cancer risk.

The risks derived from these studies are used in the setting of radiation standards for exposure of workers and the general public.

In standard setting, the International Commission on Radiological Protection (ICRP) states ‘it must be presumed that even small radiation doses may produce some deleterious effects’ (International Commission on Radiological Protection 1990). This is not to be confused with the often stated ‘there is no safe level of radiation’, which equates ‘safety’ with ‘no risk at all’. This is not the normal use of the word ‘safe’. For example, people recognise that there is some risk involved in commercial air travel, but still regard it as ‘safe’, because they consider that the level of risk is so low that it is acceptable. Similarly for exposure to radiation: it can be considered ‘safe’ if the resulting risks are low enough to be considered acceptable.

# 6 RADIATION STANDARDS AND LIMITS

## 6.1 Sources of standards

The premier international body for radiation protection is the International Commission on Radiological Protection (ICRP). The limits recommended by the ICRP have generally been adopted around the world. The recommended dose limits have changed over time as more information on the health effects of radiation has become available. However there has only been one major change to the recommended limits to workers in the past 50 years, in 1990 (International Commission on Radiological Protection 1990).

The ICRP’s most recent recommendations on standards and dose limits were published in 2008 (International Commission on Radiological Protection 2008). These recommendations update the previous recommendations published in 1990 (International Commission on Radiological Protection 1990), and maintain the three key elements of the “system of dose limitation” (see below) and the basic numerical dose limits.

The ICRP recommendations are not of themselves legally binding in Australia, but the Commonwealth, states and territories have adopted them into their own legislation. Currently it is the 1990 recommendations (ICRP 60) that are generally in place, but it is expected that the latest recommendations will be adopted in the near future.

### 6.1.1 ICRP recommendations

The ICRP recommends a “system of dose limitation” of which dose limits are only one part. The three key elements of this system are (International Commission on Radiological Protection 1990):

Justification – a practice involving exposure to radiation should only be adopted if the benefits of the practice outweigh the risks associated with the radiation exposure.

Optimisation – radiation doses received should be As Low As Reasonably Achievable, economic and social factors being taken into account (the ALARA principle).

Limitation – individuals should not receive radiation doses greater than the recommended limits.

#### 6.1.1.1 Justification

Justification is a necessary prerequisite for any decision regarding radiation exposure. Actions that alter the radiation exposure situation should do more good than harm. This means that by introducing a new radiation source, or a new practice involving radiation, one should achieve an overall societal or individual benefit that is higher than the detriment that the radiation exposure may cause. The benefits and detriments should be considered broadly, and often the radiation detriment will only be a small part of the total.

#### 6.1.1.2 Optimisation (the ALARA principle)

The ICRP sees the ALARA principle as a central element in radiation protection and, in the hierarchy of radiation protection measures, it ranks ahead of the application of 'dose limits'. The principle requires that every practice involving radiation exposure should be examined, along with the potential protection measures. Protection measures that produce a net benefit (i.e. the benefit from reducing the exposure is greater than the cost of implementing that measure) should be implemented. This procedure should be continued until the costs of further reduction measures outweigh the potential benefits of the reduced exposure and at that stage, radiation protection can be considered to be optimised. The procedure should be implemented at the design stage, and carried on into operation of the practice.

Optimisation may include the use of "dose constraints", which are upper limits on the predicted doses used in the optimisation process. These are predetermined levels of dose for particular situations, generally imposed by regulatory authorities, above which it is unlikely that radiation protection is optimised. In the case of members of the public, dose constraints recognise the possibility that individuals may be exposed to radiation originating from more than one operation. In the case of uranium mines in remote locations this is unlikely to be the case. Dose constraints are not of themselves universal prescriptive regulatory limits.

The ALARA principle applies at all levels of exposure: if there are practical, cost-effective measures that can be applied to reduce radiation exposure, then they should be applied even if exposures are already well below the recommended dose limits. Indeed, the ICRP believes that proper application of this principle will generally result in doses that are well below the individual limits, and so those limits will only rarely need to be applied.

