A HANDBOOK ON

OCCUPATIONAL HEALTH PRACTICE IN THE SOUTH AFRICAN MINING INDUSTRY

CHAPTER 13

Authors
Dr. D. Waymer
Dr. J.M. Dyson

First edition,
first impression 2001
Second edition 2026

Chapter 13

Health Effects of Radiation

This chapter describes the nature and extent of exposures to natural sources of radiation in the mining industry, the health effects of radiation, international principles of radiation protection, and the legal framework within which exposures are controlled in the South African mining industry. Best practice radiation protection guidelines are provided, including monitoring of exposures, health surveillance, and engineering and administrative controls. Further technical and regulatory information is appended, together with a comprehensive list of international references providing more detailed guidance pertinent to the identification, assessment, and control of radiation hazards in mines.

Dr. D. Wymer
Physicist

Reviewed by Dr J. M. Dyason
Occupational Medical Practitioner

13.1 Introduction

All rocks and soils contain traces of the natural radioactive elements uranium and thorium. Uranium is present as the isotopes uranium-238 (99.3%) and uranium-235 (0.7%), while thorium is present as thorium-232. These naturally occurring radionuclides have extremely long half-lives and have survived since the formation of the earth, hence their name 'primordial radionuclides'. Each forms the 'parent' of its own particular decay chain, containing other radionuclides that decay ultimately to stable isotopes of lead. Details of the two most important decay chains – uranium-238 and thorium-232 – are given in **Appendix 13.1.**

The presence of these primordial radionuclides in human habitats, together with the cosmic radiation permeating the earth and the cosmogenic radionuclides continuously generated by this radiation, have always been a source of radiation exposure to humans. This exposure can loosely be described as exposure to natural sources of radiation.

Various aspects of human behaviour, such as living and working in enclosed structures, have generally increased the level of exposure to natural sources of radiation, particularly because of increased exposure to radon-222, a gaseous decay product of uranium-238, which permeates into enclosed areas through floors and walls. These increased exposures have largely become accepted as part of our normal 'natural background exposure'.

Work activities involving natural raw materials, particularly mining and minerals processing, have further increased exposures to natural sources of radiation. In some cases, these increased exposures are significant and need to be controlled in order to protect the health of workers and members of the public. Radiation exposures of members of the public arise principally from the controlled discharge of mine effluents and from the storage and ultimate disposal of mine tailings in surface impoundments. Control of public exposures forms part of a mine's responsibility in terms of mine waste management, rehabilitation, and closure; while important, it is outside the scope of this Handbook.

Monitoring in the mining environment or any work environment where workers are exposed to ionising radiation must be undertaken by a radiation protection officer (RPO). According to the international atomic energy agency (IAEA) Safety Standards Series No. RS-G-1.4, *Building Competence in Radiation Protection and the Safe Use of Radiation Sources*, the radiation protection function shall be able to recognise and quantify all potential and actual radiation hazards during normal operations, as well as abnormal situations (1). Control measures must be prospectively implemented to ensure compliance to the dose limitation system applicable to employees as a result of normal operations and potentially abnormal situations.

Radiation protection procedures (RPPs) are guidelines for radiation gas monitoring in terms of the National Nuclear Regulator Act No. 47 of 1999 (NNRA) (2) and the Mine Health and Safety Act No. 29 of 1996 (MHSA) (3), which includes the evaluation of all situations that may lead to radiation exposure, comparison of exposures to regulated exposure limits, and the application of control practices to maintain exposure to as low as reasonably achievable (ALARA) principles (IAEA Safety Guide No. RS-G-1.6, *Occupational Radiation Protection in the Mining and Processing of Raw Materials)* (4).

13.2 Radioactivity and Radiation

Radioactivity is the spontaneous release of energy in the form of particles and waves from unstable atoms. The particles are referred to as alpha and beta radiation, and the waves as gamma radiation. The radiation produced by radioactive elements, as well as by particle accelerators and X-ray machines, has sufficient energy to produce ion pairs (ionisation) in biological materials and, for this reason, is referred to as ionising radiation.

There is a spectrum of radiation that includes non-ionising radiation like radio, cell phones, and microwaves, including visible light. Non-ionising radiation may have thermal effects, for example: microwave ovens cook food and in arc welding the ultraviolet light may cause inflammation of the cornea (arc eyes).

Ionising radiation includes X-rays and gamma rays. Gamma radiation is electromagnetic radiation of a very short wavelength. Its penetrating power depends on its energy and is capable of passing through the human body. Dense materials, such as concrete or lead, are used to provide shielding against gamma radiation.

Figure 13.1 depicts a representation of the radiation spectrum and its applications.

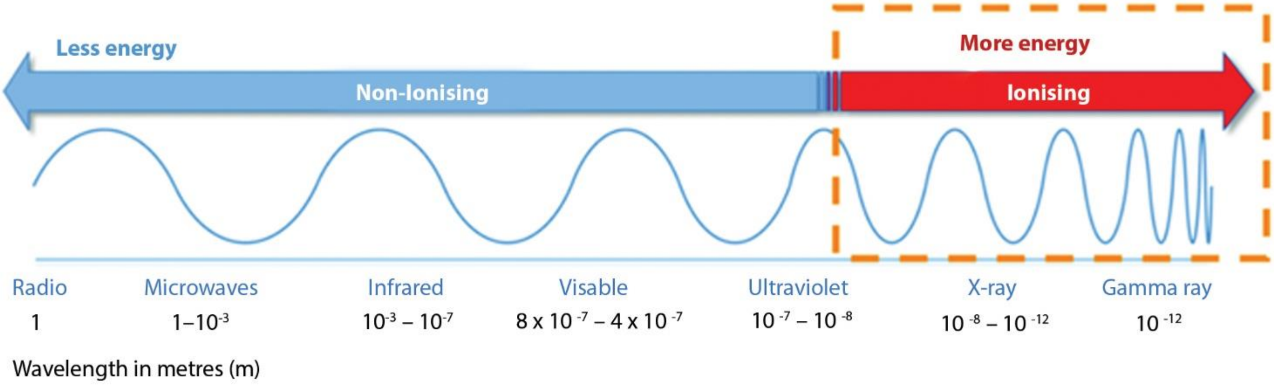


Figure 13.1. Representation of the radiation spectrum and its applications

Source: Zhang et al. (2022) (5)

Alpha radiation consists of positively charged particles composed of two neutrons and two protons. Alpha radiation will not usually penetrate the epidermis and can be stopped completely by a sheet of paper or a few centimetres of air.

Beta radiation consists of negatively charged particles in the form of high-speed electrons. It is much more penetrating than alpha radiation and can, depending on the energy, pass through 1–2 cm of water, 5 mm of human tissue, or about 3 m of air.

A brief explanation of the units of measurement used in radiation protection is provided in **Appendix 13.2.** Further useful information can be found in the Mine Ventilation Society (MVS) Data Book.[1]

13.3 Ionising and Non-Ionising Radiation

Radiation is a descriptor for energy (in the form of either particles or waves) travelling through space or another medium (6). The energy is emitted from the source and radiates in straight lines and in all directions. If the radiation is an electromagnetic wave, then it will travel at the speed of light. Because of the way the energy is radiated, radiation is relatively straightforward to detect and measure, and inferences can be made about its source. The properties of the energy emitted will determine the way it interacts with matter (and living tissue) and, therefore, its measurement technique and requirements for regulation.

There are two types of radiation:

- Ionising radiation
- Non-ionising radiation

Ionisation is the process by which a stable atom or a molecule loses or gains one or more electrons, thereby acquiring an electric charge or changing an existing charge (7). An atom or molecule with an electric charge is called an ion, which may behave differently, electrically and chemically, from a stable atom or molecule.

The altered behaviour may lead to new possibly undesired molecules, a change in the conductive properties of the material in the vicinity of the ion, a release of energy, or a combination of these effects. In the human body, these effects may lead to changes in the structure or behaviour of cells.

Therefore, ionising radiation has sufficient energy to be able to displace an electron from its orbit around an atom and, conversely, non-ionising radiation does not have sufficient energy to displace electrons (7).

