RADIATION SAFETY OFFICER'S HANDBOOK

Gunhild von Oertzen
Detlof von Oertzen

RADIATION SAFETY OFFICER'S HANDBOOK

Gunhild von Oertzen

Detlof von Oertzen

RADIATION SAFETY OFFICER'S HANDBOOK

Gunhild von Oertzen

Detlof von Oertzen

Namibian
Uranium
Association

NAMIBIAN - URANIUM - INSTITUTE

NCE
Namibian Chamber of Environment

V/O CONSULTING

Title: Radiation Safety Officer's Handbook

Publisher: Namibian Uranium Institute
PO Box 2747, Swakopmund, Namibia

Authors: Gunhild von Oertzen and Detlof von Oertzen

Cover design: Sandra le Roux; emblem by Rolf Scheffer, scheffer@fotografie-werbung.de

ISBN: 978-99945-85-88-5

Year: 2018

1st Edition 2018

Citation: G & D von Oertzen, *Radiation Safety Officer's Handbook*, 2018, www.voconsulting.net

Disclaimer

This publication and the material featured herein are provided for information and training purposes, and all reasonable precautions were taken to ensure and verify the reliability and accuracy of the material featured herein. However, readers are advised that this publication is not intended to replace any regulatory, legal, or statutory information that may be applicable. Neither the authors, nor the publisher, nor any of its officials, nor any third-party contributors provide any warranty whatsoever, including as to the accuracy, completeness, or fitness in a specific context or purpose, or use of any material featured in this publication, or regarding the non-infringement of third party rights, and they accept no responsibility or liability with regard to the use of this publication and the material featured therein.

Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less.

Marie Curie

TABLE OF CONTENTS

Foreword by the Chairperson of the Namibian Uranium Association

The Namibian Uranium Association (NUA) is the representative body of the country's uranium industry. Its members include all Namibian uranium mining operations, most uranium exploration companies, and numerous associated service providers. NUA is the leading point of contact between government, the media, public and private stakeholders, and anybody interested in the positions, policies, and procedures of the NUA as they apply to the country's uranium industry. NUA promotes the industry's adherence to sustainable development, product stewardship, and the compliance with all facets of the Namibian and international legislative and regulatory environment.

NUA's members accept that product stewardship is a pillar that supports sustainable development, which ensures that the strategic and operational focus includes local economic development, environmental impact management, and social responsibilities. Product stewardship is a means to shape operational processes, products, services, and relationships, now and in future. Members accept the responsibilities of uranium stewardship by building partnerships throughout the life cycle of the product, to ensure that production, use and disposal are consistent with global best practices and sustainable development goals. NUA is cognisant that training in the field of radiation protection and applied radiation safety is and remains of critical importance. The Association's members have embraced the fact that Radiation Safety Officers must be trained, and certified, and that continuous learning and development are needed. NUA therefore initiated the creation of a variety of industry-relevant training courses, specifically those on radiation protection and radiation safety. These are offered through the Namibian Uranium Institute (NUI), and are most valuable in contributing to the ongoing development of professionals active in these important fields.

While courses are an important tool in the training of professionals, the need for a Radiation Safety Officer's Handbook as a reference volume that can be consulted whenever needed, became apparent. NUA was able to engage two experts in the field of radiation safety, and with the subsequent allocation of funds in the budget of NUI and the much-appreciated financial support of the Namibian Chamber of Environment, the project that resulted in this Handbook took shape. The two authors, Dr Gunhild von Oertzen and Dr Detlof von Oertzen, are trained nuclear physicists, and have many years of hands-on experience in the field of radiation safety. Based on this experience, they compiled an impressive book that will without doubt be *the* reference volume in radiation safety in Namibia for a long time to come.

The book will benefit anyone concerned with radiation safety, not only Radiation Safety Officers, but also members of management or other staff members of entities where radiation safety is important.

I would like to encourage NUA members and their staff to ensure the ongoing training of their Radiation Safety Officers, both through the courses offered by NUI, and the adoption and use of this Handbook, to ensure that leading best practise and the highest standards are applied in our quest for best health and radiation safety outcomes, and the protection of the Namibian uranium brand.

Percy McCallum
Chairperson
Namibian Uranium Association

Foreword by the Executive Director of the Namibian Uranium Institute

The Namibian Uranium Institute (NUI) was established by the Namibian Uranium Association (NUA), as part of the Association's commitment to product stewardship. The NUI's main purpose is to actively promote knowledge and capacity building in specialised fields such as radiation safety, environmental management, and health, and to be the communications hub for the uranium industry in Namibia.

Since 2009, NUI offers training and certification courses for Radiation Safety Officers, as well as other specialised radiation safety courses. At the time, the Atomic Energy and Radiation Protection Act had just been promulgated, necessitating the structured training of local Radiation Safety Officers. The Institute approached Dr Gunhild and Dr Detlof von Oertzen, to design and offer courses to address the national gap in radiation safety training.

The authors of this book then created numerous radiation safety courses, including the NUI's Radiation Safety Officer's Course, which is the Institute's flagship radiation safety course, and a variety of specialist radiation safety courses, including radiation safety for sealed radioactive sources, radiation safety in the transport of radioactive materials, emergency responses in case of accidents involving radioactive materials, and others.

Since the early days, the authors have continuously refined their training courses, which have matured into highly respected offerings that lay the foundation of the application of the radiation protection principles and practices in Namibia.

Dr Gunhild von Oertzen holds a PhD in Nuclear Physics, and works at Rössing Uranium Ltd, Rio Tinto, as Principal Advisor: Radiation Safety and Product Stewardship.

Dr Detlof von Oertzen holds a PhD in High-Energy Nuclear Physics, and is the director of VO Consulting, which is an independent specialist consulting firm active in energy, the environment, and radiation safety.

With these two experts, NUI regularly evaluates the training programs offered, to ensure that our courses fulfil current industry requirements and meet local needs, as well as Namibia's obligations under various international instruments and treaties.

The development of the Radiation Safety Officer's Handbook is a significant milestone. It meets local industry requirements as well as our international obligations and will further promote the application of leading best practise across industries. The Handbook condenses many years of development and refinement of radiation safety training courses into one reference text that systematically introduces all aspects of relevance for practicing Radiation Safety Officers. As such, the book is expected to appeal to professionals active in the field, and those who are just starting their careers in radiation protection. As seasoned professionals, the authors have created an accessible guide, which shares their fascination and passion for the nuclear sciences and radiation protection.

I would like to acknowledge the financial support of the Namibian Chamber of Environment (NCE), which stands for leading best practise in environmental management and conservation. NCE's assistance is highly appreciated, and greatly contributed to realise this Handbook.

I am convinced that radiation safety professionals will find this book highly educational, and inspirational, and most importantly, of practical value and useful.

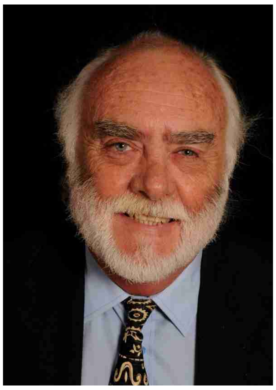
Dr Gabi Schneider
Executive Director
Namibian Uranium Institute

Foreword by the Chairperson of the Atomic Energy Board

In 2009, Namibia's Atomic Energy Board was established, following the promulgation of the Atomic Energy and Radiation Protection Act, 2005, Act No. 5 of 2005. This has since led to the establishment and operationalisation of the country's regulatory authority for radiation-related matters, i.e. the National Radiation Protection Authority, and various other initiatives.

Despite many ongoing challenges, including human, financial and technical resource constraints, the Atomic Energy Board is making steady progress in creating and applying the necessary governance structures and instruments that enable us to effectively guide and oversee Namibia's efforts and commitment to apply safe operating practices in all spheres in which nuclear material and sources of radiation are used in Namibia.

The Board is cognisant that relevant training in the field of radiation protection and applied radiation safety is and remains of critical importance. To this end, the Board devised guidelines for minimum training requirements of Radiation Safety Officers and has facilitated the formulation and implementation of various training courses that are now regularly offered by tertiary institutions as well as industry bodies, such as the Namibian Uranium Institute. These initiatives have yielded the first locally trained Radiation Safety Officers, who are key to ensuring that practices are compliant with the stipulations of the Act, as well as the Regulations under the Act.



It is therefore most encouraging to see the publication of the Radiation Safety Officer's Handbook, which concisely and systematically introduces the foundation that every Radiation Safety Officers practicing in Namibia must have a thorough grounding in. It is also most pleasing to see that the authors of this Handbook, who are seasoned professionals and pioneers who have developed the groundwork and taught applied radiation protection in Namibia from the very beginning, have decided to put their in-depth knowledge and experience in writing, thereby providing a tangible guide for future generations of professionals who are or want to become active in the field of radiation protection and radiation safety in Namibia.

It is without doubt that the application of the nuclear sciences, and the use of radiation sources, will continue to expand in years to come. Applications in many diverse fields, such as human health, the mining sector, the water and agricultural sectors, food as well as numerous applications in science and technology are already plentiful. In all these endeavours it is essential that potentially adverse impacts on humans and the environment are minimised, and that activities are compliant with local as well as international laws and regulations. This necessitates well educated and experienced professionals who can apply the often-abstract concepts used in the field of radiation protection to everyday situations – and it is here that the present Handbook will be of great benefit, especially for Radiation Protection and Radiation Safety Officers, and other radiation practitioners, irrespective of which nuclear or radiation-related field they are active in.

I am convinced that this Handbook can substantially contribute to bolster the expertise of both aspirant as well as experienced radiation protection professionals, and thereby strengthen the scientific and technical basis required to further advance the nuclear sciences and applied radiation protection in Namibia.

Dr Wotan Swiegers
Chairperson
Atomic Energy Board

Foreword by the Director-General of the Regulatory Authority

The National Radiation Protection Authority (NRPA) is Namibia's Regulatory Authority for all matters relating to radiation protection and radiation safety in the country. Established under the Atomic Energy and Radiation Protection Act, Act No. 5 of 2005, the NRPA's duties include:

a) the Atomic Energy Board's secretariat;

b) keeping the Board informed about radiation exposures and related matters;

c) inspecting radiation sources and nuclear material, to assess radiation safety conditions and other requirements, as per the Act;

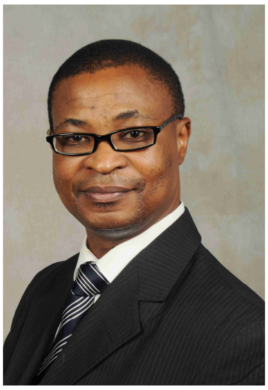
d) enforcing the provisions of the Act;

e) maintaining registers of radioactive materials, and premises where radiation sources are installed, stored, and used, and of entities that dispose of radioactive waste, and licensing importers, users, transporters, and exporters of radiation sources; and

f) facilitating compliance of Namibia's obligations related to international legal instruments in the sphere of nuclear energy and radiation safety.

Establishing and operationalising the NRPA has often been most demanding. Numerous challenges have been over-come since the Authority became active in 2009. While fully operational, the NRPA continues to experience a variety of challenges in meeting its day-to-day responsibilities, notably because of the limited human capacity pool, as well as technical and financial limitations.

As the country's Regulatory Authority, the NRPA interacts with all actors and entities that are contemplating and using sources of radiation, irrespective of the sector in which such players are active. Amongst others, this necessitates close interactions with all stakeholders, and their awareness of and understanding of the country's legal and regulatory requirements relating to radiation protection and radiation safety. Often, this is difficult, as stakeholder awareness and the technical understanding of the requirements to become and remain complaint with Namibia's legal and regulatory frameworks is limited. In this regard one cannot overemphasise the pivotal role that well-trained and experienced human resource capacities play, both as staff of the NRPA, as well as in mining, commerce, and industry.



Supported by international cooperation agreements, including with the International Atomic Energy Agency and others, our staff has benefitted tremendously from repeated training courses held in the past. Also, our tertiary education institutions have initiated courses of relevance to those active in radiation protection. These endeavours were complemented by hands-on industry-led courses, as offered by the Namibian Uranium Institute. Such training aims at imparting the necessary knowledge and skills on radiation protection staff, and therefore imperative.

The Radiation Safety Officer's Handbook by Dr Gunhild and Dr Detlof von Oertzen is a critically important contribution to further strengthen and enhance the national capacities in radiation protection and radiation safety in Namibia. As well-respected practicing specialists, the authors have put forward a clear, concise, and systematic write-up that will be of use to every practicing radiation protection professional. I am convinced that the Handbook will support all persons active in the field of radiation protection and enable them to attain the highest standard in regulatory compliance, and in this way, benefit Namibia's advancement in the nuclear sciences and radiation protection.

Axel Tibinyane
Director-General
National Radiation Protection Authority

Definitions

[x]	a reference to the source is provided in [x] under References, page 356
accident	any unintended event, including operating errors, equipment failures and other mishaps, the consequences, or potential consequences of which are not negligible from the point of view of (radiation) protection and (radiation) safety, [1]
Act	Atomic Energy and Radiation Protection Act, Act 5 of 2005, [2]
activity	the quantity A for an amount of radionuclide in a given energy state at a given time, defined as $A(t) = dN / dt$, where dN is the expectation value of the number of spontaneous nuclear transformations from the given energy state in the time interval dt. The SI unit for activity is reciprocal second (s^{-1}), termed Becquerel and abbreviated Bq, [1]
ALARA	the principle of optimisation states that radiation safety must be optimised to ensure that the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures are to be kept as low as reasonably achievable, economic, and social factors taken into account
ambient	of the surrounding area or environment
annual dose	the dose from external exposure in a year plus the committed dose from intakes of radionuclides in that year, [1]
approval	the granting of consent by a regulatory body, [1]. In Namibia, the regulatory body is termed the regulatory Authority, or Authority.
area monitoring	a form of workplace monitoring in which an area is monitored by taking measurements at different points in that area, [1]
assessment	the process, and the result, of analysing systematically and evaluating the hazards associated with sources and practices, and associated protection and safety measures, [1]
authorisation	the granting of a written permission to a person, practice, or organisation (the operator) to conduct specified (radiation-relevant) activities
Authority	National Radiation Protection Authority (of Namibia), [2]
bioassay	procedure to determine the nature, activity, location, or retention of radionuclides in the body by direct (in vivo) measurement, or by in vitro analysis of material excreted or otherwise removed from the body, [1]
clearance	the removal of regulatory control applied for radiation protection purposes from radioactive material in an authorised practice
clearance level	a value, established by a regulatory body and expressed in terms of activity concentration, at or below which regulatory control applied for

	radiation protection purposes may be removed from a source of radiation in an authorised practice
committed dose	the lifetime dose expected to result from an intake, [1]
confinement	prevention or control of releases of radioactive material to the environment in operation or in accidents, [1]
containment	method or physical structure designed to prevent or control the release and the dispersion of radioactive material, [1]
contamination	radioactive material on surfaces, or within solids, liquids or gases (including the human body), where their presence is unintended or undesirable, or the process giving rise to their presence in such places, [1]
control	in relation to any juristic person, control means the power, directly or indirectly, to direct or cause the direction of the management of that person, whether through the ownership of shares, voting, securities, partnership, or other ownership interests, or through agreements or otherwise, [2]
controlled area	a defined area in which specific protection measures and safety provisions are or could be required for controlling exposures or preventing the spread of contamination in normal working conditions, and preventing or limiting the extent of potential exposures, [1]
decontamination	the complete or partial removal of contamination by a deliberate physical, chemical, or biological process, [1]
disposal	regarding radioactive waste, disposal includes its removal, deposit, or destruction, its discharge, whether into water, air, sewer or drain, or its burial, [2]
dose	a measure of the energy deposited by radiation in a target. This may result in an absorbed dose, committed equivalent dose, committed effective dose, effective dose, equivalent dose, or organ dose, as indicated by the context, [1]
dose limit	the prescribed maximum value of the effective amount of radiation to which a person has been exposed, as determined in a manner as prescribed in the Act, [2]
dose assessment	assessment of the dose(s) to an individual or group of people, [1]
dose limit	the value of the effective dose or the equivalent dose to individuals in planned exposure situations that is not to be exceeded, [1]
dose constraint	a prospective and source related value of individual dose (dose constraint) or of individual risk (risk constraint) that is used in planned exposure situations as a parameter for the optimization of protection and safety for the source, and that serves as a boundary in defining the range of options in optimisation, [1]

dust	solid particles, ranging in size from less than 1 μm up to 100 μm, which may be or become airborne, depending on their origin, physical characteristics, and ambient conditions
effective dose, E	the quantity E, defined as a summation of the tissue or organ equivalent doses, each multiplied by the appropriate tissue weighting factor, [1]
emergency	a non-routine situation that necessitates prompt action, primarily to mitigate a hazard or adverse consequences for human health and safety, quality of life, property, or the environment. This includes nuclear or radiological emergencies and conventional emergencies such as fires, release of hazardous chemicals, storms, or earthquakes. It includes situations for which prompt action is warranted to mitigate the effects of a perceived hazard, [1]
emergency plan	a description of the objectives, policy, and concept of operations for the response to an emergency and of the structure, authorities, and responsibilities for a systematic, coordinated, and effective response. The emergency plan serves as the basis for the development of other plans, procedures, and checklists, [1]
emergency preparedness	the capability to take actions that will effectively mitigate the consequences of an emergency for human health and safety, quality of life, property, and the environment, [1]
emergency procedures	a set of instructions describing in detail the actions to be taken by response personnel in an emergency, [1]
emergency response	the performance of actions to mitigate the consequences of an emergency for human health and safety, quality of life, property, and the environment. It may also provide a basis for the resumption of normal social and economic activity, [1]
employer	a person or organisation with recognized responsibilities, commitments, and duties towards a worker in the employment of the person or organisation by a mutually agreed relationship. A self-employed person is regarded as being both an employer and a worker. [1]
environment	the conditions under which people, animals and plants live or develop and which sustain all life and development; especially such conditions as affected by human activities, [1]
environmental monitoring	the measurement of external dose rates due to sources in the environment or of radionuclide concentrations in environmental media, [1]
equilibrium equivalent concentration (EEC)	the activity concentration of ^{222}Rn or ^{220}Rn in radioactive equilibrium with its short-lived progeny that would have the same potential alpha energy concentration as the actual (non-equilibrium) mixture, [1]
equilibrium factor	the ratio of the equilibrium equivalent activity concentration of ^{222}Rn to the actual ^{222}Rn activity concentration, [1]

exemption	the determination by a regulatory body that a source or practice need not be subject to some or all aspects of regulatory control on the basis that the exposure and the potential exposure due to the source or practice are too small to warrant the application of those aspects or that this is the optimum option for protection irrespective of the actual level of the doses or risks, [1]
exemption level	a value, established by a regulatory body and expressed in terms of activity concentration, total activity, dose rate or radiation energy, at or below which a source of radiation need not be subject to some or all aspects of regulatory control, [1]
existing exposure situation	a situation of exposure that already exists when a decision on the need for control needs to be taken, [1]
exposure	the state or condition of being subject to irradiation. In this context, external exposure is exposure to radiation from a source outside the body, while internal exposure is exposure to radiation from a source within the body. [1]
exposure pathway	a route by which radiation or radionuclides can reach humans and cause exposure, [1]
fissile isotopes	radioisotopes that are capable of undergoing fission by absorbing neutrons at any energy, including low energies, i.e. 'thermal energies'. Uranium-235 is the only naturally occurring fissile isotope. Man-made fissile isotopes include uranium-233, and Plutonium-239.
fissile material	material that can sustain a chain reaction by undergoing fission when absorbing low-energy thermal (i.e. slow) neutrons. U-235, Pu-239, and U-233 are common fissile materials found in certain nuclear reactor and nuclear explosive devices. Such material undergoes fission with low-energy thermal neutrons because the binding energy resulting from the absorption of an additional neutron is greater than the critical energy required for the fission process.
fission	the splitting of the nucleus of a heavy atom into fission fragments, which are mostly in from of two lighter nuclei. The fission process is accompanied by the release of neutrons, gamma rays, and fission fragments with large amounts of kinetic energy. The absorption of a neutron usually triggers fission, but fission may also be induced by protons, gamma rays or other particles that are incident on a nucleus.
fissionable material	a nuclide that is capable of undergoing fission after capturing either high-energy (fast) neutrons or low-energy thermal (slow) neutrons. Although formerly used as a synonym for fissile material, fissionable materials also include those nuclides that can only undergo fission with high-energy neutrons, such as uranium-238. Fissile materials, such as U-235, are a subset of fissionable material.
fission products	nuclei that are created in the fission process. For example, when U-235 undergoes fission, the main fission products include isotopes of iodine,