#### 6.1.1.3 Limitation

The limits recommended by the ICRP which are of most relevance in the mining and mineral processing industries are limits are to the effective dose:

| | |
|---|---|
| Annual limit to a worker | 20mSv |
| Annual limit to a member of the public | 1mSv |

The doses received may be averaged over five years, but the dose to a worker in any one year must not exceed 50 mSv. Annual doses to members of the public should only be allowed to exceed 1 mSv in "special circumstances". There are other subsidiary limits (for doses to the lens of the eye, skin and hands or feet), but in uranium mining and processing these could only be exceeded in very unusual circumstances, which would almost certainly involve effective doses exceeding the main limits.

The annual limits apply to the total dose received from operational sources including external gamma exposure and inhalation of radon decay products and dusts (with the doses from normal natural background being excluded). There are no exposure limits for the individual dose components. Likewise there are also no specific dose limits set for shorter periods (less than a year). This is because the likely health effects depend only on the total dose accumulated over a long period (possibly decades). In an operational situation, investigation and action levels are set for each pathway at levels that ensure continued exposure will not lead to doses above these long term limits, or other goals.

## 6.2 Radiological protection of the environment

Historically, the risk assessment and management of radionuclides entering or present in the environment has been based principally on human health considerations. The ICRP has stated that the standards of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species.

Recently there has been increasing awareness of the vulnerability of the environment and of the need to be able to demonstrate that it is protected against the effects of industrial pollutants, including radionuclides. The ICRP, in its 2007 Recommendations (ICRP 2008) has given more emphasis to the protection of the environment. More detailed advice is given in ICRP Publication 91, 'A framework for assessing the impact of ionising radiation on non-human species' (International Commission on Radiological Protection 2003) which reviews the various methods that have been developed for the assessment of radiological impacts with the objective of identifying and suggesting the best framework. It recommends making an initial assessment using primary (generic) reference organisms for flora and fauna to give an order of magnitude assessment of the probability and severity of likely effects of radiation exposure on the population. Organisms or situations that are not identified as being at negligible risk can then be subjected to a more detailed assessment, if necessary using situation or organism specific data. This approach has been adopted by the European Union as part of their ERICA project (Brown, Alphonso et al. 2008).

# 7 RADIATION IN MINING AND PROCESSING

## 7.1 Sources of exposure

There are three principal ways in which radiation exposure can occur in uranium mining and processing.

- External gamma exposure - gamma rays emitted from uranium ores and concentrates can result in radiation doses to those nearby. The gamma radiation originates mainly from Ra-226 and its immediate decay products.
- Inhalation of radioactive dusts - dust from uranium ore, concentrates and wastes contain radionuclides. If inhaled, they may be retained in the lung, or transported by body fluids and deposited in other organs. Subsequent radioactive decay may result in doses to organs. The long-lived alpha emitting radionuclides (238U, 234U, 230Th, 226Ra, 210Po) and the beta emitter 210Pb are the most important for this type of exposure.
- Inhalation of radon decay products (RnDP) - one of the uranium (238U) decay products is the radioactive gas, radon (222Rn), which can diffuse out of the ore in which it is formed, and into the atmosphere. Inhalation of radon itself does not result in a significant radiation dose, because very little is retained in the lung as it is an inert gas. However, radon decays to short-lived decay products (RnDPs – 218Po, 214Bi, 214Pb and 214Po). These are solids and if they are inhaled, they lodge in the lung, and in high concentrations can result in large radiation doses from the alpha particles they emit.

There are two other ways that internal exposure may arise from mining or processing operations:

- Ingestion (swallowing) - this may arise in occupational exposure by hand-to-mouth transfer when eating, drinking or smoking with contaminated hands. In the case of environmental exposure it may arise from eating or drinking food or water that has been contaminated with radioactive materials.
- Wound contamination - radioactive material can enter the body via wounds.

These pathways are minor, and simple measures (e.g., personal hygiene and covering of wounds) can usually reduce them further.

### 7.1.1 Methods of control

- There are different ways of controlling and reducing external and internal radiation exposure:
- For external radiation the main methods are “time, distance and shielding”. Reducing the time spent near a source or increasing the distance from that source reduces the exposure. In the mining situation, this means that wherever possible, workplaces should be sited away from high (uranium) ore grade areas.

Using effective shields between the radiation source and the workplace will also reduce exposure. In mining this can be achieved by applying a concrete coating to all surfaces (e.g., shot-creating) or by leaving lower-grade material in front of high-grade ore. Mining equipment may also provide shielding.