13.3.1 Ionising radiation

Ionising radiation can occur in one of two forms: particulate or electromagnetic. Particulate ionising radiation is emitted when components of the structure of an atom are ejected, artificially or naturally. The emitted particles can be:

- Alpha particles, which include two protons and two neutrons (ionised helium)
- Beta particles, which are essentially electrons
- Neutrons
- Gamma rays and X-rays, which are pure energy (photons)

Ionising radiation has more energy than non-ionising radiation, such that it can cause chemical changes by interacting with an atom to remove tightly bound electrons from the orbit of the atom, causing the atom to become charged or ionised.

The types of ionising electromagnetic radiation are categorised according to their wavelength.

- **Ultraviolet (UV)** – the dividing line between ionising and non-ionising radiation in the electromagnetic spectrum falls in the ultraviolet portion of the spectrum, and while most UV is classified as non-ionising radiation, the shorter wavelengths from about 150 nm (UV-C or 'far' UV) are ionising. Ultraviolet-C from the sun is nearly all absorbed by the ozone layer.

- **X-rays** – X-rays are produced when electrons strike a target or when electrons are rearranged within an atom. X-rays have a wavelength smaller than about 10 nm. In medical applications X-ray machines are specifically designed to take advantage of the difference of absorption of X-rays between bone and soft tissue. In the industrial arena, non-destructive testing (NDT) using X-ray machines introduced into pipes or vessels to check for integrity, or to check welds or joints, is commonly used.

- **Gamma rays** – gamma (γ) radiation has a wavelength of less than 0.01 nm, and is comprised of photons emitted by the nucleus of some substances (radionuclides) following radioactive decay. Photons in gamma radiation are the most energetic and, therefore, the most penetrating in the electromagnetic spectrum.

13.3.2 Non-ionising radiation

Non-ionising radiation consists of part of the electromagnetic spectrum that includes radio waves, microwaves, infrared, visible, and UV light, together with sound and ultrasound, as shown in **Figure 13.1**.

Although humans have long used radiation emitted in the form of light and heat, an understanding of its nature and units is essential for the occupational health and safety (OHS) professional to understand relevant exposures and control strategies.

13.3.2.1 Units of measurement

The defining feature of any electromagnetic radiation (EMR) is its frequency; the number of oscillations per second, measured in hertz (Hz) in units of second-1.

Once frequency has been identified, the wavelength (λ, measured in metres) and energy (E, measured in electron-volts) can be calculated using the following equations:

- Wavelength (λ m) = 3 x 108 m/s / frequency (Hz s-1), where 3 x 108 m/s = speed of light (in a vacuum)
- Energy (E eV) = 4.136 x 10-15 (eV s) x frequency (Hz s-1), where 4.136 x 10-15 eV s = Planck's constant

Hence, it can be seen that the higher the frequency, the shorter the wavelength and the higher the energy. When the frequency is high enough (e.g. X-rays or gamma rays), the waves are so energetic that they become ionising. The power of an emitting source is measured in watts.

13.4 Health Effects of Ionising Radiation

When ionising radiation passes through human tissue, damage may be caused to cells, which, if not adequately repaired, may have two possible outcomes – 'deterministic' or 'stochastic' (8).

13.4.1 Deterministic effects

When the dose (the energy imparted to the cell) is greater than a certain threshold, the cell is prevented from surviving or reproducing. If the number of cells lost is large enough, observable harm reflecting a loss of tissue function will occur within a short time of the exposure. Above the threshold, the severity of the harm increases steeply with dose. This type of effect is called deterministic and is a cause-and-effect relationship, where specific doses result in a certain effect. Exposure to natural sources of radiation in mining cannot give rise to deterministic effects. Examples of deterministic effects will be in radiation accidents, where certain doses cause certain predictable effects, e.g. where an absorbed dose of between 2 to 5 Gy leads to skin erythema and hair loss. Doses of 5 Gy will lead to bone marrow suppression and a 50% chance of death in 2–4 weeks.

13.4.2 Stochastic effects

When the energy imparted to the cell is below the threshold for deterministic effects, the irradiated cell will survive, but may become modified. Because of exposure to natural background radiation, about ten million cells in an individual are hit by radiation every minute. Our ability to deal with this 'onslaught' of radiation is due to the existence of highly effective defense mechanisms. Despite this, it is still possible for a clone of cells, resulting from the reproduction of a modified but viable cell, to result in the development of a cancer after a prolonged and variable latency period. This kind of effect is called stochastic, meaning 'of random or statistical nature'. Because of the long latency period, typically decades after the exposure was incurred, radiation-induced cancer – as with most other cancers – is primarily a disease of old age, the average victim being about 65 years old.

If the radiation damage occurs in germ cells, then this damage may be transmitted and become manifest as hereditary disorders in the descendants of the exposed individual. Radiation has not been identified as a cause of such effects in humans, but it is presumed from the results of animal studies that such effects may occur; due allowance is made for them in international standards.

The average radiation dose from natural background exposure is 2.4 mSv per year. For doses of up to about 40 times this value, no firm conclusions on health effects can be drawn, despite the multitude of cellular, animal, and epidemiological studies that have been conducted. Some researchers have produced evidence supporting a linear dose-response relationship with no apparent threshold; others have produced evidence consistent with a threshold below which there are no effects, while others have produced seemingly convincing evidence of beneficial health effects at low doses. It is unlikely that this problem will be resolved in the foreseeable future by epidemiological studies, since, to be conclusive, they would need to be conducted under controlled conditions on an impossibly large population over a very long period. Even then, it is almost impossible to observe, in large population groups, minor changes in patterns of cancer incidence, and to distinguish them from similar patterns of incidence that could have a host of other causes.

According to the current knowledge of radiation health risks, the Health Physics Society (HPS) recommends against quantitative estimation of health risk below an individual dose of 5 rem [50 mSv] in one year, or a lifetime dose of 10 rem [100 mSv] in addition to background radiation (22). Risk estimation in this dose range should be strictly qualitative, accentuating a range of hypothetical health outcomes with an emphasis on the likely possibility of zero adverse health effects.

For doses greater than about 40 times the dose from average natural background exposure, there is conclusive epidemiological evidence that the probability of cancer resulting from radiation usually increases in a way that is roughly proportional to dose. For the low doses and dose rates likely to be received in the mining situation, the probability of attributable cancer per mSv of dose is estimated to be 4×10^{-5} for adult workers and 5×10^{-5} for the general population.

The system of radiation protection adopted, internationally, is designed to ensure that the probability of stochastic effects will not exceed a level that is regarded as unacceptable when viewed in perspective with other risks, so that society's resources are not inappropriately expended. In dealing with the lack of conclusive knowledge in the low dose region referred to above, international standards, for the purposes of caution and regulatory convenience, are based on the 'linear no-threshold' (LNT) hypothesis, such as on the hypothesis that health effects are linearly related to dose, with no threshold. Therefore, any dose, however small, is taken to be associated with a certain level of risk.

The LNT hypothesis, despite its adoption as the basis for international standards, remains a controversial issue. This is particularly because of the social and economic implications of extending regulatory control to exposures to natural sources, when such exposures are similar to the variations in natural background exposures.

Many cellular, animal, and epidemiological studies have been conducted to investigate the combined health effects of low doses of radiation in conjunction with other deleterious agents and, in particular, to establish whether there are significant deviations from additivity. Survivors of the Hiroshima and Nagasaki bombings constitute important material in the study of these effects (9). These populations are evaluated with comparable populations for cancer deaths to estimate the effect of ionising radiation stochastic effects.

More research is required to elucidate fully these combined effects, but, with the exception of radiation and tobacco smoking, there is no evidence at this stage that low-level exposures to multiple agents yield combined effects far from additivity. This includes exposures to multiple agents that may be found in the mining industry, such as radiation plus dust and radiation plus diesel fumes. The situation is different for the combined effects of radiation exposure and tobacco smoking (10).

The results of the most recent review of epidemiological evidence, from earlier studies on relatively highly exposed uranium miners, suggest synergism between smoking and radon progeny exposures that is statistically most consistent with a slightly sub-multiplicative interaction (11). A best estimate from miner data indicates that the lung cancer risk for smokers, expressed in absolute terms, is higher by a factor of at least three.

13.4.3 Other effects of ionising radiation

Pacemakers can be affected by radiation therapy, depending on the overall radiation exposure. It may be necessary to direct the radiation beam around the pacemaker, or move the pacemaker to a different location (refer to the Medtronic Patient Manual for more information). Pacemakers are not affected by everyday sources of radiation such as cell phone waves (non-ionising radiation), unless the phone is held too close to the pacemaker. Pacemakers can be affected by high-frequency alternating electric currents – for example, when welding or when close to electric arc furnaces. These effects are not due to ionising radiation, but to electromagnetic interference.