	caesium, strontium, xenon, and barium. Almost all fission products are radionuclides too.
graded approach	for a system of control, such as a regulatory system or a safety system, a process or method in which the stringency of the control measures and conditions to be applied is commensurate, to the extent practicable, with the likelihood and possible consequences of, and the level of risk associated with, a loss of control, [1]
hazard assessment	assessment of hazards associated with facilities, activities, or sources within or beyond the borders of a state to identify: a) those events and the associated areas for which protective actions may be required within the state; b) the actions that would be effective in mitigating the consequences of such events. [1]
incident	any unintended event, including operating errors, equipment failures, initiating events, accident precursors, near misses or other mishaps, or unauthorised act, malicious or non-malicious, the consequences or potential consequences of which are not negligible from the point of view of protection and safety, [1]
individual monitoring	monitoring using measurements by equipment worn by individuals, or measurements of quantities of radioactive substances in or on, or taken into, the bodies of individuals, or measurements of quantities of radioactive substances excreted from the body by individuals, [1]
intake	1. the act or process of taking radionuclides into the body by inhalation or ingestion or through the skin, or, 2. the activity of a radionuclide taken into the body in a given time period or as a result of a given event, [1]
investigation level	the value of a quantity such as effective dose, intake or contamination per unit area or volume at or above which an investigation would be conducted, [1]
ionising radiation	for the purposes of radiation protection, ionising radiation is understood to mean radiation that can produce ion pairs in biological material(s). For most practical purposes, it may be assumed that strongly penetrating radiation includes photons of energy above about 12 keV, electrons of energy more than about 2 MeV, and neutrons, while weakly penetrating radiation includes photons of energy below about 12 keV, electrons of energy less than about 2 MeV, and massive charged particles such as protons and alpha particles, [1]
justification	1. the process of determining for a planned exposure situation whether a practice is, overall, beneficial; i.e. whether the expected benefits to individuals and to society from introducing or continuing the practice outweigh the harm (including radiation detriment) resulting from the practice, or, 2. The process of determining for an emergency exposure situation or an existing exposure situation whether a proposed protective action or remedial action is likely, overall, to be beneficial; i.e. whether the expected benefits to individuals and to society (including the reduction in radiation detriment) from introducing or continuing the

	protective action or remedial action outweigh the cost of such action and any harm or damage caused by the action, [1]
limit	the value of a quantity used in certain specified activities or circumstances that must not be exceeded. For example, the authorised limit is a limit on a measurable quantity, established or formally accepted by a regulatory body, [1]
linear–no threshold hypothesis	the hypothesis that the risk of stochastic effects is directly proportional to the dose for all levels of dose and dose rate below those levels at which deterministic effects occur, [1]
member of the public	for purposes of protection and safety, in a general sense, any individual in the population except when subject to occupational exposure or medical exposure. For verifying compliance with the annual dose limit for public exposure, this is the representative person. [1]
monitoring	the measurement of dose, dose rate or activity for reasons relating to the assessment or control of exposure to radiation or exposure due to radioactive substances, and the interpretation of the results, [1]
natural background	the doses, dose rates or activity concentrations associated with natural sources, or any other sources in the environment that are not amenable to control, [1]
nuclear installation	a nuclear power reactor, nuclear research reactor, critical facility, conversion plant, fabrication plant, reprocessing plant, isotope separation plant, separate storage installation, or any other facility at which fresh or irradiated nuclear material or significant quantities of radioactive materials are present.
nuclear material	a) Plutonium except that with isotopic concentration exceeding 80% in Pu-238; b) uranium enriched in isotope U-235 or U-233; c)uranium containing the mixture of isotopes as occurring in nature other than in the form of ore or ore residue; and (d) any material containing one or more of the foregoing, [1]
nuclear power plant	a nuclear reactor is used as heat source to generate steam which drives a turbine connected to a generator to produce electricity
nuclear reactor	a vessel in which a nuclear fission process is initiated and sustained through the control of the nuclear chain reaction in the nuclear material. There are many types and forms of nuclear reactors, and they incorporate some or all the following key features: a vessel containing fissile or fissionable material as fuel source, a moderating material, a reflector to limit the escape of neutrons, provisions to remove heat, measuring and controlling instruments, and various protective measures and devices.
(nuclear) safety	the achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection

	of workers, the public and environment from undue radiation hazards, [1]
(nuclear) security	the prevention of, detection of, and response to, criminal or intentional unauthorised acts involving or directed at nuclear material, other radioactive material, associated facilities, or associated activities, [1]
occupancy factor	a typical fraction of the time for which a location is occupied by an individual or group, [1]
occupational exposure	exposure of workers incurred in the course of their work, [1]; all exposures of workers incurred during their work, with the exception of exposures excluded in the Act, and exposures from practices or sources as are exempted under the Act occupational radiation exposure, [2]
optimisation of protection and safety	the process of determining what level of protection and safety would result in the magnitude of individual doses, the number of individuals (workers and members of the public) subject to exposure and the likelihood of exposure being "as low as reasonably achievable, economic and social factors being taken into account" (ALARA), [1]
planned exposure situation	the situation of exposure that arises from the planned operation of a source or from a planned activity that results in an exposure due to a source, [1]
potential exposure	prospectively considered exposure that is not expected to be delivered with certainty but that may result from an anticipated operational occurrence or accident at a source or owing to an event or sequence of events of a probabilistic nature, including equipment failures and operating errors, [1]
practice	any human activity that introduces additional pathways of exposure to radiation, or extends exposure to radiation to additional people, animals or plants, or modifies the network of pathways of exposure to radiation from existing services, [1]
protection and safety	the protection of people against exposure to ionising radiation or exposure due to radioactive material and the safety of sources, including the means for achieving this, and the means for preventing accidents and for mitigating the consequences of accidents if they do occur, [1]
public exposure	exposure incurred by members of the public due to sources in planned exposure situations, emergency exposure situations and existing exposure situations, excluding any occupational exposure or medical exposure, [1]
radiation detriment	the total harm that would eventually be incurred by a group that is subject to exposure and by its descendants because of the group's exposure to radiation from a source, [1]
radiation protection	the protection of people from harmful effects of exposure to ionising radiation, and the means for achieving this, [1]

radiation source	any device, radioactive material or any other material that emits radiation, [2]
radiation risks	detrimental health effects of exposure to radiation (including the likelihood of such effects occurring), and any other safety related risks (including those to the environment) that might arise as a direct consequence of: a) exposure to radiation; b) the presence of radioactive material (including radioactive waste) or its release to the environment; c) a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation, [1]
radioactive (scientific)	exhibiting radioactivity; emitting or relating to the emission of ionising radiation or particles, [1]
Radioactive (regulatory)	designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity, [1]
radioactive material	any matter or substance containing one or more radionuclides, but excluding any material where the activity or activity concentration of which does not exceed the exemption levels as prescribed in the Act, [2]
radioactive source	a source containing radioactive material that is used as a source of radiation, [1]
radioactive substance	the 'regulatory' meaning of radioactive, i.e. designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity.' The 'scientific' meaning of radioactive refers only to the presence of radioactivity and gives no indication of the magnitude of the hazard involved. [1]
radioactive waste	for legal and regulatory purposes, material for which no further use is foreseen that contains, or is contaminated with, radionuclides at activity concentrations greater than clearance levels as established by the regulatory body, [1]
radionuclide	an atom whose nucleus undergoes radioactive decay, [2]
radon	any combination of isotopes of the element radon, usually radon refers to both ^{220}Rn and ^{222}Rn, if applicable, [1]
radon progeny	the short lived radioactive decay products of ^{220}Rn and of ^{222}Rn, [1]
Regulations	Radiation Protection and Waste Disposal Regulations, under the Atomic Energy and Radiation Protection Act, 2005 (Act No. 5 of 2005), No. 211 of 2011, [3]
reference level	for an emergency exposure situation or an existing exposure situation, the level of dose, risk or activity concentration above which it is not appropriate to plan to allow exposures to occur and below which optimisation of protection and safety would continue to be implemented, [1]

risk	a multi-attribute quantity expressing hazard, danger, or chance of harmful or injurious consequences associated with exposures or potential exposure. It relates to quantities such as the probability that specific deleterious consequences may arise and the magnitude and character of such consequences, [1]
safety assessment	a review of the aspects of design and operation of a source which are relevant to the protection of persons or the safety of the source concerned, including the analysis of the provisions for safety and protection established in the design and operation of the radiation source concerned and the analysis of risks associated with normal conditions and accident situations and which contains the prescribed information and the results of such studies as may be prescribed, [2]
safety culture	the assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance, [1]
safety measure	any action that might be taken, condition that might be applied or procedure that might be followed to fulfil the requirements of safety requirements, [1]
scenario	a postulated or assumed set of conditions and/or events, [1]
SI units	the international system of units is abbreviated SI, for *Système International d'unités*, which is French for 'international system of units'. This system is used in science to uniquely express quantities. SI has seven base units, i.e. the metre, kilogram, second, Kelvin, Ampere, Candela, and mole, from which other scientific units are derived. SI units are either expressed directly, or in terms of multiple or fractional quantities. Multiple and fractional SI units use prefix multipliers, which are expressed in powers of 10. Amongst others, the SI-derived units include the Becquerel [Bq], Hertz [Hz], Joule [J], Newton [N], Volt [V], and Watt [W].
somatic effect	a radiation-induced health effect that occurs in an exposed person, [1]
source	anything that may cause radiation exposure – such as by emitting ionising radiation or by releasing radioactive substances or radioactive material – and can be treated as a single entity for purposes of protection and safety, [1]
waste	material for which no further use is foreseen, [2]
worker	a person who works and who has recognised rights and duties in relation to occupational radiation protection, [2]
workers' health surveillance	medical supervision intended to ensure the initial and continuing fitness of workers for their intended tasks, [1]
workplace monitoring	monitoring using measurements made in the working environment, [1]

Numerical Convention

1	one
1 000	one thousand
1 000 000	one million
1 000 000 000	one billion
10^0	one
10^3	one thousand
10^6	one million
10^9	one billion
$1 / 10^3 = 10^{-3}$	one thousandth
$1 / 10^6 = 10^{-6}$	one millionth
$1 / 10^9 = 10^{-9}$	one billionth

1 Introduction

Like fish in water, we live in a permanent and ever-changing sea of radiation.

Life, as we know it, depends on the presence of radiation. Yet, if radiation carries sufficient energy to be ionising, it can be harmful. Exposure to such radiation must therefore be managed. This is done to ensure that exposure doses, which are a measure of the potential risk of exposure to radiation, remain as low as reasonably achievable (ALARA).

Many contemporary applications in which radiation is important – ranging from medical and personal X-ray scanners or those used for baggage control, XRF instruments, uranium exploration and mining, the use of sealed radioactive sources, nuclear power stations, and others, may cause exposure to ionising radiation. Often unnoticed, and sometimes involuntary, exposure to radiation occurs, whether we like it or not. Radiation is therefore a key factor shaping the environment in which we live, as well as ourselves.

Because ionising radiation cannot be seen, tasted, or otherwise detected using our bodily senses, it is often difficult to objectively quantify the inherent risk of exposure to such radiation. And a risk that is not quantified is difficult to manage.

The intangible risk of exposure to radiation has contributed to create a sense of unease, or outright fear and anxiety, when issues relating to radiation exposure are considered. Also, the images of nuclear bomb blasts at Nagasaki and Hiroshima, or the nuclear accidents at Chernobyl and Fukushima and other nuclear power installations, disturb most people, and seem to imply that all matters relating to the use of ionising radiation are inherently unsafe, and therefore undesirable. This is certainly not the case: numerous applications exist where the use of ionising radiation is important and beneficial, even though exposures must be managed to keep them ALARA. A few examples include the use of ionising radiation in the field of medical diagnostics and therapy, safety scanning, as well as the multitude of applications and uses of radioactive materials in industry, medicine, agriculture, the water and food sciences, research, and many other activities.

The above is testimony that one does not need to be in favour of smoking, airline travel, uranium mining, nuclear power or other applications which are associated with ionising radiation to be interested in radiation protection or wanting to apply contemporary radiation safety practices.

It is this realisation that defines the main purpose of this book: radiation protection is the systematic endeavour to ensure that applications involving radiation are managed and undertaken in a way that ensures the safety of workers, members of the public, and the environment. Nothing less.

Radiation protection, in the context of this book, focuses on ionising radiation only. This is not to say that non-ionising radiation is entirely benign or does not necessitate active management. However, as many contemporary applications as occur in industry, medicine, mining, science, and other fields necessitate a thorough understanding of how the exposure to ionising radiation can best be managed, and minimised, this book focuses on ionising radiation only. As such, the principal goal is to understand where and how ionising radiation is likely to occur, and what the key safety measures are that will ensure that exposures are and will be kept as low as reasonably achievable. Let's get going!

Yours in radiation safety!

2 Outline

The **Table of Contents** shows that this book comprises of 31 chapters. This chapter provides a high-level overview and description of what is covered:

The first parts of the foundation required by Radiation Safety Officers (RSOs) and others active in radiation protection and radiation safety is covered in **chapter 3**, and describes the structure of matter, while **chapter 4** introduces the concepts of radioactivity and radiation.

For readers wishing to know more about uranium, **chapter 5** offers a brief introduction, and touches on aspects of Namibia's uranium exploration and mining activities.

The RSO's understanding of basic physics is further strengthened in **chapter 6**, which introduces the key interactions of ionising radiation with matter, and **chapter 7**, which introduces radiation protection and controls. **Chapter 8** summarises the main radiation-related legal and regulatory requirements as they apply in Namibia.

Every practicing RSO must be able to quantify exposure doses resulting from the exposure to radiation. Exposure doses resulting from exposure to radiation are introduced in **chapter 9**, and further refined in **chapter 10**, which presents the main techniques to calculate exposure doses.

Chapter 11 deals with radiation monitoring instruments, and their use.

Contamination with radioactive materials occurs in settings where such substances are used and is dealt with in **chapter 12**.

Chapter 13 deals with uranium exploration and mining and describes the main exposure situations encountered in this industry.

Additional must-read topics for practicing RSOs are addressed in chapters 14 to 16, which introduce approaches for a baseline radiation assessment (**chapter 14**), occupational radiation safety (**chapter 15**), and radiation safety when dealing with members of the public and environment (**chapter 16**).

Although undesirable, emergency situations can and do arise, and **chapter 17** deals with radiation-related emergency preparedness and response measures.

Practices dealing with radiation sources must ensure that they are safe and secure, these aspects are covered in **chapter 18**.

The transport of radioactive material must be undertaken in accordance with legal and regulatory provisions, as are provided by the International Atomic Energy Agency, and is introduced in **chapter 19**.

Waste management involving radioactive materials is covered in **chapter 20**.

Data management, as it pertains to exposure data, is addressed in **chapter 21**.

The daily work routine of a practicing RSO necessitates the use of some basic mathematics. Therefore, **chapter 22,** which is Appendix A, offers some tools and elementary mathematical techniques that are useful for RSOs.

Until one demonstrates that one has mastered what was taught one cannot be sure to have properly understood a subject matter. Consequently, Appendix B (**chapter 23**) provides a sample test, which should be completed in two hours or less.

The list of figures, tables and boxes which are used in this book are summarised in Appendices C, D, and E (**chapters 24, 25 and 26**) respectively.

Acronyms and abbreviations are summarised in Appendix F (**chapter 27**).

Chapter 28 provides the list of references referred to in this book, as are indicated by a number in square brackets, i.e. [y].

An index is provided in **chapter 29**.

The authors are introduced in **chapter 30**.

Chapter 31 concludes with acknowledgements, recognising the main persons and entities who enabled and contributed to the compilation of this Handbook.

3 The Structure of Matter

This Chapter provides a brief overview of the basic properties and structure of matter and introduces the atom as the elementary building block of all physical matter in the world around us.

3.1 Properties of Matter

We experience the world around us, and specifically the material objects we use, as having a variety of properties and characteristics. These include, amongst others, their temperature, how much light they reflect, their aggregate condition and viscosity, all of which can be measured and thereby quantified.

The physical properties of matter include aspects that depend on the quantity of material present, such as the volume, mass, and size, as well as other properties that are independent of the amount of material, such as the density, temperature, pressure, colour, melting and boiling point, malleability, and others.

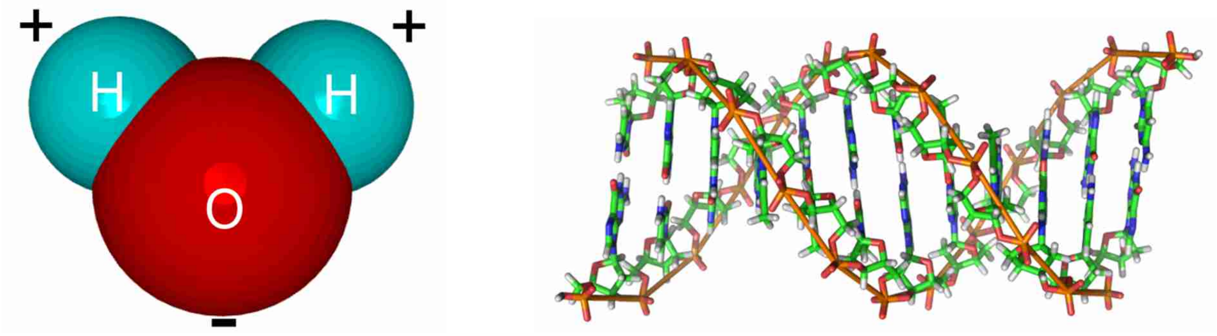
The chemical properties of matter describe the interactions of different elements with one another. These include material properties such as the solubility, reactivity, flammability, conductivity, viscosity, and others.

All matter is made up of atoms, which are the basic building blocks of the physical world in which we live. Matter consists of various types and combinations of natural elements, such as hydrogen, oxygen, iron, carbon, and others. In our daily lives, we rely on the use of and benefit from many different physical objects and materials. All such materials are made up of a small and finite number of different elements that exist in nature.

All elements are made up of atoms. These basic building blocks of matter are defined by how many protons, neutrons, and electrons they contain. The simplest atom is hydrogen, which consists of a single proton, and an electron, and no neutron. In contrast, the most complex naturally occurring atom is that of uranium. Each uranium atom has 92 protons, 92 electrons, in addition to neutrons.

A large variety of different combinations of atoms exist in nature. These are formed when their electrons bind them together. Simple combinations of atoms are called molecules. Examples include diatomic gas molecules, such as oxygen (O_2), or nitrogen (N_2). Water is a molecule. It is made up of three atoms: two hydrogen and one oxygen atom make one molecule of water, in the form of H_2O, as is illustrated in Figure 1 (left). Many complex molecules exist, and some consist of millions of individual atoms. An example of a large and most complex molecule is deoxyribonucleic acid, or DNA, which is the hereditary material in humans and most other living organisms, as shown in Figure 1 (right).

Figure 1: Water molecule (left) [6], and DNA molecule (right) [7]



3.2 The Atom

Since the earliest time, and across many of the ancient cultures, philosophers have suggested that matter consists of discrete, elementary, and indivisible units, which were termed the building blocks of matter.

The Greek philosopher Democritus, who lived some 2 500 years ago, is credited in coining the word '*atomos*', which were to indicate the smallest indivisible pieces of matter. This concept has since given rise to the modern-day word atom.

In 1904, Joseph J. Thomson proposed the so-called *plum pudding model* of the atom. It postulated that negatively charged 'corpuscles' (i.e. the electrons) were spread throughout a positively charged mass, like raisins are spread throughout the dough of a plum pudding, thereby resulting in a charge-neutral atom, as illustrated in Figure 2 (left).

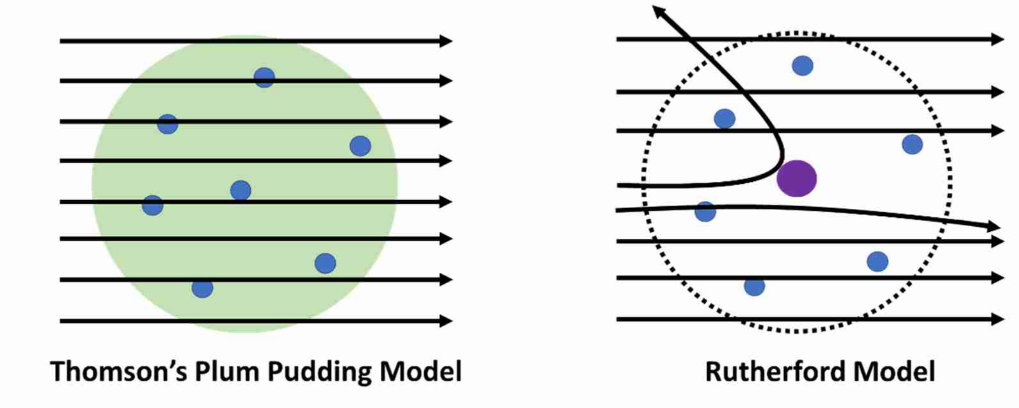
However, in 1909, Hans Geiger and Ernest Marsden, under the direction of Ernest Rutherford, who had been a student of Thomson, bombarded thin gold foils with helium nuclei (these are called alpha particles, and are made up of two protons and two neutrons each). They observed how the alpha particles were occasionally scattered from the foil. This observation contradicted the expectation raised by Thomson's model of the atom, in that alpha particles were expected to pass straight through the electric charges spread throughout the atom.

Instead, it Geiger and Marsden found that **some alpha particles were deflected from the foil**, some by more than 90°, as if they were bounced back by an object within the foil. This experimental result could not be reconciled with Thomson's model of the atom. Rutherford therefore proposed that the positive charge of an atom was concentrated in a tiny nucleus, located at the centre of each atom. This idea gave rise to the notion that atoms have an internal and therefore sub-atomic structure, as is illustrated in Figure 2 (right).

In 1913, Niels Bohr proposed the modern model of the atom, as remains in use today. It is realised that Bohr's model oversimplifies the actual atomic structure, which has since emerged from countless experiments, it still serves to explain some of the important features of an atom.

Bohr's model of the atom envisages a central inner nucleus that has a positive electric charge, which is encircled by negatively charged electrons. Distinct electron orbits exist, with a specific energy difference between one orbit and the next. Each orbit can only be populated by a given maximum number of electrons: the first orbit is home to two electrons, the second orbit contains a maximum of eight electrons, the third obit has eighteen electrons, and so on. Such electronic orbits provided the first indication of the quantum nature of the subatomic world, where matter and radiation exist only in small but fixed units, i.e. the so-called *quanta*.