- For internal exposure, the aim is to reduce the intake of radioactive materials. For inhalation, this generally means having good ventilation to quickly remove contaminated air and supply fresh air to the workplace. This is particularly important in the case of radon decay products. Poor ventilation not only reduces the dilution of radon entering the workplace air, but also it allows more time for the radon decay products to form from decay of the radon. Forced ventilation is essential in underground mining, due to enclosed spaces, but natural ventilation is generally sufficient in open-pit operations. Dust-control measures such as keeping potential sources (such as ore stockpiles) damp are also important in controlling internal exposures from dusts. In some situations, particularly where the uranium oxide concentrate (UOC) is being handled, enclosed ventilated booths may be used to contain dusts generated. Personal respiratory protection may also be used for added protection or where other methods are not effective. Releases of dusts to the environment may be controlled, for example by installing dust collection systems on discharge points, in order to reduce doses to members of the public and environmental contamination.

## 7.2 Radiation monitoring and dose assessment

### 7.2.1 Monitoring

Radiation monitoring serves two main purposes. It is an essential part of the operational control of radiation exposures, by detecting changes in conditions that may lead to exposure, and is necessary in assessing radiation doses.

There are two general types of monitoring: personal monitoring and area monitoring. Personal monitoring measures the exposure an individual receives, whereas area monitoring measures the radiation levels in an area. Personal monitoring is preferred for estimating doses, but this is not always practicable, and personal monitoring is often not helpful in finding the locations or jobs that are contributing to higher than expected exposures. To determine the exposure of individuals from area monitoring the time spent in that area(s) must be known.

The three components of radiation exposure in the mining and milling of radioactive ores (see Section 7.1) are monitored in different ways.

- External gamma radiation can be monitored using personal TLD (thermo-luminescent dosimeter) badges that are worn by the worker for a period (usually one to three months), and then returned to a laboratory for processing. They record the external radiation exposure for the badge (and thus the individual) for the period. Hand-held Geiger counters or similar instruments can be used to perform area surveys for monitoring of workplaces.

- Airborne radioactive dust levels are monitored using a small air sampling pump with a filter that collects the dust. After sampling (preferably for a full shift) the filter can be taken to the laboratory and placed in a detector that counts the alpha activity in the sample. The method can be used for personal or area sampling, but personal sampling is preferable as dust exposures are often quite localised (e.g. to a particular job).
- Radon decay products are usually sampled in a similar way to dusts, but as they have short half-lives the sampling period must be short and they must be counted immediately after sampling (typically 3 minutes). The technique is not practical for personal sampling therefore area sampling is generally used. Devices for personal sampling of RnDP decay product concentrations have been developed, but are generally more applicable to underground mining where concentrations are higher. Individual radon decay product exposures can be monitored using personal (passive) radon monitors, but assumptions must be made about the relationship between the radon concentration and that of its decay products.

Similar techniques are used for monitoring radionuclides in the environment, however usually larger samples are taken to allow the lower levels to be detected. Dusts are sampled with high-volume samplers, and the dust that is collected on the filter is then analysed using radiochemical methods. Radon decay products can be monitored using instruments that continuously draw air through a filter, while simultaneously counting the alpha particles emitted from radon decay products collected on the filter. Radionuclide concentrations in food or water, or in environmental samples can be measured using radiochemical methods.

### 7.2.2 Monitoring program

A detailed monitoring program is an integral part of the radiation management plan for any operation. It contains details of the monitoring to be undertaken, the methods of monitoring, where the monitoring will occur and how often. It also includes the methods to be used for dose assessment, including the dose conversion factors to be used. Monitoring results and the assessed doses would be properly recorded and programs put in place to implement remedial measures should results higher than pre-defined investigation or action levels be encountered. Appropriate quality assurance programs should be included.

A monitoring program would aim to measure levels across all workplaces but would focus on areas and workgroups where exposures might be higher. Usual practice is for intensive monitoring and individual assessment of dose to be undertaken for those work groups and individuals considered likely to receive more than a quarter of the 20 mSv annual limit (i.e.: 5 mSv/y). Doses to those more peripherally exposed to radiation or radioactive materials (including members of the public) are generally assessed on the basis of group averages (Australian Radiation Protection and Nuclear Safety Agency 2005). Monitoring to assess doses (or potential doses) to members of the public would also be undertaken. In the uranium mining situation this would include monitoring of airborne concentrations of radioactive dusts or radon decay products. Where relevant, waterborne pathways would also be monitored, together with radionuclide concentrations in food or drinking water that might be potentially affected by the operation. Monitoring of the general environment (flora, fauna, soils, surface and ground water) may also be undertaken.