13.5 Health Effects of Non-Ionising Radiation

The health effects (if any) of exposure to extremely low frequency (ELF) radiation will be dependent upon:

- Strength of the magnetic field at the source
- Distance from the source
- Duration of exposure

Despite the very low levels normally encountered in everyday activities, exposure to ELFs remains a source of public debate.

Concern about possible adverse health effects of ELF was initiated by studies in the 1970s, in Denver, on the association of childhood leukemia with proximity to high voltage power lines (12). This triggered a significant research effort to elucidate this issue, with the UK Government commissioning Sir Richard Doll to investigate the association between ELF and cancer (13).

In his 2001 report, Doll noted that the laboratory experiments have provided no good evidence that ELF electromagnetic fields are capable of producing cancer, nor do human epidemiological studies suggest that they cause cancer in general. There is, however, some epidemiological evidence that prolonged exposure to higher levels [more than 0.4 µT] of power frequency magnetic fields is associated with a small risk of leukemia in children. In practice, such levels of exposure are seldom encountered by the general public in the UK.

In the absence of clear evidence of a carcinogenic effect in adults, or of a plausible explanation from experiments on animals or isolated cells, the epidemiological evidence is currently not strong enough to justify a firm conclusion that such fields cause leukemia in children. Unless, however, further research indicates that the finding is due to chance or some currently unrecognised artefact, the possibility remains that intense and prolonged exposures to magnetic fields can increase the risk of leukemia in children.

In 2002, the International Agency for Research on Cancer (IARC) classified ELF magnetic fields as a *"possible human carcinogen"* and this decision was upheld by the World Health Organization (WHO) in 2007 (14). However, it can be concluded that:

> *"The scientific evidence does not firmly establish that exposure to 50 Hz electric and magnetic fields found around the home, the office, or near powerlines is a hazard to human health. In view of the epidemiological studies, however, the possibility remains that intense and prolonged exposures to magnetic fields may increase the risk of leukemia in children" (15).*

At longer wavelengths, radio frequency (RF) can induce alternating electric fields in bodies because of the water content of living tissue. The water molecule is a dipole – with one side positively charged and the other negatively charged. An electric field induces the water molecule to attempt to rotate to align with the field. Because radiations are emitted with an alternating electric field, the water molecule changes directions with the rapid changes in electric field, which causes the molecule to vibrate. The vibration causes a friction-like dissipation of energy in the form of heat.

Therefore, unlike localised heating caused by shorter wavelength radiations, longer wavelengths (such as microwaves and radio frequencies) can induce heating deep into tissue. At the low frequency end of the spectrum (such as long wavelength), it is thought that magnetically induced effects may occur that can manifest as vertigo or nausea. Exposure to sufficiently high levels of RF can heat biological tissue and, if the human body is unable to cope with the excessive heat, potentially cause tissue damage.

13 In relation to the longer wavelength RF, the UK National Radiological Protection Board (NRPB) stated that (16):

> *"The experimental evidence reviewed strongly suggested that these fields do not harm genetic material and so would not normally be expected to initiate cancer. There was, however, a possibility that they might act as tumor promoters; that is, they might increase the growth of potentially malignant cells. The results of experimental studies, when taken together were, however, inconclusive. It could not be concluded that any effect of electromagnetic fields on cells and tissues could be regarded as potentially carcinogenic in humans."*

There is much interest in the potential effects of radiations related to transmissions from mobile phone base stations and from the handsets. At typical levels, mobile phone base station emissions are well below the allowable general public exposure limit of around 450 µW/cm (frequency dependent), or some 1 000 times below allowable exposure standards (17). Mobile phone handsets radiate RF emissions close to the head and produce complex exposure patterns that are difficult to measure.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) specifies human exposure limits, in terms of specific absorption rate (SAR), that regulate the rate at which the user absorbs energy from the handset (17). The SAR limit for mobile phone handsets in Australia is 2 W/kg of tissue (averaged over 10 grams). An SAR of 4 W/kg is associated with a 1 °C rise in humans. In practice, a digital phone will only cause a temperature rise of a fraction of a degree, which is unlikely to be noticed compared with the normal daily variations in body temperature.

In 2011, the IARC noted the following points in relation to mobile phone emissions (18):

- The epidemiological evidence, while still accumulating, is currently strong enough to support a 2B

 13

classification (possibly carcinogenic to humans).
- There is limited evidence among users of wireless telephones for glioma (tumour in glial cells in brain) and acoustic neuroma (benign tumour in canal between brain and ear).
- The highest risk only applies to those users who use mobile phones most intensely, and who have been using mobile phones for the longest time. The odds ratio of > 1 was only found for highest decile users with exposures > 7 years.
- While newer 3G phones emit some 100 times less energy than older 2G phones, people are using mobile phones more.

As absorption of infrared (IR) radiation heats objects, it will also heat the human body. Heat stress through exposure to hot processes or objects is discussed elsewhere. The eye is the organ most vulnerable to excessive IR exposure, with the most vulnerable tissues being the cornea and aqueous humour, as the infrared radiation raises the overall temperature of the anterior eye. Long wavelength infrared rays also reach the retina, and can cause permanent damage to the delicate photoreceptors – for instance, through sun gazing.

Legge, in 1907, reported a 'new' UK legal occupational disease of 'glass blower's cataract' (19). Glass blowers and welders are exposed to high levels of IR light at close range. Both direct absorption by the lens and indirect heating of the lens fibres, through the absorption of the iris, can cause the lining of the lens to peel back, resulting in cataract formation and IR-induced opacities.

In general, excessive exposure to the subcategories of IR can cause:

- Erythema – mid-IR and far-IR
- Pigmentation – mid-IR and far-IR
- Photo keratitis – mid-IR and far-IR
- Cataracts – near-IR (highest energies)
- Retinal burn – near-IR

13.6 Radiation Protection Standards

Worldwide, there is a high degree of consensus on radiation safety standards and the regulatory approach to radiation, as reflected in the International Basic Safety Standards (BSS) (20). The BSS is based on the recommendations of the International Commission on Radiological Protection (ICRP), an international advisory body that provides guidance on the fundamental principles of radiation protection and safety, and updates such guidance in the light of new knowledge and thinking.

The ICRP recommendations and the standards contained in the BSS have, in turn, formed the basis for European Commission (EC) legislation through the 'Euratom Directive', and are being adopted as regulations in many individual countries around the world, recent examples being the UK's Ionising Radiation Regulations, 1999 (21) and the Australian Radiation Protection and Nuclear Safety Regulations, 1999 (22).

The basic principles of radiation protection, as recommended by the ICRP and adopted in international standards, are summarised in **Table 13.1** (20).

Table 13.1. Basic principles of radiation protection

Primary aim: *"To contribute to an appropriate level of protection for people and the environment against the detrimental effects of radiation exposure without unduly limiting the desirable human actions that may be associated with such exposure".*	
Justification principle: Any decision that alters the radiation exposure situation should do more good than harm.	
Optimisation principle: *"Doses should all be kept as low as reasonably achievable, taking into account economic and societal factors".*	Radiation dose is a measure of the amount of exposure to radiation. There are three kinds of dose: • **Absorbed dose** is the amount of energy deposited by radiation in a mass. • **Equivalent dose** is calculated for individual organs. • **Effective dose** is calculated for the whole body. It is sometimes called whole-body dose.
Limitation principle: *"The total dose to any individual should not exceed the appropriate limits".*	Dose limits help ensure that no person is exposed to an excessive amount of ionising radiation in normal, planned situations. The following dose limits are applicable for occupational exposure: **1. Effective dose:** • 20 mSv per year, averaged over defined periods of five years, with no single year exceeding 50 mSv. • After a worker declares a pregnancy, the dose to the embryo/foetus should not exceed about 1 mSv during the remainder of the pregnancy. **2. Equivalent dose:** • ***to the lens of the eye***: 20 mSv per year, averaged over defined periods of five years, with no single year exceeding 50 mSv. • ***to the skin (averaged over 1 cm² of skin regardless of the area exposed)***: 500 mSv in a year. • ***to the hands and feet***: 500 mSv in a year.