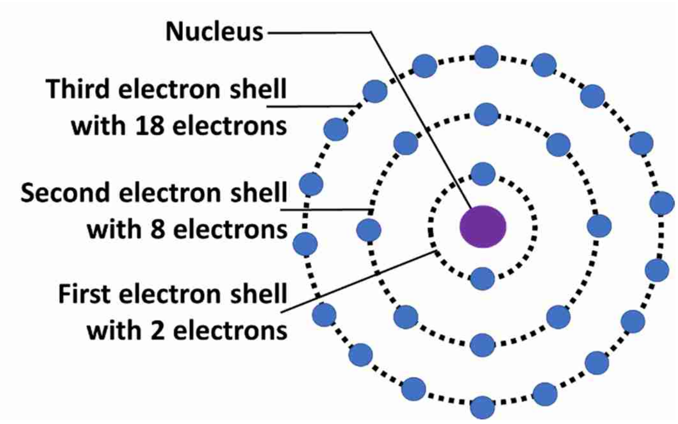
Figure 2: Thomson's plum pudding model of the atom (left), and the Rutherford model (right) [8]



Bohr's model of the atom also illustrates important aspects about the atomic structure as we understand it today, and as are shown in Figure 3:

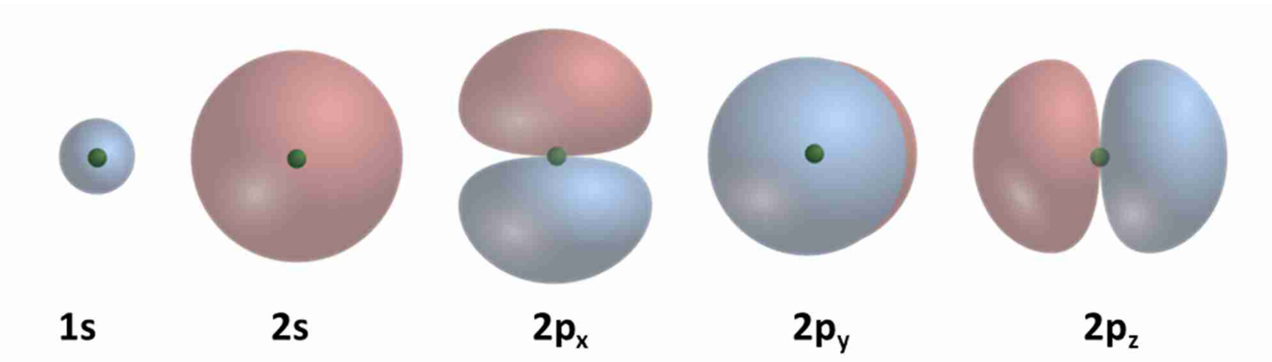
1. The atomic nucleus is positively charged. It consists of protons, which have a positive electric charge, and neutrons, which have no electric charge.
2. Negatively charged electrons move around the nucleus in orbits. Such orbits are a large distance away from the inner nucleus.
3. Almost all the total mass of an atom is concentrated in the nucleus. One therefore says that the mass of matter is mostly of *nuclear origin,* which indicates that the contribution to the total mass of an atom made by an atom's electrons is small in relation to the total mass of an atom.
4. The size of a nucleus is much smaller than the size of the atom. To illustrate: while the diameter of a *hydrogen atom* is about one Angstrom (1 Å), or 10^{-10} metres, the diameter of a *hydrogen nucleus* is about 10^{-15} metres (a femtometre, which is also called a Fermi). One therefore says that the nucleus is a factor 100 000, or five orders of magnitude, smaller that the atom.
5. The spatial dimensions of matter are therefore almost exclusively due to the size of the orbits of electrons around the *atomic nucleus*.

Figure 3: Bohr's model of the atom where electrons orbit around the nucleus [8]



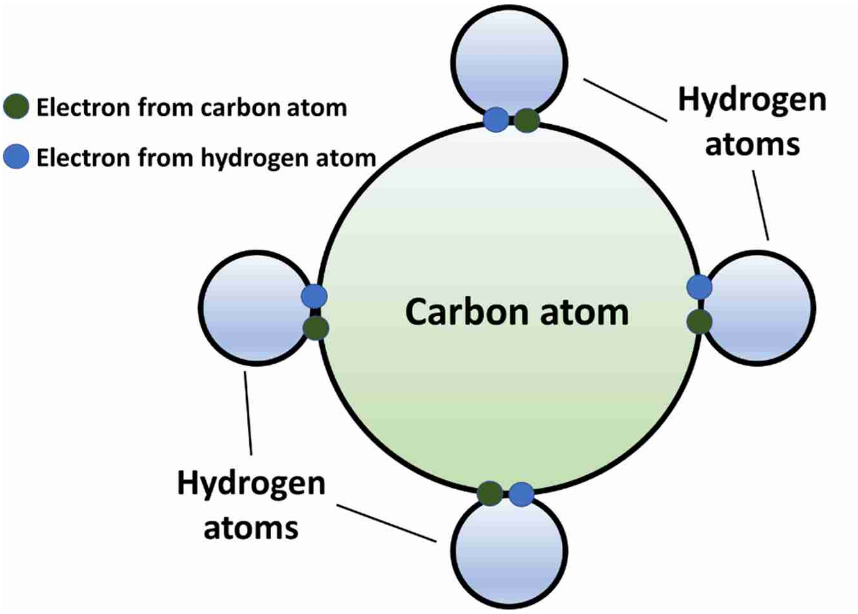
The development of *quantum mechanics* has since led to a considerable refinement of our understanding of the atom, and its structure. Today, we describe the movements of electrons around the atomic nucleus in form of probability functions, which have wave-like characteristics. In this way, the orbits of the electrons are understood to be expressed as unique wave functions that express the probability of finding an electron in a given orbit around the atomic nucleus, as is shown in Figure 4.

Figure 4: First five probability functions of the orbits of electrons around the nucleus [9]



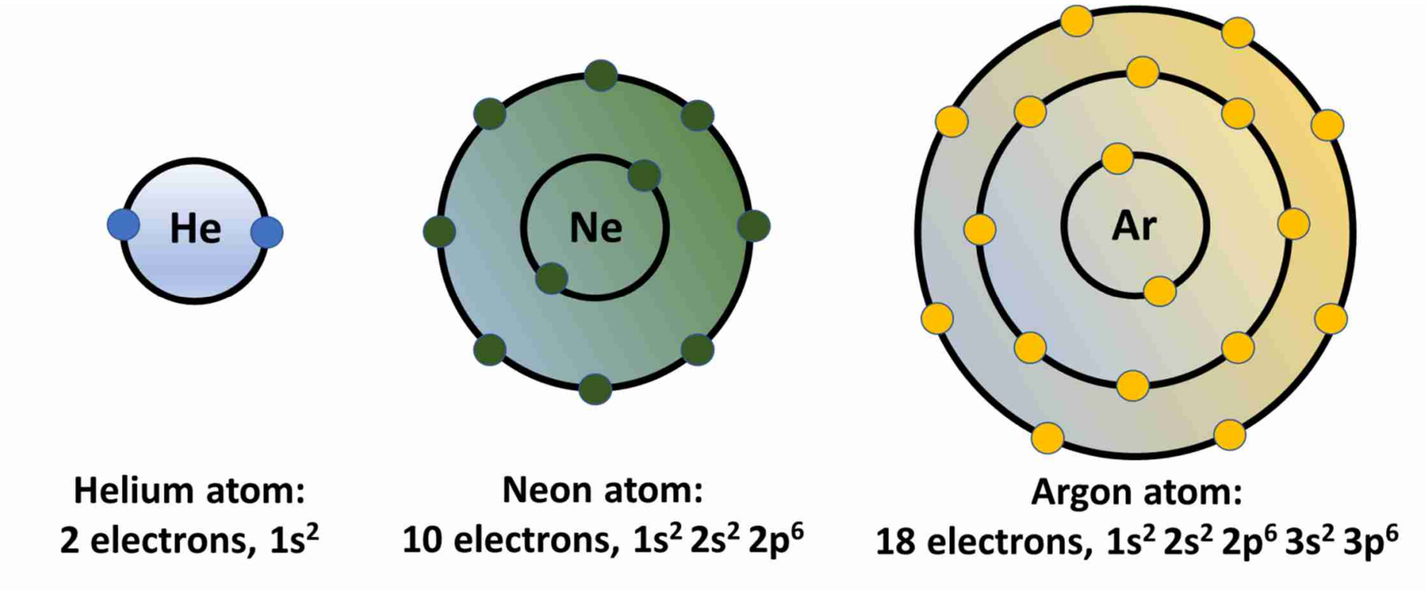
Chemical bonds between atoms occur when the electrons of atoms are shared between several atoms. In this way, electrons are the 'bonding agents' that connect atoms to one another, as is illustrated in the methane molecule shown in Figure 5.

Figure 5: Methane molecule, bonded by shared electrons of carbon and hydrogen atoms [8]



The reactivity of atoms is determined by electron vacancies, and the filling of electron orbits. If a given orbit (also referred to as shell) is filled with electrons, the atom does not readily undergo chemical reactions, as there is little potential for electrons from a full orbit to be shared with another atom. The **noble gases helium, neon and argon** are examples of atoms in which the electronic orbits are filled, as shown in Figure 6. This explains why these specific gases do not form molecules but exist as monatomic gases.

Figure 6: Bohr model of the noble gases helium, neon, and argon, with filled electron orbits [8]



3.3 The 'Emptiness' of Matter

When considering the dimensions of a typical atom, i.e. its total outer diameter versus the size of its nucleus, one realises that most of an atom consists of empty space. To illustrate: the size of a hydrogen atom is about one Å, (10^{-10} m), while the size of the hydrogen nucleus is of the order of one fm (10^{-15} m). This implies that there are five orders of magnitude difference between a hydrogen atom's outer and inner sizes. Simply said: the nucleus is *tiny* when compared to the size of the atom as a whole.

It is also helpful to reflect on the mass of the electron, versus that of the proton, which are the only two constituents of a hydrogen atom: the mass of an electron is $9.11 \cdot 10^{-31}$ kilograms (kg), while the proton's mass is $1.67 \cdot 10^{-27}$ kg. This implies that the proton is more than 1 830 times heavier than the electron and illustrates the point that most of the atomic mass is contained in the nucleus. The mass contribution of electrons to an atom can, in many calculations and circumstances, be ignored.

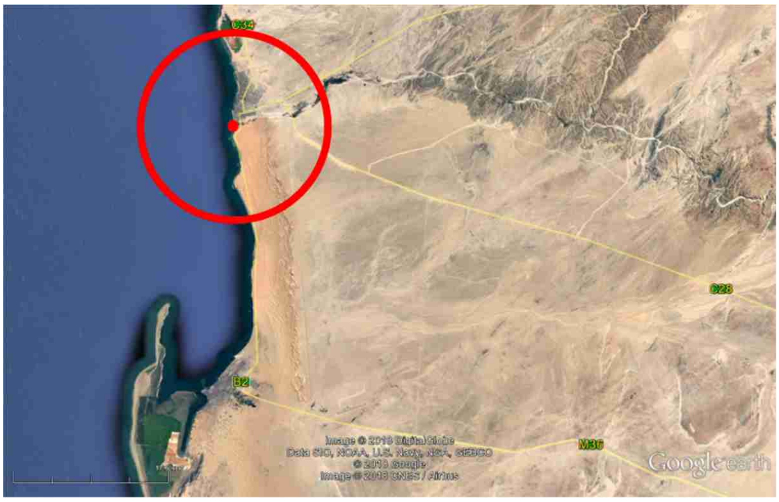
We now perform a *Gedankenexperiment*, or thought experiment, which is an experiment which we undertake by merely thinking about the issue at hand. Imagine that we increase the size of the nucleus of a hydrogen atom, from approx. 10^{-15} m, to that of a soccer ball, which has a diameter of some 0.2 m, and mass of say 0.4 kg. We thereby increase the atom's diameter from 1 fm to 0.2 m, which is an increase by a factor of $0.2/10^{-15} = 2 \cdot 10^{14}$. In this way, the electron's orbit of 1 Å, is increased by factor $2 \cdot 10^{14}$, to $10^{-10} \cdot 2 \cdot 10^{14} = 2 \cdot 10^{4}$ m. This implies that in this super-sized world, the radius of the orbit of the electron moving around the 'soccer ball nucleus' would be approx. 10 000 m, i.e. 10 km!

If one imagines the soccer ball to lie at the mouth of the Swakop River, then its 'electron' would circle it at the Swakopmund salt pans in the North, and Long Beach in the South, as is shown in Figure 7.

Realising that the ratio of the mass of the electron to the mass of the proton is approx. $5.5 \cdot 10^{-4}$, one can compute the proportional mass of the 'super-sized electron', based on the mass of the soccer ball (assume 0.4 kg). This implies $0.4 \cdot 5.5 \cdot 10^{-4}$ kg $= 2.2 \cdot 10^{-4}$ kg, or approx. 220 milligrams (mg), and therefore like the mass of about ten grains of sand with a diameter of some 2 mm each.

This thought experiment illustrates the vast difference in scales between the inner and outer dimensions of an atom such as hydrogen and highlights the enormous 'emptiness' that exists in-between the nucleus and the outer 'edges' of the atom, as are defined by the orbit of the electron.

Figure 7: Super-sizing a hydrogen atom (using Google Earth) [8]



3.4 Forces in the Atom

Modern physics recognises four fundamental forces that exist in nature:

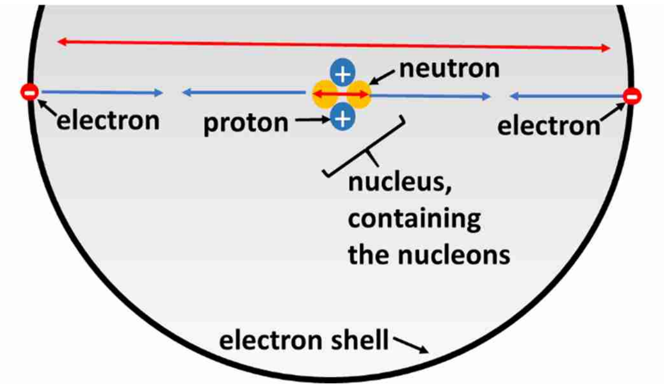
1. The gravitational force, which is attractive between all objects having a mass (which is equivalent to having an energy). For example, the gravitational force between the Earth and the Moon is responsible for keeping the Moon in orbit around the Earth. The gravitational force is a long-range force, and the weakest of the natural forces.

2. The electromagnetic force, which is attractive between opposite electric charges, and repulsive between like charges (which implies that plus is repelled by plus, and minus is repelled by minus, but plus and minus attract one another). Therefore, electrons repel each other, as they are negatively charged, while electrons and protons attract each other, as they have opposite charges. The electromagnetic force is much stronger than the gravitational force but has a shorter range than the gravitational force.

3. The strong or nuclear force, which is attractive between all *nucleons*, i.e. all particles making up a nucleus such as protons and neutrons. The strong force acts regardless of the electric charge of particles, i.e. the force of attraction between two protons is the same as the force of attraction between a proton and a neutron. The strong force is of very short range, between 1 and 2.5 fm, and rapidly tends to zero (weakens) at ranges larger than that.

4. The weak force is responsible for the transmutation of *quarks*, which are the building blocks of the nucleons. The weak force plays a role in the decay of nucleons and is responsible for the process where a neutron decays into a proton plus an electron plus an antineutrino, i.e. the beta-minus decay. The weak force is weaker than the strong and electromagnetic forces and acts at very short distances only.

Figure 8: Play of forces within an atom [8]



As illustrated in Figure 8, the forces within the atom are in constant competition with one another: t**he attractive electromagnetic force acts between electrons and protons**, and keeps electrons tied into an atom. As atoms have an equal number of protons and electrons, they are charge-neutral. Thus, positive, and negative electric charges within an atom are balanced. This makes an atom appear electrically neutral when viewed from a distance.

The attractive strong force between the nucleons, which are the protons and neutrons in the nucleus. The strong force acts as the glue between the nucleons, and is not easily overcome by the electromagnetic force, which (in the nucleus) only acts on protons. Because the strong force is of short range, the number of neutrons in larger nuclei always exceeds the number of protons.

The repulsive electromagnetic force between protons in the nucleus. If the distance between nucleons becomes large, this force of repulsion wins over the force of attraction exerted by the strong force and leads to instability in large nuclei.

The repulsive electromagnetic force between electrons in the orbit around an atom's nucleus is responsible for the considerable size of the electron cloud, when compared to the size of the nucleus.

The weak force, which contributes to nuclear stability by way of the conversion of neutrons into protons, or vice versa.

3.5 Atomic Number, Atomic Mass, and Notation

The atomic number is defined as the number of protons in a nucleus, which is abbreviated by the symbol **Z**. In a charge-neutral atom, i.e. an atom which has the same number of positively charged protons and negatively charged electrons, the atomic number Z is also equal to the number of electrons.

The atomic mass number, or mass number, A, is the sum of the number of protons Z plus the neutrons N in a nucleus, i.e.

$$\mathrm{A} = \mathrm{Z} + \mathrm{N}$$

The notation to indicate the nuclear composition of atoms is applied universally. Each element is described by its atomic number Z, its mass number A, and the chemical symbol for a given element (in this case $\boldsymbol{X}$) and is written as follows:

$$_{Z}^{A}\boldsymbol{X}$$

To illustrate: the notation $_{92}^{238}U$ indicates the element uranium. This element has an atomic number Z = 92, which is equal to the number of protons (and electrons), and atomic mass number A = 238. This implies that the nucleus, which is composed of protons and neutrons, has 238 nucleons. As A = Z + N, the number of neutrons can be determined, and is given by N = A – Z = 238 – 92 = 146.

It is noted that the element $_{92}^{238}U$ is sometimes written as $_{92}U^{238}$, or ^{238}U, or U-238.

3.6 Table of the Elements

The elements that occur naturally, or are sufficiently stable to be detected, are summarised in the *periodic table of elements,* as shown in Figure 9.

The periodic table presents the elements ordered by atomic number and grouped by chemical properties. The latter are a manifestation of the configuration of electrons in the outermost electron shell of an element. Those elements that have similar chemical properties, and therefore similar electron configurations, are clustered in columns, and are referred to as **groups**.

Each row of the periodic table corresponds to a specific electron shell within the electron configuration of an element, and each row is referred to as a **period**.

Groups with the lowest atomic numbers are named according to their chemical properties. For example, group I elements, including hydrogen (H), lithium (Li), sodium (Na) and others are *alkali metals*, while group VII elements such as fluorine (F), chlorine (Cl), bromine (Br) and others are *halogens*, while Group VIII elements such as helium (He), neon (Ne), argon (Ar) and others are *noble gases*.

Elements belonging to the same group share similarities in their atomic radius, ionisation energy, and electro-negativity. When moving from the top to the bottom within a group, the atomic radii of the elements increases, as additional electron shells are added.

When moving from the left to the right across a period, the atomic radii of elements are usually decreasing. This is because each successive element has an added proton and electron, which draws electrons closer to their nuclei and thereby reduces the atom's electronic radius.

When considering the periodic table of the elements, as shown in Figure 9, one notices that the first 94 elements, starting from atomic number 1 to 94, are naturally occurring elements. Exceptions are the elements belonging to atomic numbers 43, 61, 85 and 87, which have no stable isotopes, and only occur when synthesised.

Elements with an atomic mass of 93 and 94 are formed by the absorption of neutrons in the spontaneous fission of uranium and thorium and are therefore secondary products of naturally occurring nuclides.

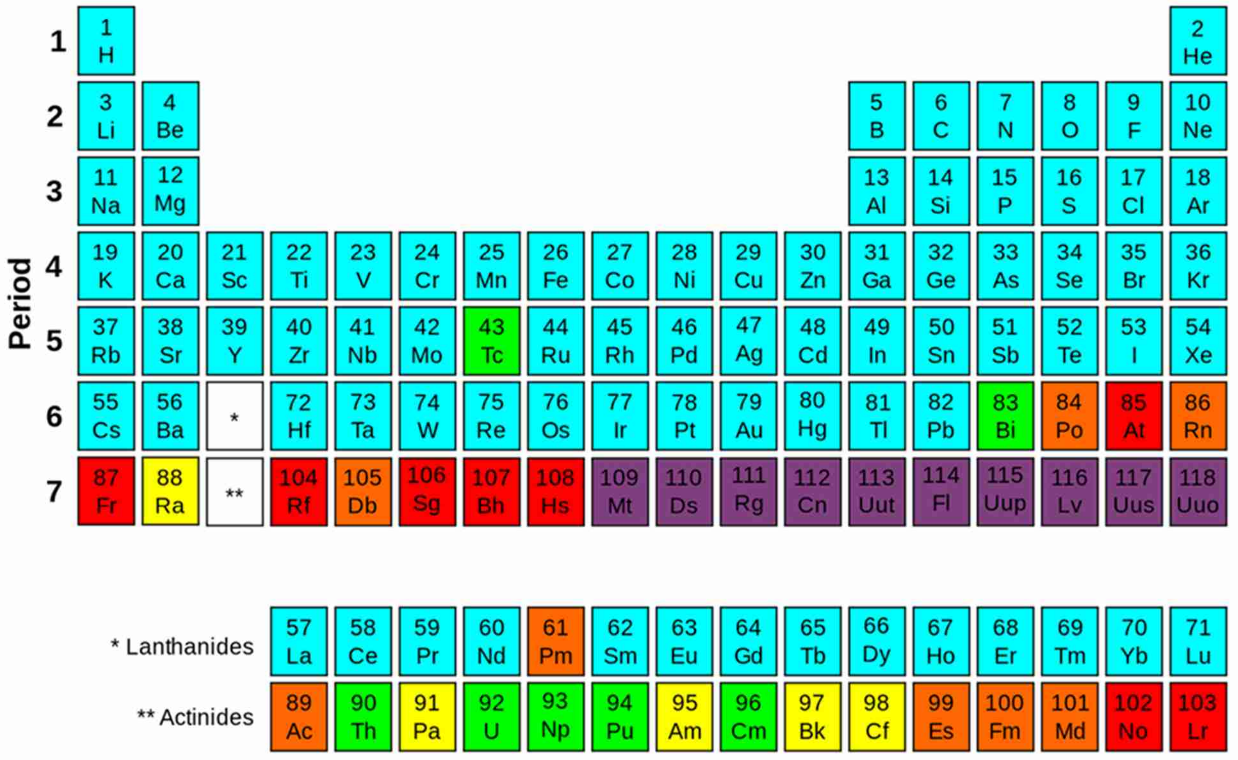
Elements with an atomic number exceeding 94, i.e. americium to ununoctium (with atomic numbers between 95 and 118), only occur when synthesised.