### 7.2.3 Dose assessment

Doses from external exposures can generally be derived fairly directly from the results of personal monitoring as described above. However this is not the case for internal exposures. The monitored results give the concentrations of the radioactive materials in air, and these need to be combined with location, occupancy times and breathing rates to estimate the intake of radionuclides into the body. To calculate the doses that will arise from these intakes, it is necessary to know how the radionuclides are absorbed into the body from the lung or gut, how they will circulate around the body, whether they will concentrate in particular organs, how long they will remain there, and how quickly they are excreted. It is then possible to calculate the dose that will arise from that intake of radioactive material.

Nationally and internationally recommended values of these 'dose conversion factors' (i.e. the dose that will arise from the intake of 1 Bq) for each radionuclide, and for different values of particle size, and solubilities in body fluids (International Atomic Energy Agency 1996; Australian Radiation Protection and Nuclear Safety Agency 2005) are then used to convert the calculated intakes to the doses that will be received. Radioactive dust generated in different parts of the operation will generally be composed of different proportions of radionuclides, and hence different factors are used. Similarly, a dose conversion factor is also used to convert radon decay product exposures to dose (Australian Radiation Protection and Nuclear Safety Agency 2002; Australian Radiation Protection and Nuclear Safety Agency 2005). All methods and data used for dose assessment (including dose conversion factors) will be based on guidelines issued by ARPANSA and the WA DMP.

The total dose to each individual is then calculated by adding the doses from the three components –gamma, RnDP and dust – obtained by the above procedure.

## 7.3 Medical surveillance

Medical assessments of mine workers are required for general "fitness for work" purposes under the Mines Safety and Inspection regulations.. However as there is no medical examination that will determine if a person is particularly susceptible to the effects of radiation, or provide early warning of cancer (other than standard screening methods as for, different cancers), these examinations are limited to general assessments of health. The results of these examinations, together with radiation dose records are generally retained indefinitely.

# 8 NUCLEAR SAFEGUARDS AND SECURITY

Australia's uranium is sold exclusively for use in the civilian nuclear power industry and there is a system of safeguards in place to ensure that it is not diverted for use in nuclear weapons.

Australia's safeguards are based on the system developed by the International Atomic Energy Agency (IAEA) under the Non-Proliferation Treaty, and the strengthened requirements known as "Additional Protocols".

This system has three main elements:

- accounting for uranium as it moves through the fuel cycle, to ensure that it is not diverted to nuclear weapons;
- physical security of nuclear material; and
- inspections to verify compliance.

## 8.1 Accounting

An international accounting system is used to trace the movement of uranium from production to fuel fabrication and its introduction into the nuclear power reactor. The tracking continues when spent fuel is removed from the reactor and is reprocessed into more fuel, or stored and disposed of as waste. The tracking also covers plutonium produced from the uranium in the reactor.

Essentially, this establishes a pool of uranium earmarked for power generation, and material can only be removed from this pool for use in civilian power reactors. All Australian produced uranium enters this pool.

## 8.2 Physical security

The requirements set minimum standards for ensuring that nuclear materials (including uranium) are protected from theft or hijacking. These include stringent measures to ensure security during transport, as well as when it is stored or processed in facilities.

## 8.3 Inspection and verification

Verification that the safeguards requirements are being properly implemented and complied with is obtained in several ways. These include auditing records of production transfer and use to ensure that there are no discrepancies, and physical inspection and accounting for nuclear material in facilities. Inspections can include physical inspection, measurements on for example amounts of material in storage, or the use of tamper proof cameras and the like to monitor operations in facilities.

## 8.4 Australia's safeguard requirements

Australia's requirements for safeguarding nuclear material go beyond those of the International Atomic Energy Agency (IAEA). Australia will only sell uranium to countries with which it has a bilateral safeguards agreement. These are formal agreements with the governments of customer countries that specify the details of how Australian-sourced uranium is to be handled. Australian uranium cannot be exported without a permit, which is only granted if a contract approved by the Australian Government is in place with the customer. Australian uranium cannot be transferred to other countries without the specific agreement of the Australian Government.

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