Because exposure to natural sources of radiation forms part of our everyday life, work activities involving such exposures may have characteristics of both practices and intervention. Further information on international recommendations, standards, and guidance, including guidance on how to deal with work activities involving exposure to natural sources of radiation, can be found in various international publications (ICRP 1991, 1993, 1997; IAEA 1996, 1999; EC 1996, 1997).

The following dose limits for occupational exposure have been adopted in international standards (ICRP-103) (23):

- An effective dose of 20 mSv per year, averaged over five consecutive years
- An effective dose of 50 mSv in any single year

13.7 Radio Protection Programme

In addition, there are separate dose limits for exposure of specific tissues (eyes, hands, feet, and skin), and for apprentices and students aged 16–18 years. Provision is also made for a temporary change in the dose limitation requirement in special circumstances.

The occupational dose limit currently imposed on the mining industry by the National Nuclear Regulator is 50 mSv in a year, but this is being reviewed as part of the drafting of new regulations on safety standards and regulatory practices.

An RPP describes the management structures, policies, procedures, and organisational arrangements to be applied and followed in practice. The principal objectives of the RPP are, first, the determination of measures for protection and safety that are optimal for the circumstances, and second, the establishment of means for preventing accidents and for mitigating the consequences of those that do occur. In so doing, the factors relevant to the circumstances are to be considered in a deliberative manner.

The complex nature of the management and radiation protection arrangements, when associated with itinerant workers, highlights the need for their work to be carried out in accordance with an effective RPP. This section describes the steps to follow in the development of suitable programmes for work carried out by itinerant workers.

13.7.1 Prior radiological evaluation and safety assessment

The nature and content of an RPP will be very dependent on the type of work to be carried out and the doses potentially associated with that work. The first step towards the development of an RPP is to conduct a prior radiological evaluation of the practice, considering both realistically expected exposures and potential exposures. The responsibility for the assessment will lie primarily with the registrant or licensee, but also with the employer of the workers potentially exposed. It follows that for most work carried out by itinerant workers, the management of the facility and the employer of the itinerant workers (the contractor) need to collaborate in carrying out the assessment.

13.7.2 Structure and content of the radiation protection programme

The prior radiological evaluation and safety assessment will provide the basis for the nature and content of the RPP. The evaluation and assessment will, in many cases, limit the complexity of the RPP to be developed and implemented. For those situations where the planned work will be solely or primarily in supervised areas, applications of graded approach methodologies will lead to the development and implementation of an RPP with appropriately limited detail.

For those situations where the planned work will be in relatively low radiation fields, and/or require only very limited occupancy within relatively low or moderate radiation fields, application of graded approach methodologies will also lead to the development and implementation of an RPP with appropriately limited detail. Ensuring compliance with applicable dose limits (and constraints) and optimisation of protection and safety remain key considerations, but for the above situations, achieving those requirements is likely to be accomplished with appropriate attention by facility and contractor management and the itinerant workers.

For those situations in which expected or possible radiation fields are relatively higher, and where occupancy factors in such radiation fields are relatively higher, the facility and contractor management and the itinerant workers will need to provide relatively higher and fully focused attention to RPP development.

The number and complexity of protection and safety measures, identified for implementation, will be expected to be relatively higher to ensure optimisation of protection and safety, based on appropriate consideration of the prevention and mitigation of accidents. In those cases where non-radiological risks need to be addressed in conjunction with the radiological risks, the complexity of the RPP may also be relatively higher.

In developing an effective RPP, the contractual agreement between the management of the facility and
13 the contractor will also be a useful reference. The following description focuses on developing an RPP for the situation in which doses anticipated or potentially received may be relatively high, or multiple (radiological and non-radiological) risks exist to worker health and safety.

The same description applies to the situation where doses anticipated or potentially received may be relatively low, but the level of detail required within the RPP would also be relatively low. For itinerant workers, the basic structure of the RPP ought to document or reference, with an appropriate level of detail, the following subjects:

- The assignment of responsibilities for protection and safety to different management levels, including the allocation of responsibilities to the management of the facility and the contractor
- The presence and extent of any controlled or supervised areas
- The local rules and procedures for workers to follow and for the supervision of work, including the system for accountability for source control and the use of protective equipment
- The names of the appropriate RPO
- The arrangements for monitoring workers and the workplace, including, where appropriate, the use and maintenance of radiation dose rate or contamination monitoring instruments
- The system for recording and reporting the relevant information related to the control of exposures and the monitoring of individuals
- Any facility-specific training requirements
- The plans to be implemented in the event of an incident or accident
- The health surveillance programme
- The methods for periodically reviewing and assessing the effectiveness of the RPP, including the methods for ensuring quality
- The integration of occupational radiation protection into a system which allocates resources for health and safety, based on a rational balance between all risks

As with the safety assessment, the registrant or licensee will have the primary responsibility for the RPP, but both the management of the facility and the contractor have specified responsibilities for the RPP. However, it is likely that one or the other will have superior knowledge of the subject and, hence, will take a lead role in its formulation and presentation for discussion between the facility management and the contractor.

Additional information is available from the IAEA (24).

13.7.3 Radiation protection officer

An RPO is a person technically competent in radiation protection matters relevant for a given type of
practice, who is designated by the registrant, licensee, or employer to oversee the application of 13
regulatory requirements.

Employers, registrants, and licensees shall designate, as appropriate, an RPO in accordance with criteria established by the regulatory body.

Radiation protection officers are employees who should be designated by the registrant or licensee to supervise radiation safety within a facility, and to ensure that work is carried out safely and in accordance with the relevant national requirements.

Additional information on radiation protection is available from the WHO (25) and the IAEA (26).

13.8 Occupational Radiation Exposures in the Mining Industry

Table 13.2 gives examples of situations in the South African mining industry (SAMI) where experience has indicated significantly enhanced occupational exposures to natural radiation sources.

Table 13.2. Situations of radiological significance in the South African mining industry

Type of situation	Example
Where the concentrations of uranium and/or thorium in the ore are typically more than about 25 times the average levels in the earth's crust, such as more than about 1 Bq/g, especially in underground mines because of the build-up of the radioactive gas radon-222	Gold mines
Where uranium, thorium, or mineral products containing these elements are extracted from the ore	Extraction of uranium as a by-product of gold or copper
Where uranium, thorium or their decay products become adventitiously concentrated during the process	Radium sulphate scales formed during the production of sulphuric acid from the roasting of pyrite, and oil and gas extraction

The three most significant types of exposure that need to be considered are:

- Exposure to alpha radiation from the short-lived decay products of radon-222 (radon daughters), through the inhalation of air in underground workplaces
- Exposure to gamma radiation external to the body, such as from the rock face, from large ore stockpiles or from localised radionuclide concentrations in surface plants
- Exposure to alpha radiation from the inhalation of ore dust, such as in underground workplaces and in dry processing operations in surface plant

Other types of exposure, such as ingestion or skin contamination, are not normally significant, but may need to be considered in certain work situations. The distribution of radiation doses received by workers during 1999, according to submissions made by mining and minerals processing facilities to the National Nuclear Regulator (27), are shown in **Table 13.3**.

Table 13.3. Distribution of radiation doses received by workers in 1999

Type of facility	Number of workers					
	0–5 mSv	5–10 mSv	10–15 mSv	15–20 mSv	> 20 mSv	Total
Gold mining	130 986	48 365	14 998	2 296	5 230	201 875
Copper mining	4 576	91	40	2	0	4 709
Mineral sands	2 871	0	0	0	0	2 871
Phosphates	290	0	0	0	0	290
Other minerals processing	2 084	1	0	0	0	2 085
Total	140 807	48 457	15 038	2 298	5 230	211 830

Gold mining accounts for most exposed workers. It is also the only type of facility where a significant proportion of the workforce receives radiation doses exceeding 5 mSv per year (or about twice the normal natural background).

A survey of 21 gold mines conducted by the Chamber of Mines in 1993 and 1994 revealed that most of the dose received by workers (71% overall) was attributable to exposure to radon daughters. Exposure to external gamma was the next most significant (25%), and exposure to dust was the least significant (4%) (28).

Radon-222, a gaseous decay product of uranium-238, is released into the mine atmosphere mainly by diffusion through ore. It may also be released from water percolating through the ore body. Because it is an inert gas, it is not retained in the respiratory system and contributes little to radiation dose. It has a half-life of 3.8 days, long enough to have a chance of escaping from the rock, but short enough for its four immediate daughter products, which have particularly short half-lives (less than half an hour), to increase in concentration rapidly when a source of radon is present.