Of the 94 naturally occurring elements, 84 are primordial, and 10 occur only in decay chains of such primordial elements. *Primordial isotopes* are those nuclides that are found on Earth and have existed in their current form since before the formation of the Earth. Such nuclides are the residues of either the Big Bang, from cosmogenic sources, or from ancient supernova explosions, which occurred before the formation of the Earth's solar system. They are the stable nuclides, as well as those long-lived fractions of radionuclides that have survived the primordial formation processes, including those that occurred when the planet Earth was formed, and they have survived until the present day.

The colour-coding used in the table of the elements shown in Figure 9 indicates whether an element is radioactive, and if it is radioactive, how long-lived it is. The following colour code is used:

- Stable elements are shown in light blue;
- Radioactive elements with isotopes with half-lives of well over a million years are shown in green, and are considered weakly radioactive only;
- Radioactive elements with half-lives of more than 500 years are marked in yellow. The low health hazards associated with such radionuclides implies that their radiation levels are like that from natural background, which allows for some commercial applications;
- Radionuclides known to pose high safety risks are marked in orange and have half-lives of longer than one day. Their radioactivity implies that they are of little commercial use, other than as short-term radiation sources;
- Highly radioactive elements are shown in red. Their short half-lives (as low as a couple of minutes) imply that they pose a severe health risk, and their use is in most parts limited to research work; and
- Extremely radioactive elements are marked in purple. In most cases, little is known about these very short-lived elements, except when used in research.

Figure 9: Table of the elements and the radioactive properties [10]



3.7 Isotopes

Each element is uniquely defined by the number of protons in the nucleus (which is the same as the number of electrons in orbit around the nucleus).

Elements with a different number of neutrons in the nucleus are called isotopes.

However, it is important to note that the number of neutrons contained in the nucleus of a given element can differ for a specific element. When an element has several manifestations of itself, which only differ because of the number of neutrons in its nucleus, these are called *isotopes*.

To illustrate: uranium has three naturally occurring isotopes. These are U-238 (having 146 neutrons), U-235 (with 143 neutrons) and U-234 (with 142 neutrons). These uranium manifestations all have 92 protons (and therefore electrons), and hence they have identical chemical properties, as the number of electrons determines these properties. However, these isotopes differ regarding their nuclear properties, and each of these uranium isotopes has a unique (and different) number of neutrons in its nucleus.

3.8 Nuclear Binding Energy

Protons and neutrons are the constituents of atomic nuclei. One may be tempted to assume that the mass of an atomic nucleus is equal to the mass of its constituents. *This, however, is not the case*. The mass of a nucleus is always less than the sum of the masses of protons and neutrons that are its building blocks. The difference in the individual masses of the protons and neutrons in a nucleus to the actual mass of a nucleus is a measure of the *nuclear binding energy,* which is the energy that holds the nucleus together. The nuclear binding energy can be calculated using Einstein's famous mass-energy relationship, which expresses the equivalence of mass and energy, i.e.

$$E_{binding} = \Delta m \cdot c^2.$$

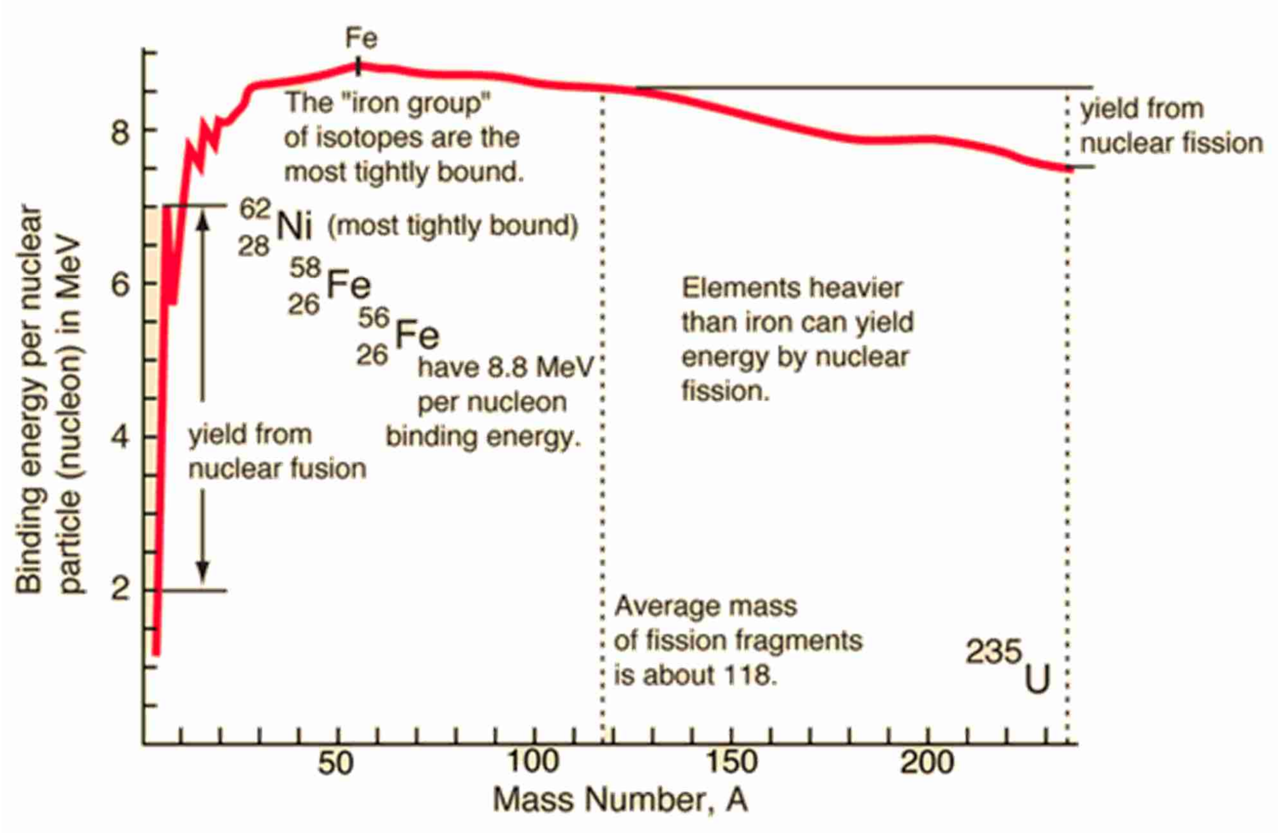
To illustrate: consider an alpha particle, consisting of two protons and two neutrons. When computing the mass of the individual constituents of the alpha particle, one finds that it is 4.03188 u, while that of an actual alpha particle is 4.00153 u (noting that one atomic mass unit u is equivalent to $1.66054 \cdot 10^{-27}$ kg). With the neutron mass of 1.00867 u, and proton mass of 1.00727 u, the mass difference Δm is 0.03035 u, which is the alpha particle's binding energy, which is equivalent to $4.5 \cdot 10^{-12}$ Joule, or 28.3 MeV.

The nuclear binding energy is the minimum energy required to disassemble a nucleus into its individual nucleonic parts. When nuclei that are heavier than iron split into two or more parts (for example as occurs when a U-235 nucleus fissions), the excess nuclear binding energy between the old and the new nuclear assemblies is emitted in terms of photons (gamma rays) and kinetic energy of the fragments, and can be used, e.g. as done in a nuclear power reactor.

Figure 10 shows the curve of the nuclear binding energy of the elements, which is obtained by dividing the total nuclear binding energy of a particular element by the number of its nucleons. Mass number 2 is deuterium, which is a hydrogen isotope with one neutron in the nucleus. As the number of nucleons is increased (think of it as adding protons and neutrons to the nucleus), the binding energy per nucleon increases, until it reaches its maximum near the atomic mass number 56, which is the mass number of the element iron.

Elements with a larger atomic mass than that of iron have a binding energy per nucleon that is less than that of iron. This implies that, when nuclei are heavier than iron, their nucleons are less tightly bound to one another than is the case in the iron nucleus.

Figure 10: Nuclear binding energy per nucleon as a function of the atomic mass number A [11]



Elements that have a nucleus that is lighter than that of iron, i.e. those having nuclei with fewer nucleons than contained in the iron nucleus, have nucleons that are less tightly bound to one another than those in the iron nucleus.

It is noted that the curve depicting the nuclear binding energy has sub-peaks, namely those at an atomic mass of four (helium), twelve (carbon) and sixteen (oxygen). This implies that such nucleonic combinations are particularly stable.

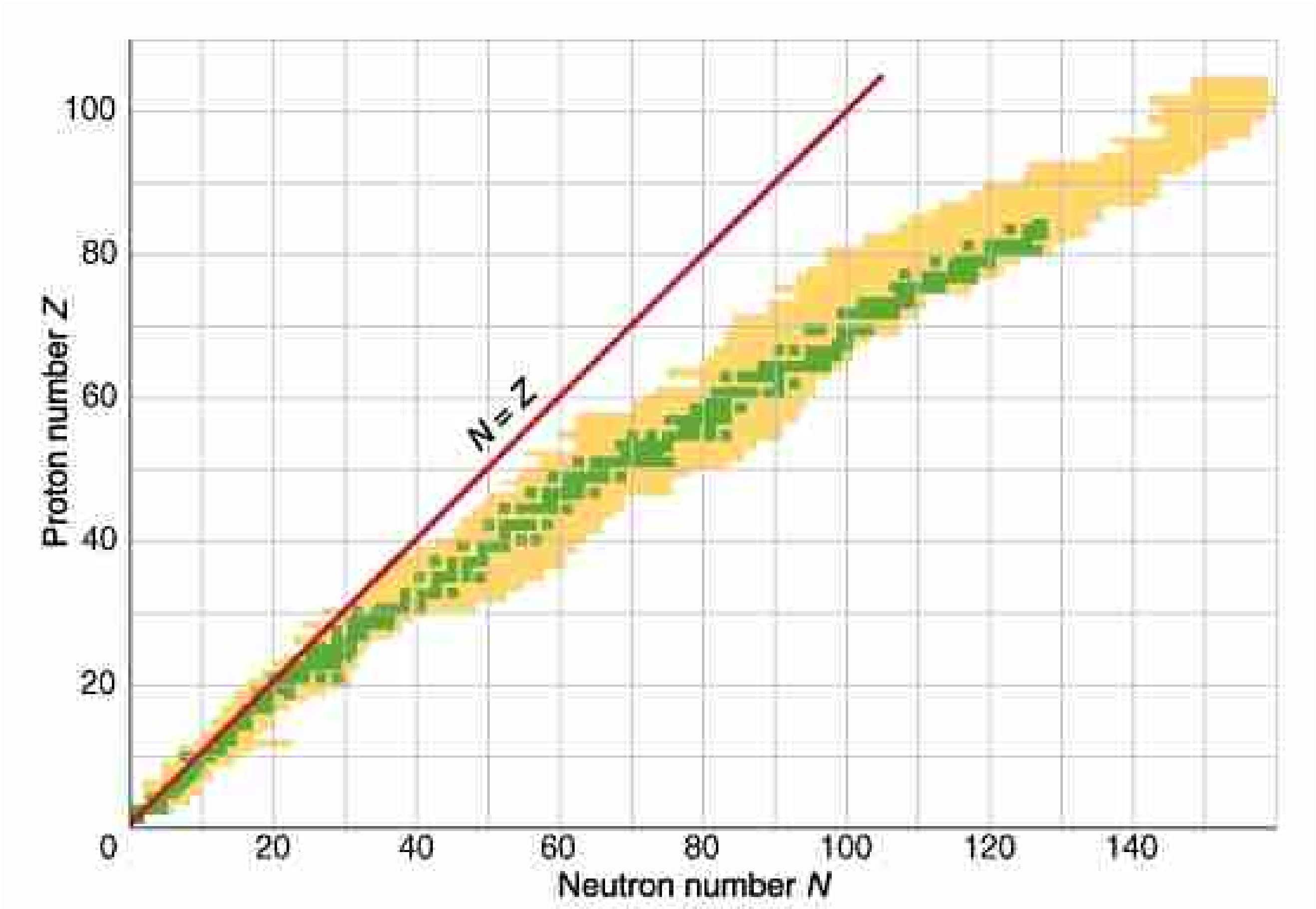
Because of the competition that exists between the strong and the electromagnetic forces in the nucleus, only a limited number of nuclei can maintain the fine balance between the interplay of these forces and are therefore permanently stable. Such nuclei remain in a state where their nucleus will not undergo a nuclear decay in time.

This brings us to the concept of *nuclear stability*, which is used to identify whether or not an isotope is stable. The two main factors that determine nuclear stability are the ratio between the protons and neutrons in the nucleus, and the total number of nucleons. When plotting the number of protons against the number of neutrons one obtains a graph of nuclear stability, as depicted in Figure 11.

Figure 11 shows those combinations of protons and neutrons that result in stable isotopes, which are indicated as green squares. Isotopes that find themselves close to this "line of stability" may exist temporarily but will eventually decay – by way of a radioactive decay – into an isotope that is on or at least closer to the line of stability.

It is noted that the line of nuclear stability, as is depicted by the green squares shown in Figure 11, is below the line N = Z, i.e. the line where the number of neutrons is equal to the number of protons. This is because as the number of protons increases, the maintenance of nuclear stability necessitates that there are more neutrons in the nucleus than there are protons, to overcome the electromagnetic force of repulsion between protons. This implies that heavy nuclei are only stable if they contain more neutrons than protons, i.e. when N > Z, which ensures that the electromagnetic force of repulsion between protons can be mitigated and overcome by the strong force that acts between and amongst the nucleons in the nucleus.

Figure 11: Nuclear stability chart – stable combinations of protons and neutrons in green [12]



3.9 Exercises

3.9.1 Periodic Table

1. Use a periodic table of the elements to answer the following questions:

   a) How many protons do the elements Rn, Ra, Ac, Th, U have?

   b) What is the atomic number of Rn, Ra, Ac, Th, and U?

3.9.2 Uranium Isotopes

1. Consider the naturally occurring isotopes of the element uranium to answer the following:

   a) How many neutrons do these isotopes have?

   b) How many protons do these isotopes have?

   c) How many electrons do these isotopes have?

   d) What is the key difference between these isotopes?

3.9.3 Mass Number

1. Which element has the mass number 209, and atomic number 83?
2. Can there be more than one element with neutron number 138?
3. Can there be more than one isotope of the same nuclide with the same number of neutrons?

3.9.4 Forces in the Atom

1. Which of the following statements is correct?
   - a) The electromagnetic force can be either attractive or repulsive
   - b) The strong force is always attractive
   - c) The strong force does not act on electrons
   - d) The electromagnetic force does not act on neutrons
2. On which subatomic particles does the electromagnetic force act?
   - a) Nucleons
   - b) Electrons
   - c) Protons and neutrons
   - d) Protons and electrons

3.9.5 Nuclear Stability

Use a chart of nuclear stability to answer the following:

- a) Which is the element that has an atomic number of 82, and has 125 neutrons? Is this element stable or unstable?
- b) Determine the number of stable and unstable isotopes of H, U, Rn, Ra, Po, Th and Pb.
- c) Is there an element Zr-120? If it exists, is it stable?
- d) Does F-18 have too many or too few protons for nuclear stability?

3.9.6 Forces in the Atom and Nucleus

Complete the table using 'A' for attractive force, 'R' for repulsive force, and 'N' for no force.

Interactions between	**Strong force**	**Electromagnetic force**
two electrons		
an electron and a proton		
two protons		
a proton and a neutron		
two neutrons		
an electron and a neutron		

3.9.7 The Atom and its Constituents

1. Which constituents of an atom determine its chemical characteristics?

   a) Number of protons

   b) Number of electrons

   c) Number of nucleons

   d) Number of neutrons?

2. Which is the more massive particle, the electron, or the proton?

3. How much larger than the nuclear diameter is the atomic diameter?

   a) 100 times

   b) 1 000 times

   c) 10 000 times

   d) 100 000 times

4. How many different elements do naturally occur in the world around us?

   a) A few millions

   b) Around 1 000

   c) 174

   d) 92

5. How many nucleons does U-234 have?

   a) 92

   b) 146

   c) 234

   d) 142

4 Radioactivity and Radiation

This Chapter introduces the concepts of radioactivity and radiation which are the principal themes of this book.

4.1 Radioactivity

Not every atomic nucleus is stable. Some nuclei undergo a decay, termed *radioactive decay*, to transition to a more stable constellation of its nuclear constituents.

Radioactive decays take place through the following decay mechanisms:

1. **Alpha decay**, where an alpha particle which consists of two protons and two neutrons is emitted from an atomic nucleus, as illustrated in Figure 12.

   An **alpha decay** is expressed as:

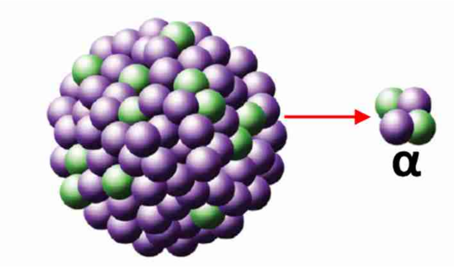
   $$\boldsymbol{{}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He}$$

   Here, a parent nucleus $\boldsymbol{{}^{A}_{Z}X}$ with an atomic mass A and atomic number Z undergoes an alpha decay. The progeny, i.e. the nucleus into which the parent decays, has an atomic mass (A – 4), which is the result of the removal of two protons and two neutrons which are carried away by the alpha particle, and an atomic number (Z – 2), as the alpha particle consists of two protons. The alpha particle in turn has an atomic mass of four, and an atomic number of two, and is the nucleus of a helium atom.

   An example of an alpha decay is the radioactive decay of U-238 to Th-234, i.e.

   $${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

Figure 12: Nuclear alpha decay [8]



2. **Beta decay,** and more specifically a *beta minus decay*, where a neutron is converted into a proton, electron, and anti-neutrino (this is the anti-particle of the neutrino), as shown in Figure 13.

   It is noted that so-called beta plus decays happen too, and such decays see the conversion of a proton into a neutron, positron (this is the anti-particle of the electron) and neutrino.

   Beta minus and beta plus decays are associated with the emission of an anti-neutrino and neutrino respectively, which are elementary particles that do not have an electric charge and are (almost) massless.

   A **beta minus decay** is expressed as:

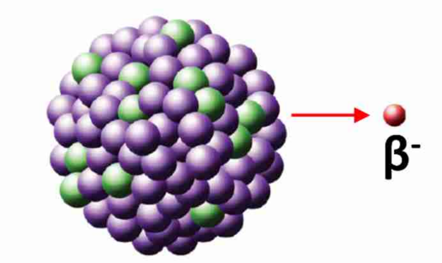
   $$\boldsymbol{{}^{A}_{Z}X \rightarrow {}_{Z+1}^{\;\;\,A}W + e^{-} + \bar{v}}$$

   Here, the parent nucleus $\boldsymbol{{}^{A}_{Z}X}$ has an atomic mass A, and atomic number Z, and undergoes a beta minus decay. The progeny has the same atomic mass as the parent, i.e. **A**, as the conversion of a neutron into a proton, electron and anti-neutrino does not change the atomic mass. However, the progeny has an atomic number (Z + 1), which is the result of the additional proton that is created when the neutron converts into a proton, electron, and anti-neutrino in the beta minus decay.

An example of a beta minus decay is the decay of carbon-14 (C-14) into nitrogen-14 (N-14), which results in the emission of an electron and anti-neutrino:

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + e^{-} + \bar{\upsilon}$$

Figure 13: Nuclear beta minus decay [8]



A **beta plus decay** is expressed as:

$$\boldsymbol{{}^{A}_{Z}X \rightarrow {}_{Z-1}^{\;\;A}W + e^{+} + \upsilon}$$

In the beta plus decay, the parent $\boldsymbol{{}^{A}_{Z}X}$ with an atomic mass A, and atomic number Z, decays into its progeny, which has the same atomic mass A as the parent. However, the progeny has an atomic number (Z - 1), which is the result of the conversion of a proton into a neutron, which results in a reduction of the atomic number by one unit, plus the emission of a positron (anti-particle of the electron, and therefore positively charged) and a neutrino.