These radon daughters are metallic ions and will very quickly attract to themselves molecules of water and other atmospheric gases to form very small particles, which in turn attach to natural aerosol particles of a diameter typically about 0.3 µm. When inhaled, most of the radon decay products attached to aerosols, together with the unattached particles, will lodge in the lungs and airways. There will usually be insufficient time for the natural clearance processes to have removed them before the short-lived daughters have decayed and, thus, deposited their energy into the lung tissue. The consequence of this is that, for exposure to radon daughters, the stochastic health effect of concern is lung cancer.

Because almost all the radiation dose arises from radon daughters, rather than from radon itself, the radiation hazard associated with underground air depends critically on the degree of ingrowth of radon daughters. This in turn depends on the age of the ventilating air as it flows through the mine. In relatively fresh (young) air, the ratio of the concentration of the daughter products to that of radon is low; it approaches unity in old (stagnant) air. The determination of this ratio (which, when expressed in terms of the available alpha radiation energy, is called the equilibrium factor) provides useful information about the source of radon and the effect of ventilation as a means of control. It also allows the conversion of the measured radon concentration to a radon daughter concentration, which is essential for calculating the radiation dose (refer to **Appendix 13.2**).

In ore bodies containing concentrations of thorium, a similar situation may arise from the inhalation of radon-220 (sometimes referred to as thoron), a decay product of thorium-232 which, like radon-222, is also gaseous and decays rapidly through a series of short half-life daughters. However, because the half-life of radon-220 is less than one minute, there is much less chance of it escaping from the ore and it is unlikely to be a problem in most South African mines.

Radiation gas monitoring (RGM) done in 2005 by Van Schalkwyk showed a significant decrease in RGM doses (radon gas exposures), following improved ventilation measures taken in gold mine shafts (29). The doses were also below the first target of 50 mSv/a.

13.9 The Legal Framework

In common with the situation elsewhere in the world, the South African approach to the regulatory control of work activities involving radiation was focused originally on exposure to artificially produced radiation, such as that associated with nuclear power and the use of fabricated radioactive sources in science, medicine, and industry.

Occupational exposure to radiation in mining is regulated in terms of two laws, the NNRA (30) and the MHSA (3), both of which fall under the Minister of Mineral and Petroleum Resources, as there is considerable overlap in this legislation. Section 6 of the NNRA addresses this by requiring the Minister, after due consultation, to make regulations regarding the conclusion of co-operative agreements that will avoid unnecessary duplication and omissions regarding safety requirements, and the issuing of conflicting instructions.

The National Nuclear Regulator (NNR) is required, in terms of section 6 of the NNRA, to conclude such co-operative agreements with every relevant organ of state. These co-operative agreements have, therefore, been reached with the Department of Forestry, Fisheries and the Environment, the Department of Water and Sanitation, the Department of Employment and Labour, and the Department of Transport.

The NNR has several requirement documents (RDs) relating to mining activities and other nuclear-related activities on the NNR website. A list of the relevant RDs is attached in **Appendix 13.3**. There are RDs dealing with Radioactive Waste Management (RD-004), Control of Radiation Hazards (RD-006), Control of Radioactive Effluent Discharges (RD-007), and for Medical Surveillance and Control of Persons Occupationally Exposed to Radiation (RD-011).

The National Radioactive Waste Disposal Institute Act No. 53 of 2008 (NRWDIA) (31) deals with the establishment of a waste disposal institute, and requires any person who has to dispose of radioactive waste to apply for a waste disposal certificate, and comply with national policy in the development of site-specific waste management plans. The NRWDIA deals with radioactive waste generated from nuclear energy production, radioisotope production, and mining and minerals processing. The radioactive waste management policy and strategy classifies the waste into six classes. Mining waste will typically be naturally occurring radioactive material (NORM)-L, which is potential radioactive waste containing low concentrations of NORM, or NORM-E, radioactive waste containing an enhanced concentration of NORM.

Details of regulatory responsibilities are given in **Appendix 13.3**.

13.10 Monitoring of Exposure Levels

Monitoring radiation exposure levels is conducted for two main purposes. Firstly, it is necessary to acquire the data needed to establish the significance of the various types of radiological hazard and to determine the appropriate control measures. Secondly, there is a requirement to assess the doses received by individual workers. Further information on monitoring at mines is provided by the IAEA (1989) (32)

13.10.1 Monitoring for operational control

Physical measurements of the parameters relevant for radiation protection, for example, radon concentrations in underground air, as part of an initial hazard assessment, will enable management to identify the sources of radiation exposure that are significant enough to require control. Such measurements also provide the diagnostic information needed for the management of radiation protection. They provide a method of quickly detecting departures from normal operating conditions and signal the need for corrective action. A well-conceived programme will also facilitate the prediction and understanding of trends and significant sources of exposure, as the mining operation develops.

During the initial hazard assessment, comprehensive surveys of external gamma radiation, airborne radioactive dust, and radon and its daughters should be carried out. In uranium plants, particularly in the final product areas, surface contamination should also be measured to determine whether there are likely to be any problems caused by the resuspension of dust. The results of the initial hazard assessment, particularly the dose rates, the concentrations of radionuclides, and their fluctuations over time, will determine the nature of the ongoing operational monitoring programme, in terms of the parameters to be measured and the frequency of measurement.

13.10.2 Monitoring for the assessment of occupational exposure and doses

The main purpose of the dose assessment programme is to:

- Demonstrate compliance with the individual regulatory limits
- Demonstrate that doses are as low as reasonably achievable
- Provide information to be incorporated into the dose records

Exposures to radon daughters may be determined by fixed workplace monitoring, by individual monitoring or, quite commonly, by a combination of the two. Workplace monitors should be positioned where the samples are likely to be representative of the air breathed by workers. Individual dose assessments, based on workplace monitoring, should take account of the occupancy times at different locations. Individual radon monitoring of workers is generally more expensive than workplace monitoring, but may be necessary where conditions vary widely and where there is a possibility of exposures approaching or exceeding regulatory limits. It is often more convenient and cost-effective to monitor routinely the concentration of radon rather than of its daughters. In this event, it will be necessary to conduct a limited number of radon daughter measurements as well, so that a representative estimate of the equilibrium factor can be established for dose calculation purposes.

Where external gamma radiation exposure is significant enough to require monitoring (more than, say, 10% of the dose limit), it is usual to provide workers with individual dosimeters, which are inexpensive and reliable, and which can provide integrated dose measurements over periods of one to three months.

In those few areas where exposure to radioactively contaminated dust needs to be monitored, dust sampling devices may be deployed either at fixed locations or on a personal basis. Personal air sampling for gravimetric purposes is already adopted in South African mines, and is likely to be the more reliable method where a worker is exposed to widely varying dust concentrations.

13.10.3 Monitoring methods

Radiation monitoring involves using various devices and methods to detect and measure radiation levels in the environment or on individuals. A detailed description of radiation monitoring methods used generally in mining situations is provided by the IAEA (32). The methods commonly used in the SAMI are summarised below.

13.10.3.1 Radon-222 and daughter products

Most mines measure radon-222 daughters in underground mine air directly by a portable radiation spectrometer, developed especially for the SAMIas part of a SIMRAC project (28). The instrument, known as the ML98, measures individual short-lived radon daughters, as well as long-lived alpha emitters in dust and external gamma radiation. The instrument has been designed for use in the harsh environment of South African mines and is certified by the South African Bureau of Standards (SABS) as intrinsically safe.

For personal monitoring, integrated measurements of radon gas concentrations are conducted over one-month periods using passive track-etch detectors worn on the body. When alpha particles from the decay of radon impinge upon a film of plastic contained within the detector, they cause damage tracks in the material. The tracks are made detectable by chemical etching. The number of tracks is equal to the number of alpha particles that have reached the plastic and can, thus, be related to the average concentration of radon over the wearing period. The detectors, and a film processing and counting service, are available locally.

Although passive track-etch radon gas monitors are convenient and relatively inexpensive, they suffer from the disadvantage that the equilibrium factor needs to be determined separately to calculate the dose from radon daughters. The ML98 radon spectrometer is commonly used for this purpose on a spot sampling basis. A track-etch detector capable of measuring radon daughters directly was developed as part of a SIMRAC project (20), and others are available internationally. These are active dosimeters, in that a known volume of air is drawn through a filter by a battery-powered pump, and the alpha particles emitted by the radon daughters attached to the dust trapped on the filter are recorded on a nuclear track film. These devices have not yet found wide acceptance in South African mines.