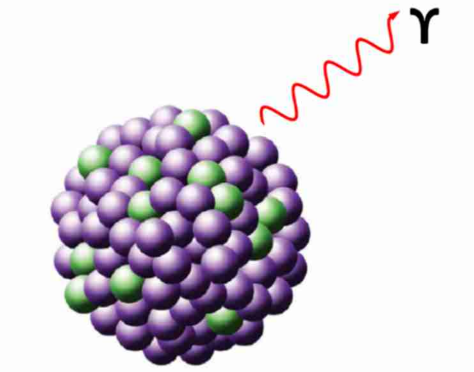
An example of a beta plus decay is the radioactive decay of magnesium-23 (Mg-23) into sodium-23 (Na-23), emitting a positron and neutrino:

$$^{23}_{12}\mathrm{Mg} \rightarrow {}^{23}_{11}\mathrm{Na} + \boldsymbol{e^{+}} + \boldsymbol{\upsilon}$$

Following an alpha or beta decay, the nucleus of the progeny undergoes a considerable nuclear rearrangement process, which leads to the emission of additional energy (other than the particles that were released as part of the decay), in form of highly energetic electromagnetic *gamma radiation*.

The gamma energy of each radioactive nucleus is specific to a given decay mode. This implies that the nuclear gamma emission spectrum can be used to identify the radionuclides present in a specific material, which has many useful applications, for example using gamma spectroscopy, and for the identification of specific radionuclides in sample material.

Figure 14: Gamma emission by way of a γ ray [8]



4.2 Discovery of X-rays and Radioactivity

In 1895, the German scientist *Wilhelm Röntgen* (refer to Figure 15) discovered X-rays .

Röntgen worked with vacuum tubes, which he filled with a special gas, through which he then passed an electric current. Such tubes would produce a fluorescent glow. When shielding the tubes with paper, Röntgen found that a green-coloured light could be seen on a screen set some distance away. He realised that he had produced an unknown form of light, which manifested itself in form of rays that were emitted from such tubes. Röntgen also noted that these rays could pass through paper shielding, and more perplexing, he found that the rays would pass through most objects in his laboratory. In addition, they would cast shadows of solid objects, a phenomenon which could be captured on photographic film.

Not knowing what these rays were, Röntgen named them *X-rays*, following the convention used in mathematics by which the letter "X" indicates an unknown quantity.

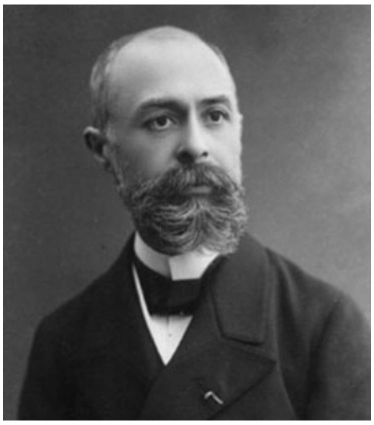
Figure 15: Wilhelm Röntgen discovered X-rays in 1895 [13]

One of the first photographic images produced using X-rays was that of the hand of Röntgen's wife, shown in Figure 16. As early as 1896, X-rays were already used for diagnostic medical purposes, specifically to detect bone fractures, and to investigate gunshot wounds. For his discovery, Röntgen was the first recipient of the Nobel Prize in Physics, which was awarded in 1901.

Figure 16: First X-ray showing the hand of Röntgen's wife in 1895 [13]

In 1896, the French scientist *Henri Becquerel* (shown in Figure 17) discovered the phenomenon which we today call *radioactivity*. At the time, Becquerel experimented with uranium-bearing compounds, specifically investigating the properties of fluorescent minerals. Becquerel's experiments often included the use of photographic film, which had to be wrapped in paper to protect it from exposure to light.

Figure 17: Henri Becquerel discovered radioactivity in 1896 [14]



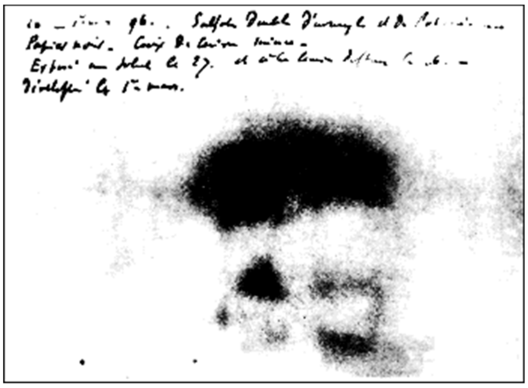
One day, Becquerel placed a piece of uranium-bearing rock on top of an unexposed film. However, as it had been a cloudy day which prevented him from exposing the sample to the sun, he placed the rock and the film in a chest of drawers.

A few days later, Becquerel decided to develop the film anyway, and then discovered that the film was showing an image of the uranium rock sample, as shown in Figure 18. As he had wrapped the film in light-proof paper, he recognised that the image could not have been due to exposure to stray light. He speculated that the image could have been caused by rays given off by the uranium compound, which had penetrated the paper shielding, thereby exposing the photographic film.

Becquerel continued to test a variety of other sample compounds and concluded that the reason for the invisible exposure was caused by the presence of the uranium-bearing substance.

Since Becquerel's discovery, the invisible agent causing the exposure of photographic plates has been named *radiation* and was found to be the result of a 'phenomenon' taking place in select substances, including uranium.

Figure 18: Image on the film exposed by radiation from a uranium compound [14]



It was *Marie Curie*, shown in Figure 19, who developed the *theory of radioactivity*, and who coined the term *radioactivity* to characterise substances that emit energetic radiation because of nuclear decays. Since then, elements that emit radiation because of radioactive decays are called *radioactive elements*, or *radionuclides*. Today, it is known that *uranium* is one of the naturally occurring radioactive elements.

Figure 19: Marie Curie developed the theory of radioactivity [15]

Marie Curie developed a variety of methods to isolate *radioisotopes* (i.e. isotopes that are radioactive), and she also discovered the radioactive elements *radium* and *polonium*.

In 1903, Marie Curie won the *Nobel Prize in Physics*, which she shared with her husband Pierre Curie and with Henri Becquerel, thereby becoming the first woman to win this prize. In 1911, Madame Curie was also awarded the *Nobel Prize in Chemistry*, thereby becoming the first person to ever be distinguished in this way.

During World War I, Marie Curie developed *mobile X-ray machines* to provide radiography services to field hospitals. Aged 66, Curie died in 1934, from significant exposure to radiation which she had incurred during her pioneering work with radioactive substances, and her considerable exposure to X-rays during the war years.

4.3 Types of Radiation

Radiation is travelling energy. Radiation is in form of electromagnetic waves or consists of highly-energetic particles. Both these fundamental manifestations of radiation are introduced in the sections below.

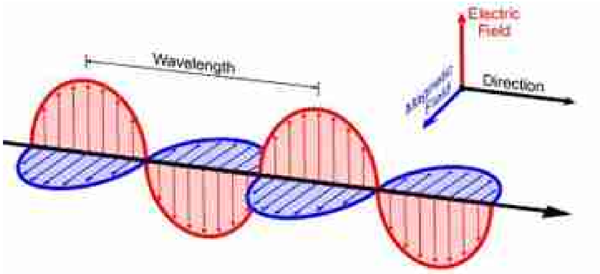
4.3.1 Electromagnetic Radiation

Electromagnetic radiation or electromagnetic waves are synchronised oscillations of electric and magnetic fields, as shown in Figure 20.

In vacuum, electromagnetic waves travel at the *speed of light*, c, which is one of the fundamental constants in nature:

$$\begin{aligned} \mathbf{c} &= \mathbf{299\,792\,458\ m/s} \\ &\approx \mathbf{3 \cdot 10^{8}\ m/s} \\ &= \mathbf{3 \cdot 10^{5}\ km/s} \\ &\approx \mathbf{10^{9}\ km/h.} \end{aligned}$$

Figure 20: Electromagnetic waves [16]



Electromagnetic radiation has a large range of origins and energies. The energy of electromagnetic radiation determines its specific properties. The energy, *E*, and wavelength, λ, of electromagnetic radiation are related by the following mathematical relationship:

$$\boldsymbol{E = h \cdot f = \frac{hc}{\lambda}},$$

where

$\boldsymbol{E}$ is the *photon energy* (the photon is the 'particle' associated with electro-magnetic radiation), in Joules [J];

$\boldsymbol{h = 6.6 \cdot 10^{-34}}$ **J·s**, is *Planck's constant,* in Joule seconds [J.s];

$\boldsymbol{f}$ is the frequency of the radiation, in Hertz [Hz];

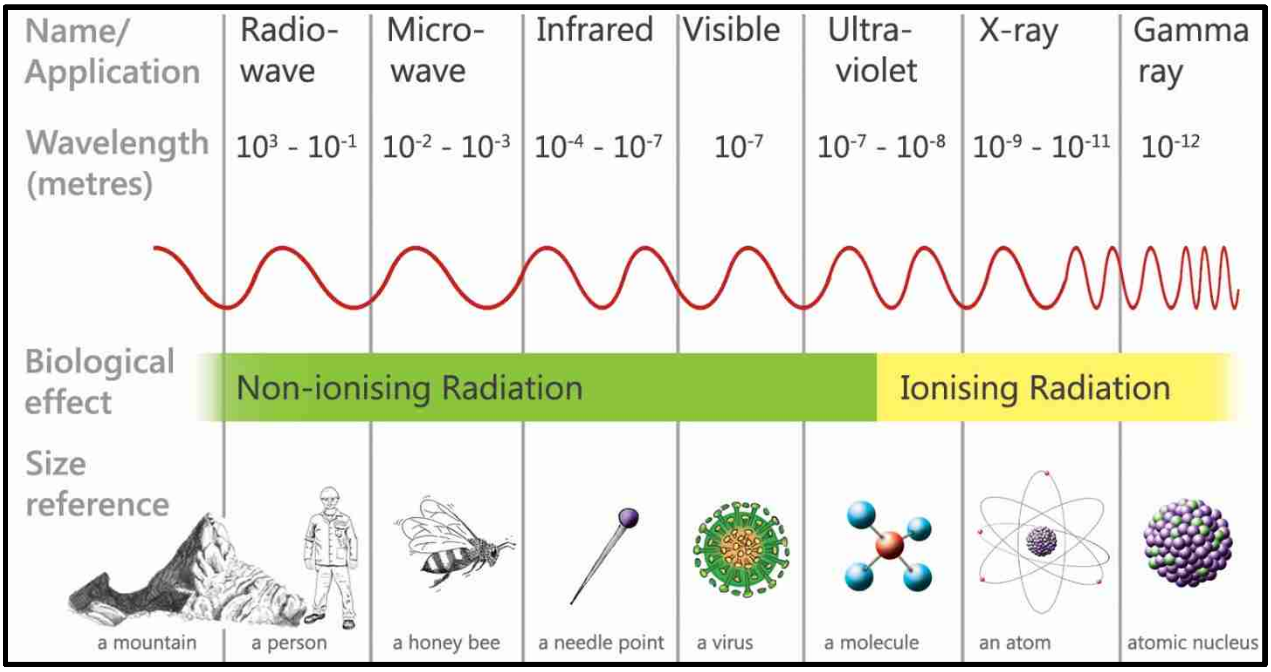
$\boldsymbol{\lambda}$ is the wavelength of the radiation, in metres [m]; and

$\boldsymbol{c}$ is the speed of light, in metres per second [m/s].

The relationship between the energy and frequency of electromagnetic radiation is such that an increased frequency implies an increase in the energy of such radiation. In contrast, the inverse relationship between the energy and wavelength of electromagnetic radiation implies that the energy increases as the wavelength decreases.

The immense spectrum of electromagnetic radiation is depicted in Figure 21. The figure also includes a brief description of the names, associated wavelengths, energies, and scales for each of the main types of this important radiation manifestation.

Figure 21: Spectrum of electromagnetic radiation [8]



Electromagnetic radiation exists in a variety of types. It can be in the form of *non-ionising radiation*, which implies that its energy is insufficient to strip off an electron from an atom. On the other hand, the electromagnetic spectrum also includes *ionising radiation*, such as hard ultraviolet light, X-ray, and gamma radiation. Ionising radiation is so energetic that it can strip off an electron from an atom, and in this way, create an *ion*, i.e. an atom that is electrically charged as it no longer has all the electrons required to render it charge-neutral.

The energy required to ionise an atom varies from one element to the next. Once radiation has an energy exceeding about 10 to 30 eV (the unit of electron-Volt, abbreviated eV, is an energy unit which is used in subatomic physics) which is characteristic of highly energetic ultraviolet radiation, such radiation is termed ionising radiation. The wavelengths associated with such radiation are in the range between 10^{-7} and 10^{-8} metres, i.e. between 100 and 10 nm (nanometres, where 1 nm = 10^{-9} m).

From the lowest to the highest energy carried by such electromagnetic radiation, one distinguishes between the following main types:

- **Radio waves**:
  Radio waves span the spectrum from the extremely low frequency band (ELF), with frequencies between 1 to 100 Hz, to the very low frequency band (VLF), with frequencies between 100 to 100 000 Hz.
  Radio waves are, amongst others, emitted by stars, lightning (which explains the interference one hears when listening to the radio during a thunderstorm) and electric sparks.
  They are used for radio communications, and its frequencies are between 100 kHz to 300 MHz.
  Of all the different electromagnetic waves, radio waves have the largest wavelengths, spanning from a few kilometres in length, down to a few metres.
  Radio waves have the lowest energy of all radiation waves in the electromagnetic spectrum.
  Radio waves are non-ionising. However, substantial long-term exposure to large doses of radio waves is believed to cause cancer, leukaemia as well as other medical conditions in humans,

and may also negatively affect other life forms.

- **Microwaves:**
  Microwaves are very high frequency radio waves, and occur in the band between approx. 300 MHz (with a wavelength of about one metre), and 300 GHz having a wavelength of about 0.1 cm.
  Technologies using microwaves include microwave ovens, mobile telephones, Wi-Fi transmitters, select fixed traffic cameras, and radar installations. In nature, stars emit microwaves.
  Microwaves are non-ionising. However, extensive exposure to microwaves is considered to negatively affect people's health. For example, persons working on aircraft carrier decks wear special microwave-reflecting suits to minimise exposure to radar units as are used on such ships.
  The World Health Organisation has advised that prolonged exposure to microwaves, as emitted by mobile phones, may negatively affect the normal functions of the brain [17].

- **Infrared radiation:**
  Infrared (IR) radiation occurs in the band between approx. 300 GHz, which has a wavelength of about one millimetre, and 430 THz, with a wavelength of about 700 nm.
  "Infra" means "below" and indicates that the energy of IR radiation is just below that of visible red light in the electromagnetic spectrum.
  Humans perceive the exposure to IR radiation as an exposure to a heat source.
  Fires and hot objects emit IR radiation, and one can feel the exposure to IR as a warm sensation on the skin. In addition, IR radiation is also emitted by stars, incandescent lights, and warm or hot objects, and humans are a source of IR radiation.
  Common remote controls for television sets, DVD and video recorders use IR radiation to convey signals between the handset and the electronic device, and IR radiation is also used for the short-range communication between a variety of mobile devices. Physio-therapists use IR lamps to stimulate and assist the body's healing mechanisms and processes.
  IR radiation is non-ionising. The risk of over-exposure is the result of overheating tissue, which is the sensation that one has when being too close to an open source of fire.

- **Visible light:**
  The eyes of humans are only sensitive to a tiny part of the electromagnetic spectrum, i.e. the visible spectrum.
  Visible light ranges from red light, that has a wavelength of 760 nm and frequency of 400 THz, to blue light, with a wavelength of 380 nm and frequency of 790 THz.
  Light waves are emitted by anything that is sufficiently hot to glow. Our eyes experience the various wavelengths within the range of visible light as having different colours.
  Visible light is non-ionising. Exposure to too much light can however damage the retina of the eye, which happens if one were to look – without using protection – at a very bright source of light, such as the sun or a welding arc.

- **Ultraviolet radiation:**
  Ultraviolet (UV) radiation has a slightly higher energy than visible light, and its wavelengths (frequencies) are between 380 nm (790 THz), and 10 nm (30 PHz).
  UV radiation is emitted by the sun, as well as by special lamps, as are for example used in tanning beds.
  UV radiation is used to kill off microbes, and UV lamps are used to sterilise surgical and related medical equipment, and the air in operating theatres. Some food and drug companies use UV radiation for product sterilisation.

The higher-energy part of the radiation in the UV spectrum is ionising. Large doses of UV can damage the eye's retina, and UV is the main contributor to sunburn when spending too much time in the open without protecting the skin. Excessive exposure to UV radiation may cause skin cancer, which is the result of the ionising characteristics of this highly energetic type of electromagnetic radiation.

- **X-rays:**
  X-rays are very high frequency electromagnetic waves and are very energetic. The wavelengths of X-ray radiation are between 10 nm (at a frequency of 30 PHz) and 0.01 nm ($3 \cdot 10^{19}$ Hz).
  X-rays are emitted by stars as well as certain stellar nebulae. In X-ray machines such radiation is generated using a beam of electrons that is accelerated to high speeds, and then fired at a "target", resulting in the emission of X-rays on impact.
  X-rays pass through most substances. This characteristic renders them useful in diagnostic medicine, as well as for industrial applications, such as the assessment of welding seams in steel and other metal joints, as is done in non-destructive evaluation and testing.
  X-rays are ionising radiation. They can cause cell damage and trigger a variety of cancers. As a result, radiographers using X-ray machines in hospitals use shielding (e.g. lead aprons) when operating such instruments.

- **Gamma rays:**
  Gamma rays are extremely high-frequency electromagnetic waves and are the most energetic form of this form of radiation.
  The wavelengths of gamma radiation are below 0.01 nm, and its frequency is above 10^{19} Hz.
  Gamma radiation is emitted by stars, and radioactive substances. They readily pass through most materials, and they are difficult to stop. In many applications, lead, concrete, or depleted uranium are used as shielding material, which attenuates gamma rays rather than stopping them completely.
  Because gamma rays can kill living cells, they are used in radiation therapy to irradiate cancer cells to kill them off without having to resort to surgery. Such radiotherapy can be effective as healthy cells can repair themselves when damaged by gamma rays, which cancer cells cannot. In another type of targeted radiotherapy, radioactive substances are injected into the blood stream and used to irradiate cancer cells, for example the use of radioactive iodine to fight cancer in the thyroid gland.
  Gamma rays are highly ionising, and can cause cell damage, and give rise to a variety of cancers. Gamma radiation also causes mutations in human tissue, especially when it is rapidly growing, which implies that unborn babies are particularly vulnerable to exposure to gamma radiation.
  Gamma radiation emitted by radioactive substances has an energy spectrum that is uniquely associated with each radionuclide. For example, the alpha decay of a U-238 atom is accompanied by gamma radiation with distinct energies of 49.5 or 113.5 keV respectively.

4.3.2 Nuclear Radiation

When atoms undergo a radioactive decay, they emit radiation. This emission of radiation is in form of one or several subatomic particles, and often gamma radiation too.

Each radioactive element decays via a specific decay mode. The decay modes can be alpha decay, or beta decay, or a ratio of alpha and beta decays. The types of radiation that are emitted in different radioactive decays includes the following:

- **Alpha radiation:** alpha particles are helium nuclei, which means that alphas are composite particles consisting of two protons and two neutrons each. Because alpha particles consist of four nucleons, they are heavy subatomic particles. In addition, alphas are doubly charged due to the two positively charged protons they contain.
  On the subatomic scale, alpha particles have a considerable mass. Because of their reactivity, alpha particles only travel for a very short distance, e.g. a few centimetres in air, before they are stopped. Alphas do not penetrate (i.e. go through) the outer layers of human skin, which are layers of dead skin cells, nor do they penetrate clothing. Exposure to alpha radiation is therefore not harmful when externally applied. When an alpha emitter is wrapped in paper, the alpha radiation emitted by the radiation source does not penetrate such shielding.
  On the other hand, alpha-emitting radionuclides that are inhaled or ingested, and thereby reach the interior unprotected parts of our bodies, are hazardous, as an alpha decay and the subsequent emission of an alpha particle implies that the energy associated with the alpha particle is readily deposited into surrounding tissue, which is a most destructive cellular process.
  A well-known example of the internal risk associated with the uptake of alpha-decaying radionuclides was the case of Alexander Litvinenko, who was poisoned by the intake of polonium-210, which is a poisonous radioactive isotope and alpha emitter, which had been added to his tea, and led to acute radiation syndrome and his death.
  The energies of alpha particles released in radioactive decays are typically between a few tenths to several MeV. For example, the alpha particle released in the decay of U-238 has an energy of 4.3 MeV.
  Irradiation with alphas does not make objects radioactive.

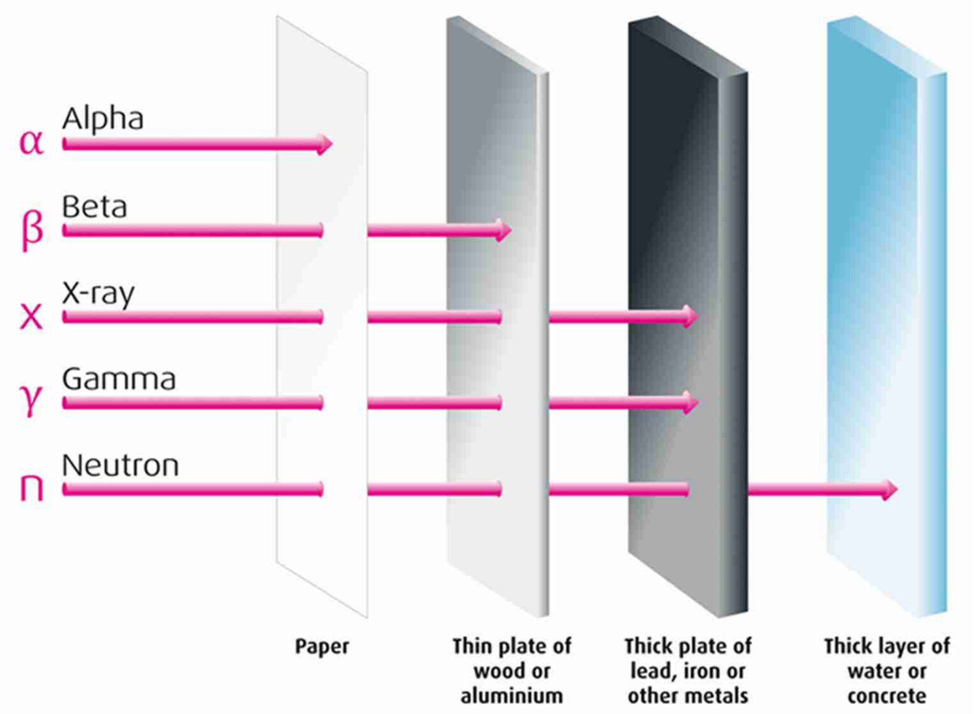
- **Beta radiation:** beta particles are electrons emitted from the nucleus during beta decay. Betas are much lighter than alpha particles, and are only singly charged, which implies that they are more penetrating and less ionising than alphas. Beta particles are stopped by a thin sheet of aluminium foil, a thick layer of plastic or many sheets of paper.
  In air, beta particles travel for several metres, while they penetrate about a centimetre deep into human tissue. If high levels of beta-emitting contaminants remain on the skin for a prolonged period, they may cause skin injury through burns.
  The energy of beta particles does not uniquely identify a specific radioactive decay, as electrons are emitted across a range of velocities (which is the result of sharing the decay energy with the antineutrino associated with beta minus decay).
  Irradiation with betas does not make objects radioactive.

- **Gamma radiation:** gamma rays are the least ionising and most penetrating of the three radiation types associated with radioactive decays. Unlike alpha and beta radiation, gamma radiation merely accompanies the emission of alpha/beta particles during a decay.
  Dense materials, such as lead, concrete or depleted uranium are used to shield against gamma radiation. It is important to recognise that ordinary clothing, including heavy-duty personal protective gear, does not provide an effective shield

against gamma radiation. Because of the penetrative capacities of gamma radiation, it is sometimes referred to as *penetrating radiation*.
Irradiation with gamma radiation does not make objects radioactive.

- **Neutron radiation:** neutron radiation consists of a free neutron, usually emitted because of spontaneous or induced nuclear fission. Neutrons can travel hundreds or even thousands of meters in air but can be effectively absorbed by hydrogen-rich material, such as gelatine, water, or concrete.
  Neutrons do not directly ionise an atom, as they are not electrically charged. Instead, ionisation from neutrons occurs indirectly, by being absorbed into the nucleus of an atom, thereby rendering it unstable and increasing the likelihood of a subsequent radioactive decay.
  Note: unlike alpha, beta and gamma radiation, irradiation with neutrons can render objects radioactive.

Figure 22: Radiation types and shielding characteristics of various materials [18]



4.4 Radioactive Half-life

The radioactive half-life is the time it takes for one half of a given substance to undergo radioactive decay.

Radioactive half-life is a measure for how radioactive a substance is: the shorter its half-life, the more radioactive it is.

Radioactive decay is governed by the *law of radioactive decay*, also called the *law of exponential decay*. It states that every unstable nucleus has a specific probability to decay at any given time. This probability of decay remains unchanged, no matter how long a given substance has existed. In other words, a given unstable nucleus does not keep the time or has a 'memory' for how long it has been around, and its probability of decay remains the same, irrespective of how long it has already existed.

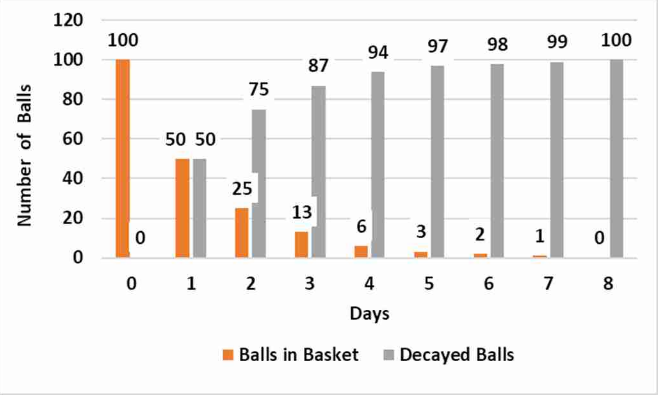
One cannot predict when a given radionuclide will decay, or which specific nucleus from a set of nuclei will decay next. The law of radioactive decay describes the statistical behaviour of a large collection of nuclei which all have identical properties. This implies that the probability of decay of a given nucleus is known and expresses the likelihood that it will decay within a specific period. To illustrate: the probability for each and every nucleus of the unstable noble gas radon, Rn-222, to decay within the next 3.8 days, is 50%. This is a statement of probability and underlies the definition of the radioactive half-life.

The following example illustrates the concept of the radioactive half-life: assume that you have a basket containing balls, and that these balls have a half-life of one day. At the start of this thought experiment, i.e. at the time t = 0, assume that you have 100 balls. After 1 day has passed, i.e. after one half-life, one half of the total number of balls has decayed. If one half of the 100 balls have disappeared because of the decays that took place within one half-life, then 50 balls remain in the basket. After the next day, i.e. at t = 2 days, one half of the remaining balls will have decayed, and one half of those remaining after day one will remain – this implies that 25 balls remain in the basket. At t = 3 days, ½ · 25 ≈ 13 balls remain in the basket, and 12 will have decayed, noting that it is not possible for one half of a ball to decay. Table 1 provides the decay history of the balls in the basket, which are also illustrated in Figure 23. No balls remain in the basket after day eight. In other words, after eight half-lives, all balls have decayed.

Table 1: Life of 100 balls with a half-life of 1 day

Time [day]	Balls in the basket	Decayed balls
0	100	0
1	50	50
2	25	75
3	13	87
4	6	94
5	3	97
6	2	98
7	1	99
8	0	100

Figure 23: Decay history of 100 balls with a half-life of 1 day [8]



The simple decay process demonstrated by 100 decaying balls in a basket illustrates that a given quantity of a radioactive substance is considered to have 'fully decayed' after eight to ten half-lives have gone by. At this point in time, a radioactive substance has decayed to such levels that its remaining contribution to the natural background radiation field can no longer be identified. Simply put: a radioactive substance has fully decayed after eight to ten half-lives have elapsed.

The half-lives of the *naturally occurring isotopes of uranium* are the following:

- U-238: 4.47 billion years;
- U-235: 704 million years; and
- U-234: 246 thousand years.

Each of the three naturally occurring uranium isotopes has a unique half-life. This also implies that the rate at which these isotopes decay is unique for each of these radionuclides.

The longest-living naturally occurring uranium isotope is U-238. Because its half-life is the largest of the three naturally occurring uranium isotopes, it is and will remain the uranium isotope that is the most abundant uranium isotope found in nature.

In the Earth's past, there was a time when the percentage of U-235 in the mix of naturally occurring uranium isotopes was much higher than it is today and allowed for chain reactions involving spontaneous fission processes to occur, provided the uranium concentration was sufficiently high. Indeed, Oklo in Gabon, which was discovered by French physicist Francis Perrin in 1972, is one such location on Earth where such self-sustaining nuclear fission reactions took place some 1.7 billion years ago and generated some 100 kW of thermal power for a few hundred thousand years.

A selection of some important radionuclides and their radioactive half-lives is listed in Table 2.

Table 2: Select radionuclides and their radioactive half-lives [18]

Element	Half-life
Pu-239	24 thousand years
Pu-238	87.7 years
U-238	4.47 billion years
U-235	704 million years
U-234	246 thousand years
Th-232	14 billion years
Ra-226	1 600 years
Rn-222	3.8 days
Rn-220	56 seconds
Cs-137	30.2 years
I-131	8 days
I-129	15.7 million years
Tc-99m	6 hours
Sr-90	28.8 years
Co-60	5.3 years
K-40	1.25 billion years
Cl-36	308 thousand years
C-14	5 730 years
H-3	12.3 years

Mathematically, the law of radioactive decay expresses the exponential rule, which is written as follows:

$$\boldsymbol{N(t) = N_0\, e^{-\lambda t} = N_0\, e^{-t/\tau}}$$

where

$\boldsymbol{N(t)}$ is the number of radionuclides present at time t;

$\boldsymbol{N_0}$ is the number of radionuclides present at time t = 0;

$\boldsymbol{\lambda}$ is the so-called decay constant, which is expressed as a rate per unit of time; and

$\boldsymbol{\tau}$ is the average lifetime of a radionuclide before decay.

As shown in Box 3, the half-life $t_{1/2}$ of a radionuclide with decay constant λ is

$$\boldsymbol{t_{1/2} = \frac{ln(2)}{\lambda} = \tau \cdot ln(2).}$$

The equations above use the natural logarithm *ln(x)*, and the exponential function $e^y = \exp(y)$. These are related to one another as:

$$\boldsymbol{ln(x) = y,}$$

with

$$\boldsymbol{e^y = x,}$$

and noting that

$$\boldsymbol{ln(1) = 0,}$$

and

$$\boldsymbol{e^1 = 2.7182.}$$

The examples presented in Box 1 and Box 2 below illustrate how the law of exponential decay is applied in practice, describing the formation of radioactive carbon and the so-called carbon-14 dating method, which is one of the important techniques that is used to determine the age of organic matter.

Box 1: Carbon-14 formation in the Earth's atmosphere

This box describes how radioactive *carbon-14*, which is abbreviated C-14, is formed in the upper layers of the troposphere and the stratosphere, in the interaction between cosmic radiation and atmospheric nitrogen.

Cosmic rays, which inundate the upper layers of the Earth's atmosphere, provide the neutron feedstock for nuclear reactions such as the following:

$$\boldsymbol{n^0 + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + p^+}$$

In this way, carbon-14 is produced in the atmosphere. The rate of production of such C-14 remains near-constant in time. This implies that the atmosphere's abundance of C-14 is well-known, and ranges between 1 and 1.5 atoms per 10^{12} carbon atoms.

The half-life of C-14 is 5 730 years. Following the law of radioactive decay, the half-life implies that there are some 14 radioactive decays taking place per minute for each gram of natural carbon, as is elaborated below.

The number of carbon atoms per gram rests on the definition of the *mole*, which is a unit of measurement in the SI for a specific amount of a given substance. The *mole* is defined as the amount of a chemical substance that contains as many representative particles, for example atoms, molecules, ions, or electrons, as there are atoms in 12 grams of carbon-12, which is expressed by the Avogadro constant, i.e. $A = 6.02 \cdot 10^{23}$ mol^{-1}.

Therefore, if 12 g of carbon contains A atoms, 1 g of carbon contains A/12 atoms. The number of carbon atoms per gram of carbon is therefore $6.02 \cdot 10^{23} / 12 = 5.02 \cdot 10^{22}$.

If there are 1.5 C-14 atoms per 10^{12} carbon atoms, the number of C-14 atoms per gram of carbon is $1.5 / 10^{12} \cdot 5.02 \cdot 10^{22} \approx 7.5 \cdot 10^{10}$.

One can now compute the number of decays taking place per minute per gram of carbon. To this end one uses the mathematical form of the exponential law, i.e.

$$\boldsymbol{N(t) = N_0\, e^{-t/\tau}}.$$

Because $\tau = \frac{t_{1/2}}{\ln(2)} \approx \frac{5\,730}{0.693} \approx 8\,267$ years, one has the following for $t = 1$ year:

$$\frac{\boldsymbol{N(1)}}{\boldsymbol{N_0}} = \boldsymbol{e^{-1/\tau}} \approx \boldsymbol{e^{-1/8\,267}} \approx 0.9998.$$

This implies that there are $N_0 - N(1) \approx N_0 - 0.9998 \cdot N_0 \approx 7.5 \cdot 10^{10} \cdot 0.0001 = 7.5 \cdot 10^6$ disintegrations (i.e. radioactive decays of C-14 atoms) per gram of carbon each year.

Dividing the number of C-14 disintegrations per gram of carbon per year by 365 days, 24 hours, and 60 minutes, one obtains the number of C-14 disintegrations per gram of carbon per minute, which is 14, as is the observed rate of the number of disintegrations of C-14 atoms per gram of carbon.

Box 2: Using the carbon-14 dating method

This box introduces the *carbon-14 dating method* for organic material, which uses the radioactive decay of C-14 to determine the age of a given sample.

The half-life of C-14 is 5 730 years. As was shown in Box 1, there are some 14 C-14 decays per minute, i.e. radioactive *disintegrations per minute* (dpm), per gram of natural carbon.

Living organisms continuously absorb atmospheric carbon. This implies that the abundance of C-14 in such a living organism is identical to that in the atmosphere. However, once the organism dies, the absorption of carbon from the atmosphere stops.

As a result, the radioactive C-14 which is contained in the organism is no longer replenished. From this point onwards, the abundance of the C-14 that remains in the organism is governed by the radioactive rate of decay of C-14, which leads to the successive depletion of C-14 from the carbon that is contained in the remnants of the dead organism.

The following example illustrates the above: an organic sample is to be dated and is measured to undergo four (4) disintegrations per minute per gram of carbon. Based on this measurement one can determine the age of the organic sample.

As shown in Box 1, the C-14 has 14 radioactive decays per minute per gram of carbon. On the other hand, the organic sample that is to be dated is characterised by only four radioactive decays per minute per gram of sample material.

Since

$$t_{1/2} = \frac{ln(2)}{\lambda} = \tau \cdot ln(2),$$

and noting that the half-life $t_{1/2}$ = 5 730 years for C-14, the average lifetime of a radionuclide before decay, τ, can be determined:

$$\tau = t_{1/2} \,/\, ln(2) = 8\,267 \text{ years.}$$

Noting that the to-be-dated organic sample is characterised by N = 4 radioactive decays per minute per gram, and that the atmospheric C-14 when the organic matter was alive resulted in N_0 = 14 radioactive decays per minute per gram of carbon, one can use the exponential rule to rewrite the equation for the exponential rule as follows:

$$\frac{N}{N_0} = e^{-t/\tau} = \frac{4}{14}$$

Using the natural logarithm on both sides of the above equation one finds that

$$ln\left(\frac{N}{N_0}\right) = -\frac{t}{\tau}$$

which allows one to compute the age of the sample, t, as follows:

$$t = -\tau \cdot ln\left(\tfrac{N}{N_0}\right) = 8\,267 \cdot ln\left(\tfrac{4}{14}\right) \approx 10\,357 \text{ years.}$$

4.5 Units of Radioactivity

Radioactivity is quantified in terms of the number of radioactive decays per unit of time.

By measuring the number of radioactive disintegrations taking place in a given period, one determines the radioactive decay rate of the material in which such decays take place.

One of the first radioactive elements to be studied extensively was radium, Ra-226. At the time, Ra-226 was extracted from the mineral *pitchblende*, which is the mineral uraninite. The study of radium laid the foundation for the definition of the activity of radioactive materials, and the basic unit for radioactivity, i.e. the curie, symbol Ci, was defined. This unit, which honours Pierre and Marie Curie for their fundamental work on radioactivity, expresses the radioactivity of one gram of radium-226, i.e.

$$\mathbf{1\ Ci\ \equiv 3.7 \cdot 10^{10}\ decays\ per\ second.}$$

However, the unit Ci was found to be too large for many applications, especially when dealing with materials with a much smaller radioactivity than that of radium.

Therefore, and as part of the introduction and use of the metric system of units, i.e. the *Système International d'unités* (SI), the unit of Becquerel (with the symbol Bq) was introduced, honouring Henri Becquerel who discovered radioactivity.

Today, the Bq is the SI unit of radioactivity, and is defined as

$$\mathbf{1\ Bq\ \equiv 1\ decay\ per\ second.}$$

The radioactivity concentration, or specific activity, is the radioactivity per unit mass, and is measured in Bq/g.

Often, for example when quantifying radon concentrations, one uses the radioactivity per unit volume as a measure, i.e. the Bq/m^3. In the Unites States, the radioactivity per unit volume is given in pCi/L, where the conversion between the two is

$$\mathbf{1\ pCi/L\ \equiv 37\ Bq/m^3.}$$

The concentration of dust in air, such as the PM_{10} concentration, is quantified in µg/m^3, or mg/m^3. If the radioactivity concentration is known, it can be expressed in Bq/m^3.

4.6 Activity and Specific Activity

Today, radioactive materials are quantified using the following two metrics:

Activity:

The activity, or radioactivity of a given material, refers to the number of radioactive disintegrations per unit of time, and is expressed in units of Becquerel, with the symbol Bq.

For example, the activity of one gram of recently concentrated natural uranium is approx. 25 000 Bq, or 25 kBq.

Specific activity:

The specific activity, or activity concentration, is the activity per unit mass of a given material.

As a measure of the radioactivity concentration or the amount of radioactivity per mass, it is expressed in units of Becquerel per gram, i.e. Bq/g.

For example, the specific activity of recently concentrated natural uranium is approx. 25 000 Bq/g, which is the same as 25 kBq/g or 25 MBq/kg.

A selection of some important radionuclides, their radioactive half-lives, and associated specific activities is presented in Table 3, while Box 3 illustrates how the specific activity of a radionuclide is calculated using its half-life.

Table 3: Select radionuclides, their half-lives, and specific activities

Element	Half-life [s]	Specific activity [Bq/g]
Pu-239	$7.6 \cdot 10^{11}$	$2.3 \cdot 10^{9}$
Pu-238	$2.8 \cdot 10^{9}$	$6.3 \cdot 10^{11}$
U-238	$1.4 \cdot 10^{17}$	$1.2 \cdot 10^{4}$
U-235	$2.2 \cdot 10^{16}$	$8.0 \cdot 10^{4}$
U-234	$7.8 \cdot 10^{12}$	$2.3 \cdot 10^{8}$
Th-232	$4.4 \cdot 10^{17}$	$4.1 \cdot 10^{3}$
Ra-226	$5.0 \cdot 10^{10}$	$3.7 \cdot 10^{10}$
Rn-222	$3.3 \cdot 10^{5}$	$5.7 \cdot 10^{15}$
Rn-220	$5.6 \cdot 10^{1}$	$3.4 \cdot 10^{19}$
Cs-137	$9.5 \cdot 10^{8}$	$3.2 \cdot 10^{12}$
I-131	$7.0 \cdot 10^{5}$	$4.6 \cdot 10^{15}$
I-129	$5.0 \cdot 10^{14}$	$6.5 \cdot 10^{6}$
Tc-99m	$2.2 \cdot 10^{4}$	$2.0 \cdot 10^{17}$
Sr-90	$9.1 \cdot 10^{8}$	$5.1 \cdot 10^{12}$
Co-60	$1.7 \cdot 10^{8}$	$4.2 \cdot 10^{13}$
K-40	$3.9 \cdot 10^{16}$	$2.6 \cdot 10^{5}$
Cl-36	$9.7 \cdot 10^{12}$	$1.2 \cdot 10^{9}$
C-14	$1.8 \cdot 10^{11}$	$1.6 \cdot 10^{11}$
H-3	$3.9 \cdot 10^{8}$	$3.6 \cdot 10^{14}$

Box 3: Computing the specific activity using a radionuclide's half-life

This box illustrates how one determines the specific activity using a radionuclide's half-life. With the law of exponential radioactive decay, the number of atoms N(t) at one half-life, i.e. at time $t_{1/2}$, is given as $N(t_{1/2}) = N_0\, e^{-\lambda\, t_{1/2}} = N_0 / 2$.

When taking the natural logarithm on both sides of the above equation one finds

$$\boldsymbol{\ln\left(\frac{N(t_{1/2})}{N_0}\right) = \ln\left(\frac{1}{2}\right) = \ln\left(e^{-\lambda\, t_{1/2}}\right) = -\,\lambda\, t_{1/2}},\ \text{which implies that } \boldsymbol{\lambda = \frac{\ln(2)}{t_{1/2}}}.$$

λ is related to the specific activity a and the mass per mole m as $\lambda = a \cdot m / N_A$, where N_A is Avogadro's constant (i.e. the number of atoms per mole). Solving this equation for a yields

$$\boldsymbol{a = \frac{\lambda \cdot N_A}{m} = \frac{\ln(2) \cdot N_A}{t_{1/2} \cdot m}}.$$

Box 4: Specific activity of U-238

This box illustrates how the specific activity of U-238 is computed using the formula for the specific activity as derived in Box 3.