13.10.3.2 External gamma radiation

Portable detectors that measure dose rates in μSv per hour directly are readily available for workplace monitoring. For personal monitoring, the Thermos Luminescent Dosimeter (TLD) is the device most suitable for the temperature and humidity conditions in mines. It is deployed for periods of up to 3 months. TLDs, and a processing service, are available locally.

13.10.3.3 Radioactive dust monitoring

Alpha radiation from dust samples collected from the workplace atmosphere is measured in the laboratory, using an alpha counter. Depending on the time that elapses between the sampling and the counting, and whether the dust contains uranium or thorium, the alpha radiation detected may or may not include a significant contribution from short-lived decay products. This needs to be considered when using the results to calculate the inhalation dose.

13.10.4 Biological monitoring

The use of biological monitoring to assess the exposure of workers has limited applicability in mining and minerals processing operations, and is generally restricted to workers in a uranium extraction plant. The solubility characteristics of uranium concentrates depend strongly on the specific extraction and postextraction conditions. Uranium contained in non-calcined or low-temperature calcined yellowcake is likely to be more biologically transportable and, in this case, routine urine analysis may be appropriate for workers handling such materials.

Workers suspected of having an accidental high intake of radioactivity, through the inhalation or ingestion of dust containing radionuclides at high concentrations, should have a urine analysis done within 24 hours of the suspected intake. Other appropriate bioassay methods, such as faecal assay, should be employed if indicated by the result of the urine analysis, to evaluate the intake and the consequent dose. Where the results of urine monitoring following a suspected high accidental intake indicate a consistently high uranium (or thorium) concentration, a measurement of the activity content of the thorax should be made with a whole-body counter.

13.11 Health Surveillance

Health surveillance of workers exposed to radiation should form part of the mine's *normal* health surveillance programme. No specific radiation-related medical examinations are required for workers exposed to radiation at mines, because there are no diagnostic tests that yield information relevant to exposure at doses below the threshold for deterministic effects. Health surveillance should, therefore, follow general occupational medical practice for determining fitness for work.

Health surveillance is the responsibility of the occupational health practitioner, whose functions include the assessment of the health of workers, ensuring the initial and continuing compatibility of the health of workers and the conditions of their work, and the maintenance of confidential medical records in accordance with regulatory requirements.

13.12 Engineering and Administrative Control Measures

13.12.1 Basic principles

Engineered control measures, such as good design, installation, maintenance, operation, administrative arrangements, and instruction of personnel, should be used to the maximum extent practicable before the use of personal protective equipment (PPE) is considered. Adequately designed and properly controlled ventilation systems are the most effective methods of minimising exposure to airborne radioactive substances in underground mines and processing plants.

13.12.2 Control of radon underground

Ventilation is particularly critical to the control of radon in underground workplaces and is the only practical means of limiting the build-up of radon daughters. Situations that need particular consideration include those where the heat load and, thus, the amount of ventilation required for cooling is moderate, where the air must travel large distances underground before reaching the workplace, where the air passes through worked-out areas, and where workplaces are ventilated in series rather than in parallel.

The degree of dust control required to provide adequate protection of workers against non-radiological dust hazards will normally be sufficient to protect against radiological hazards.

13.12.3 Control measures in ore-processing plants

In addition to dust control measures, attention should be given to good design, and operating and general housekeeping measures, including procedures for the clean-up of spills of concentrated radioactive material, to minimise the spread of radioactive contamination. Particular care is needed to protect workers carrying out maintenance operations, where they may become exposed to scales and sediments in which radionuclides have become highly concentrated.

13.12.4 Personal protective equipment

Except in the case of temporary and unforeseen situations, or for particular repair and maintenance operations, reliance on personal respiratory protective devices should be avoided. They should not be considered as a substitute for good engineering control measures. Further guidance on the use of personal respiratory protective devices is given by the IAEA (33).

Depending on the risk of radioactive contamination, overalls, head coverings, gloves, and impermeable footwear and aprons should be provided to workers whose personal clothing or skin is likely to become contaminated.

13.12.5 Personal hygiene

- Where necessary, suitable washing, showering, changing, and laundering facilities should be provided to prevent the spread of contamination.
- Appropriate attention should be given to measures for the prevention of potential intake of radioactivity through eating, drinking, and smoking, including the instruction of workers in this regard.
- Precautions should be taken to prevent the possible contamination of wounds in areas where concentrated radioactive materials are present.

13.12.6 Job rotation

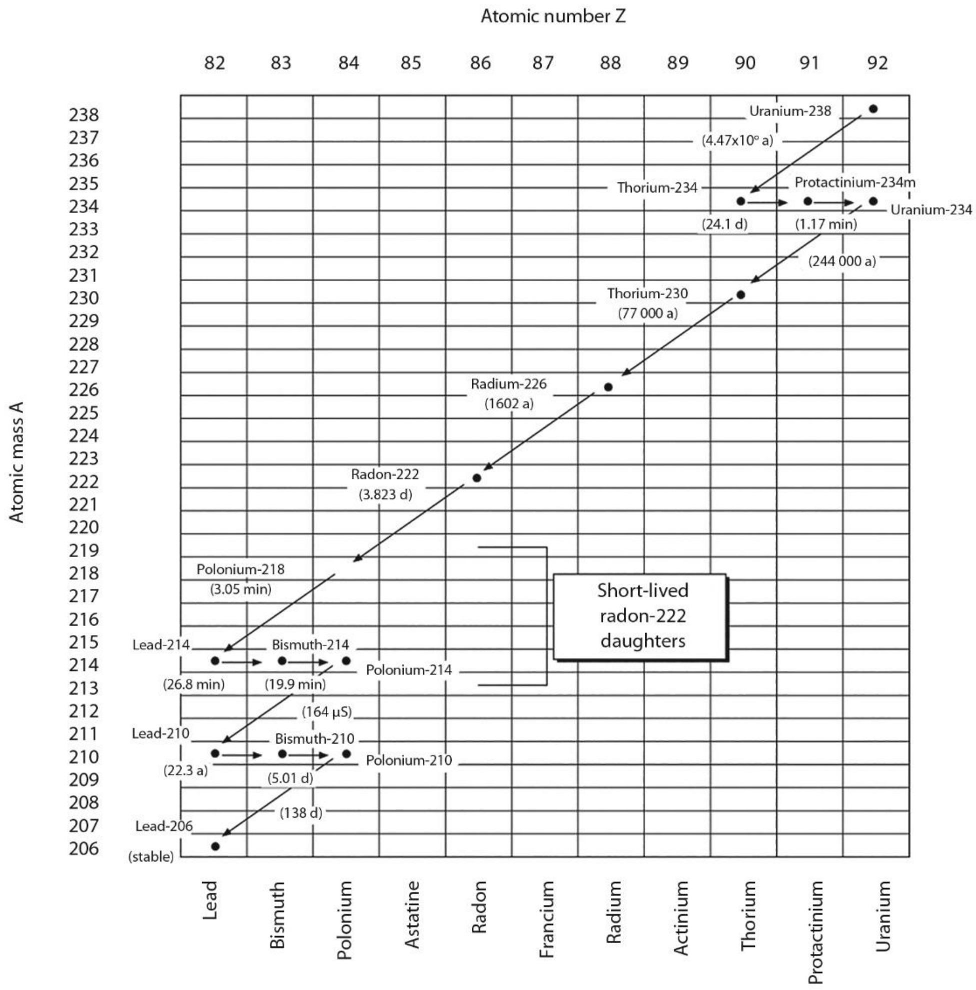
In mines having high levels of radiation exposure, when no other practical means of control are available, job rotation may be considered, in consultation with the workforce, to reduce the exposure of individual workers. Job rotation should not be used as a substitute for the development and use of other radiation control methods.