The half-life of U-238 is approx. 4.468 billion years, i.e. $4.468 \cdot 10^9$ years. When expressed in seconds, the half-life of U-238 is

$$t_{1/2} = 4.468 \cdot 10^9 \text{ years} \cdot 365 \text{ days/year } \cdot 24 \text{ hours/day} \cdot 60 \text{ minutes/hour } \cdot \text{ 60 seconds / minute,}$$

which implies that $t_{1/2} = 1.41 \cdot 10^{17}$ s. Now using the formula for the specific activity as derived in Box 3 implies that

$$a = \frac{\ln(2) \cdot 6.022 \cdot 10^{23}}{1.41 \cdot 10^{17} \cdot 238} = 12\,447 \text{ Bq/g} \approx 12\,450 \text{ Bq/g} \approx 12.5 \text{ kBq/g.}$$

Box 5: Specific activity of U-235

This box illustrates how the specific activity of U-235 is computed from first principles.

The half-life of U-235 is approx. 703.8 million years, i.e. $7.038 \cdot 10^8$ years, or $2.22 \cdot 10^{16}$ s.

Using the formula for the specific activity as previously derived in Box 3, one finds

$$a = \frac{\ln(2) \cdot 6.022 \cdot 10^{23}}{2.22 \cdot 10^{16} \cdot 235} = 80\,028 \text{ Bq/g} \approx 8 \cdot 10^4 \text{ Bq/g} = 80 \text{ kBq/g.}$$

Box 6: Specific activity of U-234

This box illustrates how the specific activity of U-234 is computed from first principles.

The half-life of U-234 is approx. 245 500 years, i.e. $7.74 \cdot 10^{12}$ s.

Using the formula for the specific activity as previously derived in Box 3, one finds

$$a = \frac{\ln(2) \cdot 6.022 \cdot 10^{23}}{7.74 \cdot 10^{12} \cdot 234} = 230\,405\,187 \text{ Bq/g} \approx 2.3 \cdot 10^8 \text{ Bq/g} = 230 \text{ MBq/g.}$$

Box 7: Specific activity of Cs-137

This box illustrates how the specific activity of Cs-137 is computed from first principles.

The half-life of Cs-137 is approx. 30.17 years, i.e. $9.51 \cdot 10^8$ s.

Using the formula for the specific activity as previously derived in Box 3, one finds

$$a = \frac{\ln(2) \cdot 6.022 \cdot 10^{23}}{9.51 \cdot 10^8 \cdot 137} = 3\,202\,312\,628\,007 \text{ Bq/g} \approx 3.2 \cdot 10^{12} \text{ Bq/g} = 3.2 \text{ TBq/g.}$$

4.7 Specific Activities of Uranium Isotopes: Natural Uranium and Compounds

The specific activities of the uranium isotopes provided in Table 3 is different from the specific activities of the uranium isotopes in natural uranium. This is the result of the abundance of the three naturally occurring uranium isotopes as are contained in natural uranium, which is illustrated in Table 4.

Of note is that the specific activities of U-238 and U-234 as are contained in natural uranium is the same, although their natural abundance is hugely different. This is because of the state of secular equilibrium in which these isotopes find themselves.

On the other hand, while the specific activity of U-235 is approx. 80 kBq/g, its specific activity in natural uranium is 580 Bq/g, which is the result of the low abundance of this uranium isotope.

Table 4: Specific activity of uranium isotopes as contained in natural uranium

Uranium isotope	Isotopic abundance [%]	Specific activity [Bq/g]
U-238	99.27%	12 350
U-235	0.72%	580
U-234	0.005%	12 350
Total	**100.0%**	**25 280**

Table 5 summarises the specific activity of some common uranium-bearing compounds.

Table 5: Specific activities of select uranium-bearing compounds

Name of uranium-bearing compound	Specific activity [kBq/g]
Uranium-bearing ore with a uranium concentration of 100 parts per million, in secular equilibrium, refer to Box 9	0.017
Uranium-bearing ore with a uranium concentration of 1 000 parts per million, in secular equilibrium, using the same calculational approach as demonstrated in Box 9	0.17
Freshly extracted uranium concentrate, refer to Box 10	25
Uranium concentrate, 100+ days after extraction, refer to Box 11	50
Freshly extracted uranium concentrate, taking the U-238 and U-235 decay chains into account, refer to Box 12	25.3
Depleted uranium, refer to Box 13	15
Enriched uranium containing 5% U-235 (reactor fuel), refer to Box 14	48
Enriched uranium (90% U-235), refer to Box 15	~2 000

4.8 Decay Chains

When radionuclides having a small atomic number (i.e. less than 82) undergo a radioactive decay (refer to the elements 'above' and below' the curve of stability shown in Figure 11), they usually reach stability after a single decay. In other words, lighter radionuclides often decay into an element that does not itself undergo further radioactive decays.

However, when heavy elements such as uranium and thorium decay, another radionuclide is formed. The progeny in turn decays into yet another radioactive element, thus forming a chain of elements that are successively created in such radioactive decays. The sequence of such radioactive decays is called a *decay chain,* or *radioactive cascade*.

The decay products of the original radionuclide form decay chains. They are called *daughter products*, or *progeny*. The element leading a given decay chain is called the *parent* of the chain, or the *head-of-chain member*. All decay chains end in a stable non-radioactive element.

There are four main decay chains, namely the uranium-238, the thorium-232, the uranium-235 and the neptunium Np-237 decay chains. All the above decay chains, except the neptunium decay chain, are discussed in further detail in the subsections below.

Regarding the *neptunium decay chain*, which has Np-237 as the head-of-chain member, it is important to note that neptunium has a half-life of only 351 years. Such a short half-life implies that the primordial remnants of this element have long since decayed. This is not surprising, as the Earth is estimated to have an age of approx. 4.5 billion years. Today, only two radionuclides from the neptunium decay chain are found in nature, and these are the bismuth isotope Bi-209, and the stable element thallium Tl-205.

Box 8: Radionuclides with the longest half-lives: Bi-209 and Te-128

Bi-209 – with a nucleus containing 83 protons and 126 neutrons – was long thought to be a stable element. However, since 2003 it is known that Bi-209 is a radioisotope of bismuth, and decays via an alpha decay, with a half-life of some $1.9 \cdot 10^{19}$ years. This extraordinarily long half-life implies that Bi-209 is the longest-living alpha-decaying radionuclide.

The radionuclide that holds the overall half-life record is tellurium-128 (Te-128), which is a beta-decaying isotope of tellurium, with an estimated half-life of approx. $7.7 \cdot 10^{24}$ years.

The Earth's age is estimated to be about 4.5 billion (i.e. $4.5 \cdot 10^{9}$) years, and the age of the universe is estimated to be about 13.8 billion (i.e. almost $1.4 \cdot 10^{10}$) years. In contrast, the half-lives of Bi-209 and Te-128, are a factor 10^{9} (i.e. one billion) and 10^{14} respectively greater than the age of the universe! Such half-lives are truly staggering, and it is no wonder that the longevity of these radionuclides qualify them as quasi-stable elements.

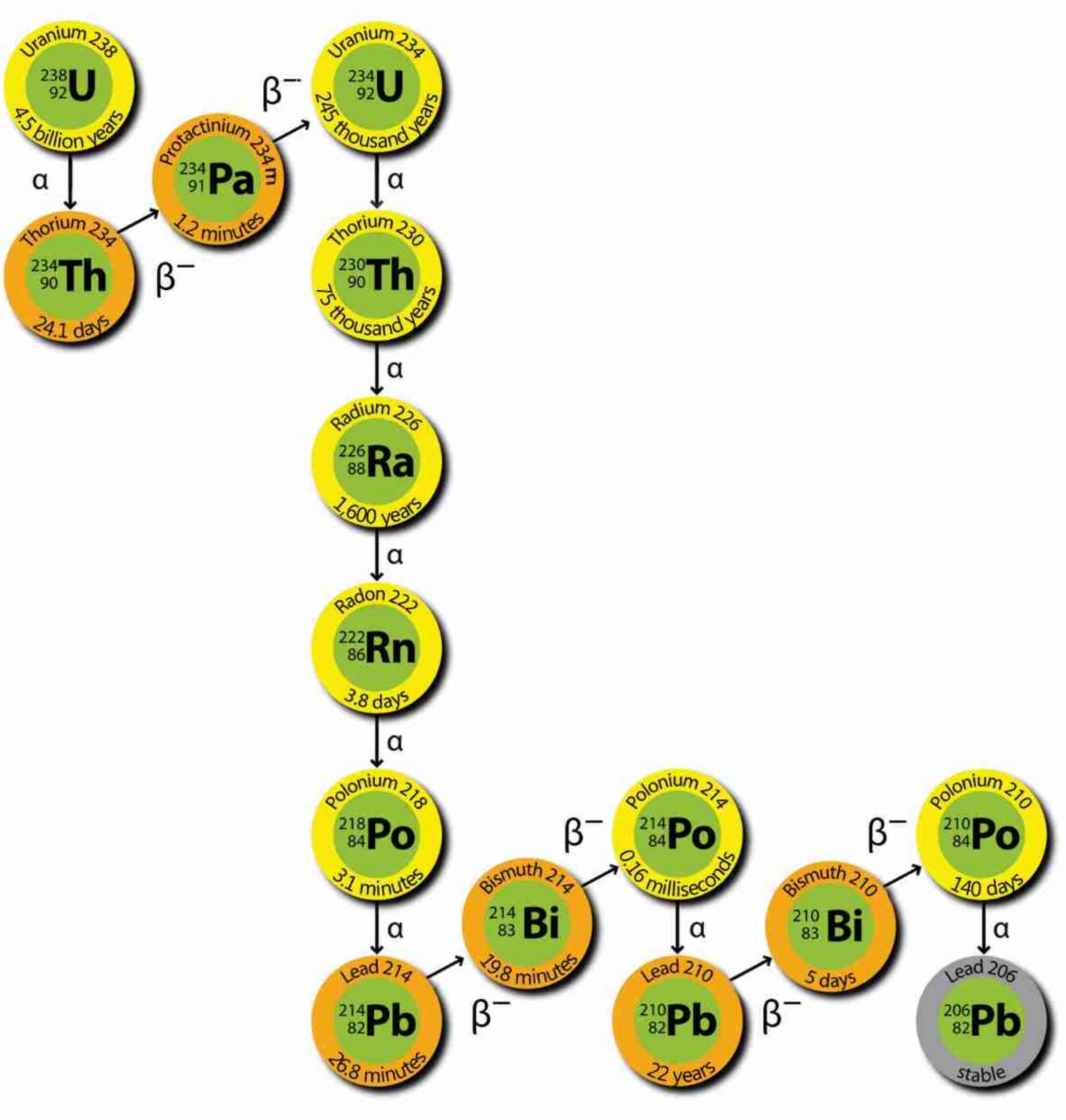
4.8.1 Uranium-238 Decay Chain

For the uranium-238 decay chain, the main chain encompasses 14 radioactive elements, until the stable isotope lead-206 (with symbol Pb-206) is reached, as shown in Figure 24.

The first six radionuclides in this decay chain are the so-called *long-lived daughters of U-238*, even though Th-234 and Pa-234 have short half-lives, of about a month and a minute respectively.

Radon-222, which has a half-life of approx. 3.8 days, is short-lived, and its four immediate decay products are called *short-lived radon progeny*, because of their very short half-lives.

Figure 24: Uranium-238 decay chain [8]



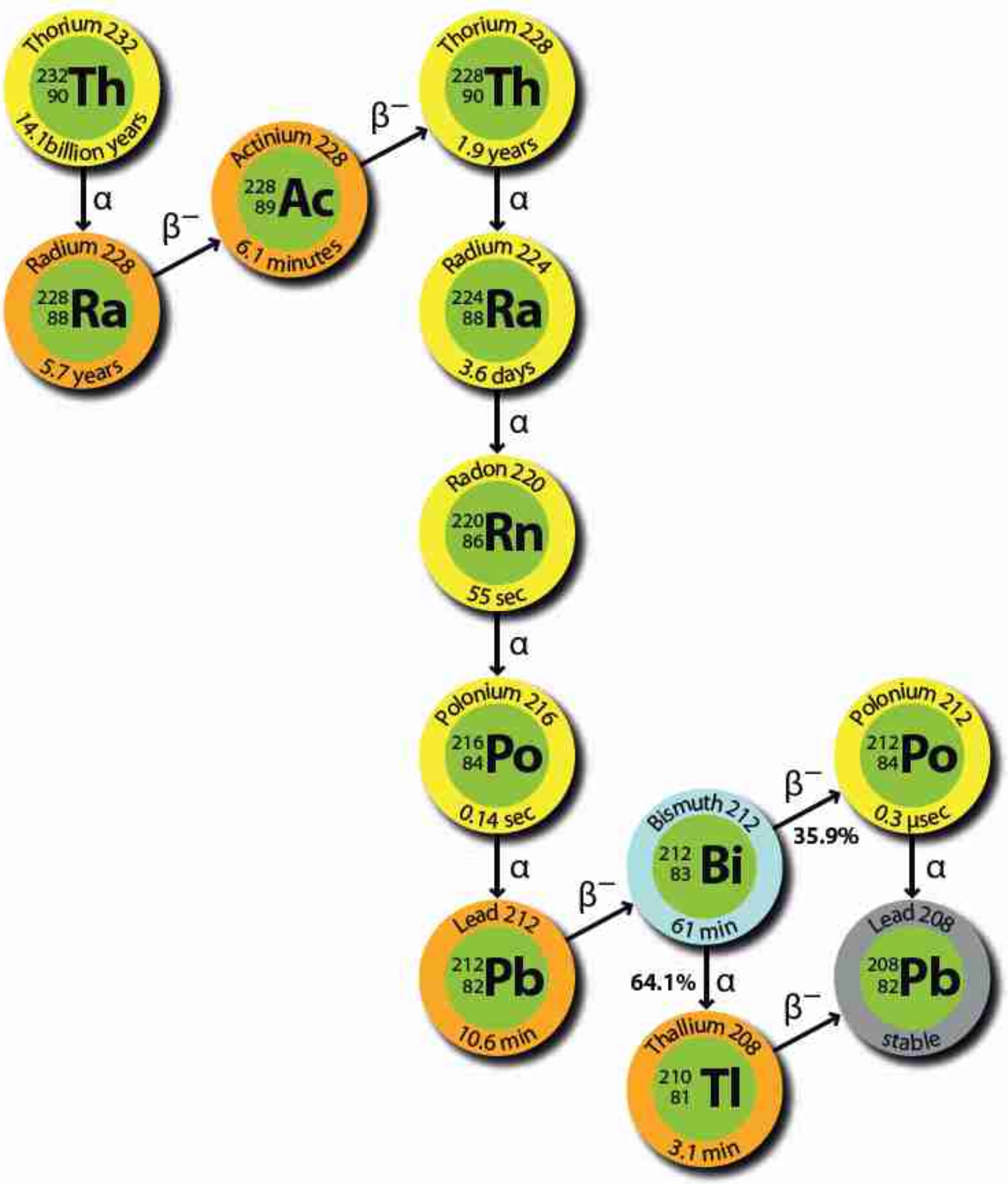
4.8.2 Thorium-232 Decay Chain

The thorium decay chain, as shown in Figure 25, includes 11 main radioactive decay chain members.

The contributions from the thorium chain to background radiation tends to be similar to that of the members of the uranium-238 decay chain.

It is of interest to note that one of the thorium chain's radionuclides is the radon isotope Rn-220, which is also often called *thoron*. This radionuclide is much more short-lived than the radon isotope Rn-222, which is a member of the uranium decay chain, as shown in Figure 24.

Figure 25: Thorium decay chain [8]



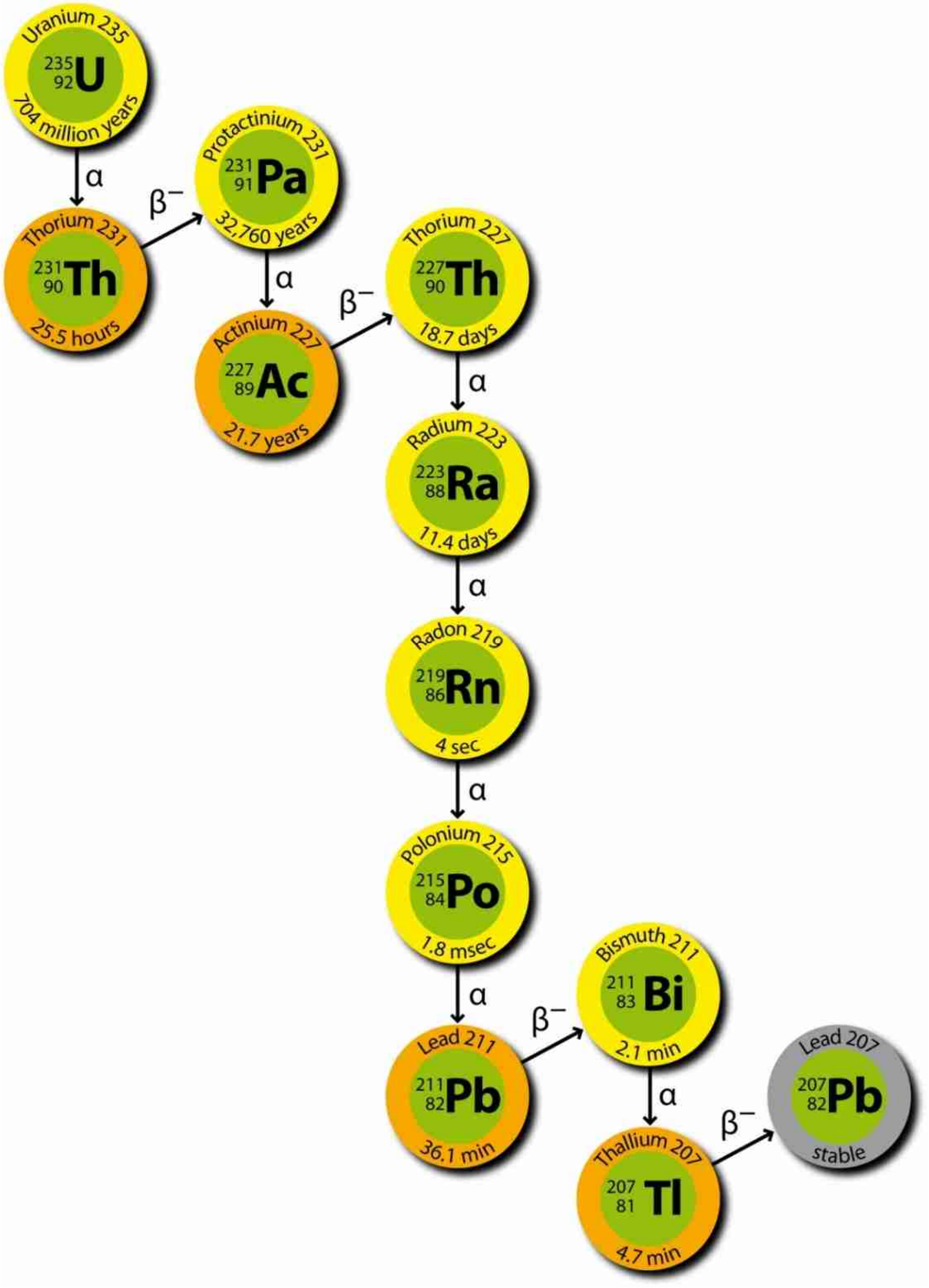
4.8.3 Actinium-235 (U-235) Decay Chain

The decay chain for the uranium isotope U-235, which is also called actinium, is shown in Figure 26, and encompasses 11 main radioactive decay chain members.

The contribution by U-235 to the activity of natural uranium is small, amounting to some 2% only.

However, uranium-235 is the only naturally occurring fissile element, and is therefore of considerable economic and political importance, even though its natural abundance is low (refer to Table 4).

Figure 26: Actinium decay chain [8]



4.9 Secular Equilibrium

The radionuclides that are part of the uranium, thorium, and actinium decay chains each have different radioactive half-lives. It is also noted that all daughters in the decay chains headed by the head-of-chain members U-238, Th-232 and U-235 respectively, decay more quickly than they are formed. In other words, the parent isotopes of the uranium, thorium and actinium decay chains have a much longer half-life and therefore decay much slower than any of their progeny. This is an important observation which has considerable implications.

When the rate at which daughters are formed is much slower than the rate at which such daughters decay, a situation begins to establish itself where isotopes within the same decay chain undergo radioactive decay at the same rate at which they are formed. Once such a stable feed-and-decay constellation has established itself, i.e. when all radionuclides in one decay chain undergo radioactive decays at the same rate, the radioactivity of each element in the chain is the same. Such a state is called *secular equilibrium*, and the radionuclides in the decay chain are said to be in equilibrium.

The scenario described above is illustrated by the following *Gedankenexperiment*: consider a series of buckets, as shown in Figure 27, each having a different holding capacity. Imagine that water is poured from the top bucket, into the bucket directly below it. From the second bucket, water flows into the bucket immediately below it, and so on. First, the smaller buckets below the head-of-chain bucket will fill up. Once each bucket reaches its filling capacity, water starts to overflow, pouring into the bucket below it. If all buckets are full, the rate at which water flows through the cascade of buckets is the same as the rate at which water is flowing from the topmost bucket. This implies that the rate at which water enters a given bucket is the same as the rate at which it overflows, and this rate is the same for every bucket in the chain, which illustrates the concept of secular equilibrium.

Figure 27: Overflowing water buckets illustrating the concept of secular equilibrium [8]

In radioactive decay chains, secular equilibrium usually establishes itself after a few half-lives of the parent have elapsed. In the case of the uranium, thorium and actinium series, secular equilibrium occurs in sediments that have remained *in situ* for many thousands of years.

In most cases, uranium extracted from primary geological deposits is found to be in secular equilibrium, or close to secular equilibrium, with its progeny. On the other hand, uranium that is dissolved in water-bearing aquifers, or uranium in secondary deposits having been exposed to repeated weathering, may not be in secular equilibrium.