13.13 References

1. Williamson M. Building Competence in Radiation Protection and the Safe Use of Radiation Sources, Safety Guide No. RS-G-1.4. International Atomic Energy Agency Safety Standards Series, 2006.
2. South Africa. Nuclear Safety Act No. 47 of 1996. Government Printers, Pretoria.
3. South Africa. Mine Health and Safety Act No. 29 of 1996 as amended. Government Printers, Pretoria.
4. Eichholz GG. Occupational radiation protection in the mining and processing of raw materials - Safety Guide No. RS-G-1.6. International Atomic Energy Agency, 2004.
5. Zhang J, Xiang Y, Wang C, Chen Y, Tjin SC, Wei L. Recent advances in optical fiber enabled radiation sensors. Sensors, 2022 Feb. 1;22(3):1126.
6. Wakeford R. Radiation in the workplace—a review of studies of the risks of occupational exposure toionising radiation. Journal of Radiological Protection, 2009 May 19. 29(2A):A61.
7. Schmid R and Wakelam M. Radiation—ionising and non-ionising. InPrinciples of Occupational Health and Hygiene. Routledge., 2020 Jul 30 . (pp. 356-395).
8. Talapko J, Talapko D, Katalinić D, Kotris I, Erić . Health effects of Ionizing Radiation on the human body. Medicina, 2024 Apr. 18;60(4):653.
9. Douple EB, Mabuchi K, Cullings HM, Preston DL, Kodama K, Shimizu Y, Fujiwara S, Shore RE. Long-term radiation-related health effects in a unique human population: lessons learned from the atomic bomb survivors of Hiroshima and Nagasaki. Disaster medicine. 2011.
10. Laking GR. Human exposure to radioactivity from tobacco smoke: Systematic review. 21(9):1172-80. Nicotine and Tobacco Research, 2019 Sep.
11. Semenova Y, Pivina L, Zhunussov Y, Zhanaspayev M, Chirumbolo S, Muzdubayeva Z, Bjørklund G. Radiation-related health hazards to uranium miners. Environmental Science and Pollution Research, 2020 Oct. 27:34808-22.
12. Kleinerman RA, Kaune WT, Hatch EE, Wacholder S, Linet MS, Robison LL, Niwa S and Tarone RE. Are children living near high-voltage power lines at increased risk of acute lymphoblastic leukemia. American Journal of Epidemiolo, 2000.
13. Philips A. *Doll II-ELF EMFs and the Risk of Cancer.* s.l. : Docs of the NRPB, 2001. Vol. 12 No. 1.
14. Carlberg M, Koppel T, Ahonen M, Hardell L. Case-control study on occupational exposure to extremely low-frequency electromagnetic fields and the association with acoustic neuroma. Environmental research, 2020 Aug. 1;187:109621.
15. Van Deventer E. Environmental health criteria 238: Extremely low frequency fields. World Health Organization. Geneva: WHO Ofset Publication. 2007.
16. UK National Radiological Protection Board. Terrential trunked radio (TETRA): Health effects from exposure. [Online] 2001. [Cited: 28 March 2025.] https://www.gov.uk/government/publications/terrestrial-trunked-radio-tetra-health-effects-from-exposure.
17. International Commission on Non-Ionizing Radiation. Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). Health physics, 2020. 118(5):483-524.
18. Samet JM, Straif K, Schüz J, Saracci R. Commentary: mobile phones and cancer: next steps after the 2011 IARC review. Epidemiology, 2014 Jan. 1;25(1):23-7.
19. Oriowo OM, Chou BR, Cullen AP, Robinson BE. Occupational exposure to optical radiation and the ocular health status of glassblowers. Ophthalmic and Physiological Optics, 1997 Nov. 17(6):483-91.
20. International Basic Safety Standards. EB131 EB. Radiation protection and safety of radiation sources. International Atomic Energy Agency, 2014.
21. United Kingdom. Ionizing Radiation Regulations 1999. UK Legislation, 1999.
22. Protection AR. Australian Radiation Protection and Nuclear Safety Regulations 1999. Government of Australia, 1999.
23. Protection R. ICRP publication 103. Ann ICRP, 2007. 37(2.4):2.
24. International Atomic Energy Agency. HERCA Workshop on implementation of Radiation Protection Expert (RPE) & Radiation Protection Officer (RPO), Montrouge, France. [Online] 6-8 July 2015. [Cited: 10 March 2025.] https://www.herca.org/herca-workshop-on-the-implementation-of.
25. World Health Organization. Radiation protection of workers in the mining and milling of radioactive ores. Code of practice and technical addendum. 1983.
26. Cruz Suarez R, Gustafsson M, Mrabit K. IAEA occupational radiation protection programme. Radiation protection dosimetry, 2001 Jul . 1;96(1-3):17-20.
27. National Nuclear Regulator. 1999-2000 NNR Annual Report . [Online] 2000. [Cited: 19 March 2025.] https://nnr.co.za/wp-content/uploads/2020/10/1999-2000-NNR-Annual-Report.pdf.

28. Van der Linde A and Roberts DA. Radiation protection. SIMRAC Final Project Report GEN 004. Mine Health and Safety Council, 1996. 1094pp.
29. Van Schalkwyk A. A radiation monitoring program in a South African gold mine. Doctoral dissertation, North-West University, 2005.
30. South Africa. National Nuclear Regulatory Act No. 47 of 1999. Government Printers, Pretoria.
31. South Africa. National Radioactive Waste Disposal Institute Act No. 53 of 2008. Government Printers, Pretoria.
32. International Atomic Energy Agency. Radiation monitoring in the mining and milling of radioactive ores - IAEA Safety Series No. 95: Safety Guide. Jointly sponsored by the IAEA, ILO and WHO, 1989.
33. International Atomic Energy Agency. Radiation protection of workers in the mining and milling of radioactive ores - IAEA Safety Series No. 26. Vienna : Code of Practice and Technical Addendum sponsored by the IAEA, ILO and WHO, 1983.

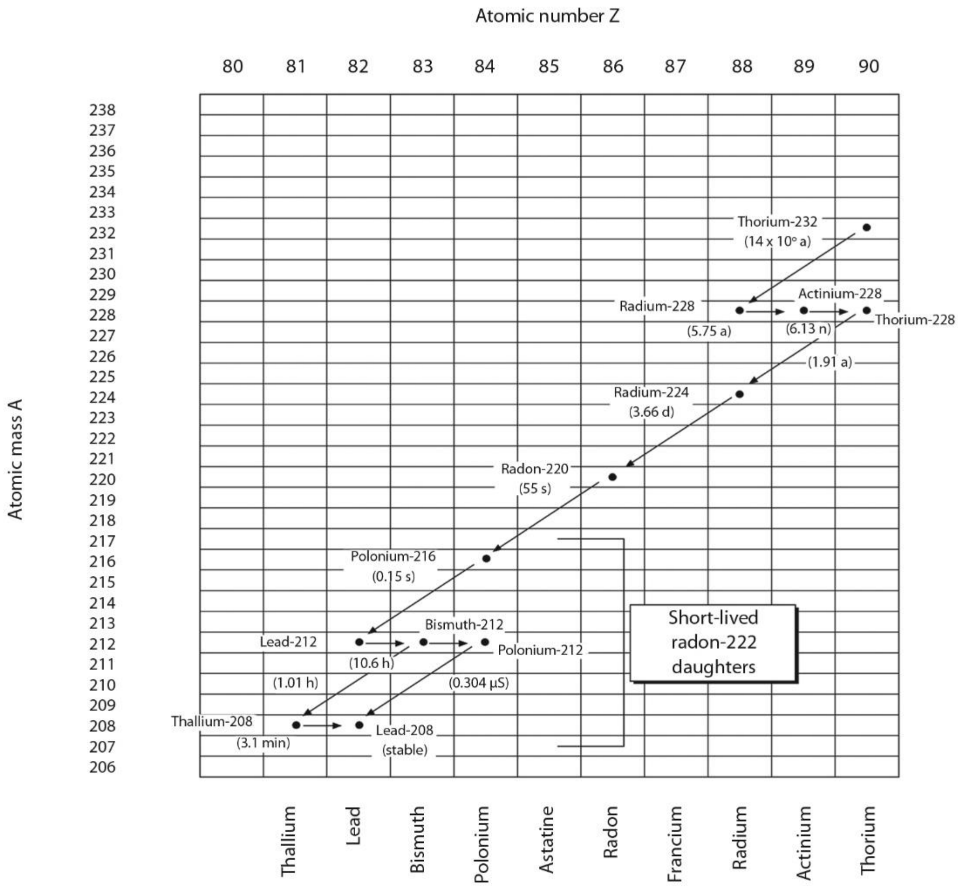
13



The time periods noted on the figure are the half-lives of the radionuclides named.

13

Figure 13.2. Uranium-238 decay chain



The time periods noted on the figure are the half-lives of the radionuclides named.

Figure 13.3. Thorium-232 decay chain

Appendix 13.2 Units of Measurement in Radiation Protection

The unit of radioactivity (or 'activity') is the becquerel (Bq), defined as one nuclear disintegration per second and having the dimension s^{-1}. The 'activity concentration' of radioactivity in a material is usually expressed in units of $Bq.g^{-1}$.

The fundamental measure of dose in radiation protection is the energy absorbed per unit mass of tissue or organ (the absorbed dose). However, the stochastic effects of radiation depend on more than just the absorbed dose. They depend also on the type and energy of the radiation (dealt with by a 'radiation weighting factor') and on the distribution of dose within the body (dealt with by a 'tissue weighting factor'). The doubly weighted absorbed dose, called the 'effective dose', then becomes the overall measure of radiation detriment or harm. The 'effective dose', often referred to simply as the 'dose', has the dimensions joule per kilogram ($J.kg^{-1}$), and is named 'sievert' (Sv). Since the sievert is a very large dose, effective dose is often expressed in µSv or mSv. When radioactive material is ingested or inhaled, it leads to varying doses to different tissues over time. The committed effective dose considers the time integral of these doses over a standard period (usually 50 years for adults and to age 70 years for children). The overall radiation detriment, taking all tissues into account, is then known as the 'committed effective dose'.

Radon in air is conveniently measured in terms of its concentration ($Bq.m^{-3}$). However, the real quantity of interest is the concentration of alpha energy available from its short-lived daughters, as this is what determines the dose to the lung. This quantity is expressed as the 'potential alpha energy concentration' (PAEC) of the short-lived daughters, expressed in units of joule per cubic metre of air ($J.m^{-3}$). If the short-lived daughters of radon-222, at a concentration of 1 $Bq.m^{-3}$, are allowed to grow into equilibrium with their parent, then the PAEC will be 5.56×10^{-9} $J.m^{-3}$. At equilibrium, the activity concentration of each daughter becomes equal to that of the parent radionuclide (radon-222).

The PAEC of any mixture of radon daughters in air can also be expressed in terms of the so-called 'equilibrium equivalent concentration' (EEC). The EEC is defined as the concentration of radon in equilibrium with its daughters that would have the same PAEC as the actual (non-equilibrium) mixture and is, thus, expressed in units of $Bq.m^{-3}$. The ratio of the EEC to the actual radon concentration will vary between 0–1, depending on the degree of ingrowth of daughters into the mixture, and is known as the equilibrium factor, F. In underground workplaces, F usually varies between 0.2 (young air, containing relatively low concentrations of radon daughters) to 0.8 (old air, containing relatively high concentrations of radon daughters). A value of 0.4 is often taken as a representative value.

The exposure of an individual to radon progeny, over a given period, is defined as the time integral of the PAEC over that period, and is expressed in units of $J.h.m^{-3}$ (or, more conveniently, $mJ.h.m^{-3}$). If the PAEC is constant, then the exposure is simply the PAEC multiplied by the exposure time in hours.

13

The dose received by workers exposed to radon-222 daughters can be determined directly from the exposure. A potential alpha energy exposure of 1 $mJ.h.m^{-3}$ will give rise to a committed effective dose of 1.4 mSv.

The dose received by workers can also be determined from the time-weighted average radon concentration, which is more readily measurable, provided that the equilibrium factor and the exposure time are known:

- A radon-222 concentration of 1 $Bq.m^{-3}$, if in equilibrium with its daughters (F = 1), would represent a radon daughter PAEC of 5.56×10^{-9} $J.m^{-3}$ (see above).
- Multiplying by 0.4 (the assumed equilibrium factor) gives an actual PAEC of 2.22×10^{-9} $J.m^{-3}$.
- Multiplying by 2 000 (the assumed annual exposure time in hours), gives an exposure of 4.44×10^{-6}

J.h.m^{-3}.

- Multiplying by 1.4 to convert to dose, gives an annual dose of 6.36×10^{-6} Sv.

13 Thus, a radon concentration of 1 Bq.m^{-3}, at an equilibrium factor of 0.4 and an annual exposure time of 2 000 hours, gives an annual dose of approximately 6 µSv.

Appendix 13.3 Regulatory Responsibilities

Minister of Mineral and Petroleum Resources

In terms of the NNRA, the Minister appoints the NNR Board members and Chief Executive Officer and, in addition to making regulations on co-operative governance agreements, must also make regulations on safety standards and regulatory practices. These regulations will establish, among other things, the criteria for determining which activities must be regulated and the general safety requirements that must be satisfied. These regulations have been drafted and are available on the NNR website.

In terms of the MHSA, the Minister of Mineral and Petroleum Resources may, after consulting the Mine Health and Safety Council (MHSC), make regulations on a wide range of health and safety matters on mines, prohibit or restrict work on mines for health and safety reasons, and declare health hazards and measures to be taken in respect thereof. These regulatory powers relate to any health hazard, including exposure to radiation.

National Nuclear Regulator

In terms of the NNRA, the NNR is responsible for exercising regulatory control over mining and minerals processing facilities to protect persons, property, and the environment against nuclear damage. This regulatory control is exercised through the granting of nuclear authorisations, the imposition of conditions of authorisation, and the implementation of compliance inspections.

The NNR's Regulatory Framework consists of legally binding requirements by international safety conventions, laws passed by Parliament that govern the regulation of South Africa's nuclear industry, regulations, authorisations, conditions of authorisations, requirements, and guidance documents that the NNR uses to regulate the industry. Requirements are developed in conjunction with the applicable authorised action, and effectively cover all the relevant requirements on the holder.

The NNR enforces these requirements on all applicants and authorisation holders. Certain requirements in the legislation are prescriptive to the extent that no further elaboration is necessary. Other requirements are broad in nature.

The NNR establishes additional requirements based on international best practices. These requirements are registered either directly in the authorisations or in 'RDs'. The following list contains mining related RDs:

- RD 004 Requirements for a Radioactive Waste Management: Mining and Minerals Processing
- RD 005 Quality Management Requirement for Activities Involving Radioactive Material: Mining and Minerals Processing
- RD 006 Requirements for the Control of Radiation Hazards: Mining and Minerals Processing
- RD 007 Requirements for the Control Over Radioactive Effluent Discharges and Environmental Surveillance: Mining and Minerals Processing
- RD 008 Requirements for Emergency Preparedness: Mining and Minerals Processing
- RD 009 Verbal Emergency Communication with the National Nuclear Regulator: Mining and Minerals Processing
- RD 010 Requirements for Radiation Dose Limitation: Mining and Minerals Processing
- RD 011 Requirements for Medical Surveillance and Control of Persons Occupationally Exposed to Radiation: Mining and Minerals Processing
- RD 012 Notification Requirements for Occurrences: Mining and Minerals Processing

- RD 013 Requirements on Public Information Document (PID) to be Produced by Applicants for New Authorisations

The authorisation holder is required, in all cases, to carry out an assessment to identify and quantify the risks. Based on the results of the risk assessment, the authorisation holder must then establish and submit to the NNR a radiation protection programme embodying accounting and record systems, controls, surveillance programmes, and reporting procedures, as required in terms of the conditions of authorisation. The areas generally covered by occupational health requirements include:

- Radiation dose limitation
- Radiation protection capability, including the availability of competent, qualified, and trained staff
- Control procedures with respect to designated areas and persons working therein
- Health surveillance
- Radiation dose monitoring
- Quality assurance
- Notification of occurrences

Mine Health and Safety Inspectorate

The Mine Health and Safety Inspectorate ensures that the provisions of the MHSA are complied with and enforced. These provisions include the identification of health and safety hazards at mines, and the elimination, control, and minimising of the associated risks. Exposure to ionising radiation is a recognised health hazard in mines and is, therefore, included in the scope of the MHSA. Specific health and safety hazards are addressed through regulations and guidelines for Codes of Practice, which are drawn up in consultation with the tripartite institutions established in terms of the MHSA (the MHSC and the Mining Regulation Advisory Committee).

National Radioactive Waste Disposal Institute

The National Radioactive Waste Disposal Institute (NRWDI) was founded to develop and implement a management approach for the long-term care and disposal of radioactive waste that is safe, technically sound, socially acceptable, environmentally responsible, and economically feasible.