If a decay chain is in secular equilibrium, all its radionuclides exhibit the same radioactivity. To illustrate, the specific activities of U-238 and U-234 are 12 450 Bq/g and 230 MBq/g respectively (refer to Table 3). However, in natural uranium, these two uranium isotopes are often found to be in equilibrium and have a specific activity of 12 350 Bq/g each, as shown in Table 4.

It is important to note that U-235 is not part of the uranium-238 decay chain, and therefore has a different specific activity than U-238 and U2-234, refer to Table 4.

Box 9: Activity of 100 ppm uranium-bearing ore in secular equilibrium

Compute the activity of one gram of uranium-bearing ore with a uranium concentration of 100 parts per million (ppm), i.e. an ore grade of 100 / 1 000 000 = 0.01%.

The specific activity of U-238 in natural uranium is approximately 12 350 Bq/g (Table 4). Because the head-of-chain isotope U-238 is assumed to be in full secular equilibrium with all 14 members of the decay chain, the total activity of 1 gram of such ore is

$$\text{Activity} = \frac{100}{1\,000\,000} \cdot 14 \cdot 12\,350 \approx 17.3\ \text{Bq}.$$

Box 10: Activity of freshly extracted uranium concentrate (U-238 chain only)

Compute the activity of one gram of uranium as contained in freshly extracted uranium concentrate, ignoring the contribution of U-235, using the specific activity of U-238 in natural uranium as 12 350 Bq/g (Table 4).

Freshly extracted uranium has no progeny. However, the head-of-chain member of the uranium-238 decay chain remains in secular equilibrium with U-234. Hence the activity of one gram of such uranium concentrate, and ignoring the contributions of U-235, is

$$\text{Activity} = 2 \cdot 12\,350\ \text{Bq} = 24\,700\ \text{Bq} \approx 25\,000\ \text{Bq} = 25\ \text{kBq}.$$

Box 11: Activity of 100+ day old uranium concentrate (with in-growth)

Compute the activity of one gram of uranium as contained in100+ days old uranium concentrate, using the same assumptions as employed in Box 10.

Uranium concentrate that is older than 100 days begins to show in-growth of the decay products of uranium-238, as is demonstrated in section 20.4. This implies that the first four radionuclides of the U-238 decay chain contribute to the activity of such concentrate, i.e.

$$\text{Activity} = 4 \cdot 12\,350\ \text{Bq} = 49\,400\ \text{Bq} \approx 50\,000\ \text{Bq} = 50\ \text{kBq}.$$

Box 12: Activity of freshly extracted uranium concentrate (U-238 and U-235 chains)

Compute the activity of one gram of uranium as contained in freshly extracted uranium concentrate, taking both the U-238 and U-235 decay chains into account.

The specific activity of U-238 in natural uranium is approximately 12 350 Bq/g, while the corresponding specific activity of U-235 is approx. 580 Bq/g (rounded, refer to Table 4).

Taking the two uranium isotopes from the uranium decay chain, as well as the uranium isotope from the actinium decay chain into account, and if the head-of-chain member of the uranium-238 decay chain remains in secular equilibrium with U-234, the activity of one gram of freshly extracted uranium concentrate is

$$\text{Activity} = 2 \cdot 12\,350\ + 580\ \text{ Bq} = 25\,280\text{ Bq}\ \approx 25.3\text{ kBq}.$$

When comparing the above result with what was computed in Box 10 (which ignored the actinium chain), it is evident that the contribution from U-235 is so small that it is only relevant if the activity is calculated to at least three significant digits. Therefore, and when approximations are warranted, calculations often ignore the activity contribution of U-235.

Box 13: Activity of depleted uranium containing 0.3% of U-235

Compute the activity of one gram of uranium as contained in so-called depleted uranium which contains 0.3% U-235, if the sample also contains 0.001% U-234.

Depleted uranium has a lower proportion of U-235 (typically 0.3% or less) than what is contained in natural uranium, which is approx. 0.72% U-235. It is a waste product of the uranium enrichment process leading to fuel used in nuclear power stations.

The specific activity of U-238 is approx. 12 450 Bq/g, of U-235 is approx. 80 kBq/g, and of U-234 is approx. 230 MBq/g (refer to Box 4, Box 5 and Box 6). This implies that the activity of one gram of depleted uranium containing 0.3% U-235 is

$$\text{Activity} = 99.699\% \cdot 12\,450\ + 0.001\%\ \cdot 2.3 \cdot 10^8 + 0.3\%\ \cdot\ 8 \cdot 10^4\text{ Bq} = 14\,953\text{ Bq}\ \approx 15\text{ kBq}.$$

Box 14: Activity of enriched uranium containing 5% U-235

Compute the activity of one gram of uranium as contained in enriched uranium containing 5% U-235, if the sample contains 0.014% U-234.

Uranium that is used as a fuel source in a nuclear power reactor is enriched, implying that the proportion of U-235 is increased from the natural uranium concentration to between 3% and 5% U-235. Using the specific activities for U-238, U-235 and U-234 as per Box 4, Box 5 and Box 6, the activity of one gram of enriched uranium containing 5% U-235 is

$$\text{Activity} = 94.986\% \cdot 12\,450\ + 0.014\%\ \cdot 2.3 \cdot 10^8 + 5\%\ \cdot\ 8 \cdot 10^4\text{ Bq} = 48\,026\text{ Bq}\ \approx 48\text{ kBq}.$$

Box 15: Activity of enriched uranium containing 90% U-235

Compute the activity of one gram of uranium as contained in enriched uranium containing 90% U-235, if the sample contains 0.85% U-234.

Using the specific activities for U-238, U-235 and U-234 as per Box 4, Box 5 and Box 6, the activity of one gram of enriched uranium containing 90% U-235 is computed to be

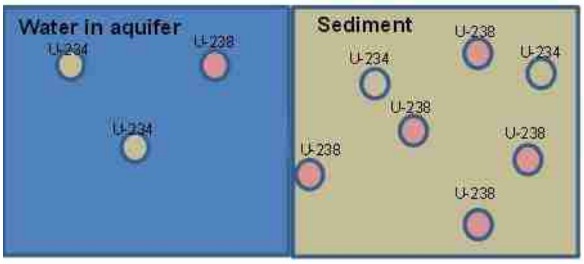
$$\text{Activity} = 9.15\% \cdot 12\,450\ + 0.85\%\ \cdot 2.3 \cdot 10^8 + 90\%\ \cdot\ 8 \cdot 10^4\text{ Bq} = 2\,028\,139\text{ Bq}\ \approx 2\text{ MBq}.$$

4.9.1 Alpha Recoil – Secular Equilibrium in Practice

An interesting application where the concept of secular equilibrium is applied is in the assessment and interpretation of specific radionuclide abundances in borehole water.

Consider the water contained in an underground aquifer. Because of leaching, which may have taken place over many tens or even hundreds of years, such water will contain a certain concentration of dissolved uranium, as illustrated in Figure 28.

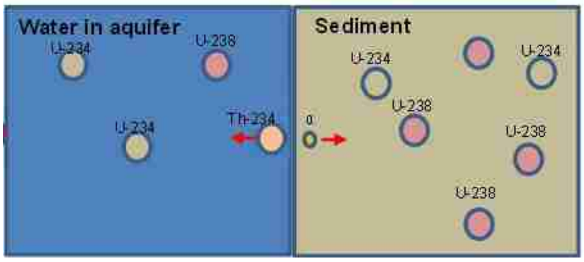
Figure 28: Aquifer-sediment interface [20]



If the aquifer is in contact with uranium-bearing sediments, there is a mechanism, which is called *alpha recoil*, that mobilises radionuclides that are bound in the sediment, and releases these into the water of the aquifer. This is the result of a radioactive decay of a uranium nucleus which is close to the interface between the sediment and the water in the aquifer.

When U-238 radionuclides decay within the sedimentary layers, their decay products will remain trapped in the sediment, which will perpetuate the secular equilibrium between U-238 and its daughters. As the result of such a radioactive decay of a U-238 radioisotope, an alpha particle is released, and thorium, Th-234, is created. At the interface between the water and the sediment, a decaying radioisotope, such as U-238, may receive sufficient energy from the recoil of the decay to be ejected from the crystal lattice, thereby ending up in the water of the adjacent aquifer, as is depicted in Figure 29.

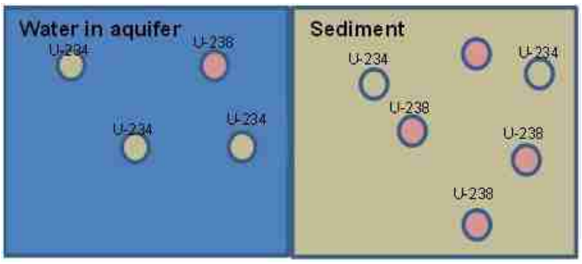
Figure 29: Alpha recoil [20]



Because of the recoil caused by the alpha decay, some Th-234 radioisotopes are kicked into the water of the aquifer, where they will later decay into U-234. In this way, alpha recoil enhances the concentration of U-234 in the aquifer's water relative to that of the long-lived U-238 radionuclides in the same medium.

Consequently, the ratio of U-238 to U-234 in aquifer water which has been in long-term contact with natural sediments is less than 1 and is typically of the order of 0.8. At the same time, and because of the 'loss' of U-234 isotopes from the sediment, the ratio of U-238 to U-234 in the sediment increases to above 1, as illustrated in Figure 30.

Figure 30: Increased abundance of U-234 in aquifer water [20]



On the other hand, when considering water which is released from a tailings storage facility (TSF) of a uranium mine, one realises that the mineral source from which the uranium-bearing ore has recently been extracted will not have had any significant exposure to environmental forces that could have changed the ratio between U-238 and U-234. As a result, when analysing the seepage water released from a TSF, it contains uranium isotopes that are close to or in secular equilibrium, yielding a ratio of isotopes of around 1.

The above difference between 'old' water as found in boreholes, and water which is 'enriched' with residues from the uranium mining industry, allows a conclusion as to the origin of such water: if a ratio between U-238 and U-234 is at or close to 1, the presence of recently extracted uranium is likely. On the other hand, when the ratio of the U-238 and U-234 isotopes is below 1, for example 0.8, it indicates that the water originated from natural sediments, and is not mixed with residues released from a nearby uranium mine.

The phenomenon of alpha recoil is a natural process that takes hundreds to thousands of years to lead to a measurable disequilibrium. However, when measured, the U-238 to U-234 ratio in ores and sediments is typically between 1 and 1.2, while it ranges between 0.8 and 1 in aquifers which are in close contact with such sediments.

For ores originating from sources where secondary uranium mineralisation occurs, secular equilibrium may not have been reached. This is because such ore bodies were disturbed in recent geological times prior to the commencement of mining activities. Hence, in such ore bodies, one can often not automatically draw conclusions as to the activity ratio found in water that has been in contact with recently extracted uranium from such ores.

4.10 Exercises

4.10.1 Abundance of the U-238 Isotope

The natural abundance of U-238 is

a) 12 450 Bq/g
b) 174 kBq/g
c) Approximately 99.3%
d) 4.5 billion years

4.10.2 Radioactive Decay

1. Which of the following statements, describing beta decay, are correct?
    a) Beta minus decay occurs when a neutron turns into a proton, and an electron is emitted.
    b) Beta plus decay occurs when a proton turns into a neutron, and a positron is emitted.
    c) In beta minus decay, the atomic number remains unchanged.
    d) In beta minus decay, the atomic number increases by 1.

2. Use the periodic table of elements to determine the decay element of the following nuclides:
    a) U-238 (alpha)
    b) U-234 (alpha)
    c) Ra-226 (alpha)
    d) Th-230 (alpha)
    e) Cs-137 (beta-)
    f) Pb-210 (beta-)

3. Which of the following statements, describing alpha decay, are correct?
    a) Alpha decay leads to progeny which has an atomic number of the parent minus 2.
    b) Alpha decay leads to progeny which has an atomic mass of the parent plus 2.
    c) Alpha decay leads to progeny which has an atomic mass of the parent minus 2.
    d) Alpha decay leads to progeny which has an atomic number of the parent plus 2.

4. Gamma radiation, when compared to alpha and beta radiation, is
   a) more ionising than alpha but less ionising than beta radiation.
   b) more ionising than alpha and more ionising than beta radiation.
   c) less ionising than alpha and more ionising than beta radiation.
   d) less ionising than alpha and less ionising than beta radiation.

5. Alpha radiation, when compared to gamma and beta radiation, is
   a) the most long-range form of all known ionising radiation.
   b) only of concern when acting directly on the outer skin.
   c) the least long-range form of ionising radiation.
   d) without any effect when inhaled in form of long-lived radioactive dust.

6. Beta radiation, when compared to gamma and alpha radiation, is
   a) the least ionising form of all known forms of ionising radiation.
   b) not affecting the internal organs when applied externally to the body.
   c) only of concern when inhaled and acting in the lung.
   d) the most long-range form of ionising radiation.

4.10.3 Half-life

1. How many half-lives does it take for 750 g of a total of 1 kg of pure U-238 to decay?

2. How many years does it take for 500 g of a total of 1 kg of pure U-235 to decay?

3. How many years does it take for 90%, 95% and 99% of a total of 1 kg of pure U-234 to decay?

4. The half-life of radon-222 is about 3.8 days. If no new radon is formed, how many days does it take for 1 kg of radon to decay to less than 30 g?

5. The activity of uranium 238 – when compared to all other decay chain members in the U-238 decay chain – is
   a) the largest because U-238 has the longest half-life.
   b) is the lowest because its specific activity is the highest.
   c) is the lowest because it has the longest half-life.
   d) is the lowest because it is the most abundant uranium isotope in nature.

4.10.4 Specific Activity

1. The specific activity of U-238 is 12.4 kBq/g. There are 14 radioactive elements in the decay chain. What is the specific activity of U-238 in secular equilibrium with its progeny?

2. Assume that your ore grade has a uranium concentration of 100 ppm. Work out the activity of 1 kg of ore from the U-238 decay chain.

3. Calculate the activity of 1 kg of Canadian ore with a U-grade of 20%.

4. Calculate the activity of 1 g of ore with ore grade 350 ppm. ONLY take the uranium decay chain (14 elements) into account, using the specific activity of 12,500 Bq/g for U-238. Remember that natural uranium contains 99.3 % U-238 and 0.7 % U-235.

5. The specific activity of uranium 238 – when compared to uranium 234 and uranium 235 – is
   a) negligible because it has a half-life of 4.5 billion years.
   b) is the most important because it is in secular equilibrium with its decay chain members.
   c) is the lowest because it has the longest half-life of the three naturally occurring uranium isotopes.
   d) is 12 400 Bq/g when in secular equilibrium with its decay chain members.

6. The contribution of uranium 238 to the total activity of concentrated uranium oxide
   a) is the most important as it is in secular equilibrium with one other decay chain members.
   b) is the least important of the three naturally occurring uranium isotopes because it has the highest natural abundance.
   c) is the most important because uranium 238 is not fissionable.
   d) is the least important because it is in secular equilibrium with U-234.

7. The contribution of uranium 235 to the total activity of concentrated uranium oxide
   a) is the most important as it is in secular equilibrium with 11 other decay chain members.
   b) is the least important of the three naturally occurring uranium isotopes because its natural abundance of only 0.7% is low.
   c) is the most important because uranium 235 is the only naturally occurring element that is fissionable.
   d) is the most important because it is in secular equilibrium with U-238.

4.10.5 Total Activity

1. Uranium oxide is often drummed in the form of uranium oxide, U_3O_8, and 84.8% of the oxide is in form of uranium. Compute the total activity of a drum containing 380 kg of U_3O_8.

2. Compute the total activity of a sea freight container packed with 36 drums of freshly extracted uranium concentrate, where each drum contains some 400 kg of 96% pure U_3O_8.

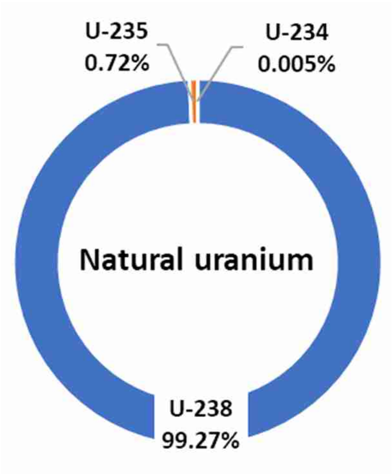
5 Uranium

This Chapter deals with uranium and includes an introductory section on Namibian uranium exploration and mining activities.

5.1 Abundance of Natural Uranium

Uranium is a naturally occurring radioactive element of low radioactivity. Natural uranium occurs in the form of three isotopes, i.e. U-238 (which has an abundance of 99.27%), U-235 (0.72%), and U-234 (0.005%), as shown in Figure 31.

Figure 31: Composition of natural uranium [8]



Uranium (U-238) and actinium (U-235) each have their own decay chains, as elaborated in sections 4.8.1 and 4.8.3 respectively. U-234 on the other hand is a daughter of uranium U-238 and is the fourth member in the U-238 decay chain.

The isotopic composition of natural uranium is the same all over the world. The uranium that is found in the Earth's crust is a remnant of the primordial material that was already present when our planet Earth formed. However, because of the different half-lives of the three naturally occurring uranium isotopes, as summarised in Table 2, the ratio of naturally occurring uranium isotopes has changed over the eons, which has seen the percentage of U-235 decreasing steadily over time.

5.2 Some Properties of Uranium

Pure uranium is a silvery-white metal, as shown in Figure 32. Of the primordial isotopes, uranium has the second-highest atomic weight, following plutonium (Pu-244) of which some near-negligible natural quantities are reported to exist in nature as primordial radionuclide.

Uranium has a density of 19.1 g/cm^3, i.e. 19.1 ton/m^3. Its density is nearly 70% higher than that of lead (11.3 g/cm^3), and only slightly lower than that of gold (19.3 g/cm^3).

Uranium's high density implies that one litre of uranium metal weighs just over 19 kilogram (kg). In contrast, one litre of water weighs one kg.

Namibian uranium mines produce uranium concentrate, such as uranium oxide (U_3O_8), and yellowcake (for example $Na_2U_2O_7 \cdot 6H_2O$), which weigh some 16 and 12 kg per litre respectively.

Figure 32: Enriched uranium metal [21]

5.3 Occurrence of Uranium

Uranium occurs naturally in soil, rocks, and water, including in sea water, mostly in concentrations of a few parts per million (ppm).

Uranium is found in many mineral forms, the most common one being uraninite, UO$_2$, which has historically been called *pitchblende*, as shown in Figure 33. Other uranium-bearing minerals include alaskite, autunite, brannerite, carnotite, coffinite, tyuyamunite, torbernite, and others.

Figure 33: Uraninite crystal [22]

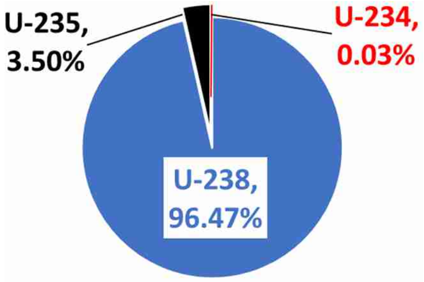
5.4 Radioactivity of Uranium

Uranium is weakly radioactive. As summarised in Table 3, the most abundant naturally occurring uranium isotope, i.e. U-238, has a half-life of some 4.5 billion years, which is comparable to the age of the Earth. U-238's long half-life implies that it has a low specific activity, i.e. 12 450 Bq/g (refer to Table 3). This implies that there are some 12 450 radioactive decays taking place in each gram of pure U-238 per second. While such a rate may seem high, it is actually quite low when compared to short-lived radionuclides, such as radium Ra-226, caesium Cs-137, or radon Rn-222, which have specific activities of $3.7\cdot10^{10}$ Bq/g, $3.2\cdot10^{12}$ Bq/g, and $5.7\cdot10^{15}$ Bq/g, respectively (refer to Table 3).

5.5 Enrichment of Uranium

The isotopic composition of natural uranium is changed to create fuel for nuclear power reactors. This process is called *enrichment* and leads to the increase of the percentage of U-235 concentration in the nuclear material. The U-235 concentration in fuel rods used in contemporary nuclear power reactors ranges between 3 and 5%.

Figure 34: Composition of nuclear reactor fuel [8]



The enrichment of uranium involves converting concentrated uranium feedstock, for example in the form of U$_3$O$_8$, into the gaseous form *uranium hexafluoride* (UF$_6$). Then, using a cascade of high-speed centrifuges, the slightly lighter U-235 is separated from the heavier U-238 isotope. This process is technically complex, and energy-intensive. The enriched material is then re-converted into solid uranium oxide (UO$_2$), and pressed into pellets, which are the constituents of fuel rods, as used in nuclear power plants. Enrichment generates nuclear waste, called *depleted uranium*, which is a mix of uranium isotopes which contains less U-235, and more U-238, than contained in natural uranium. The nuclear fuel chain is illustrated in Figure 36. To produce nuclear weapons from uranium, the U-235 concentration must be at 90% or larger.

Figure 35: Composition of weapons-grade U [8]

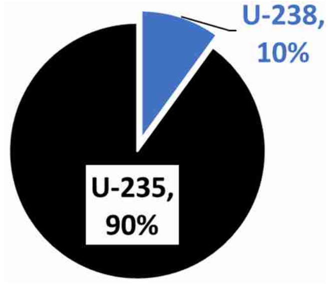
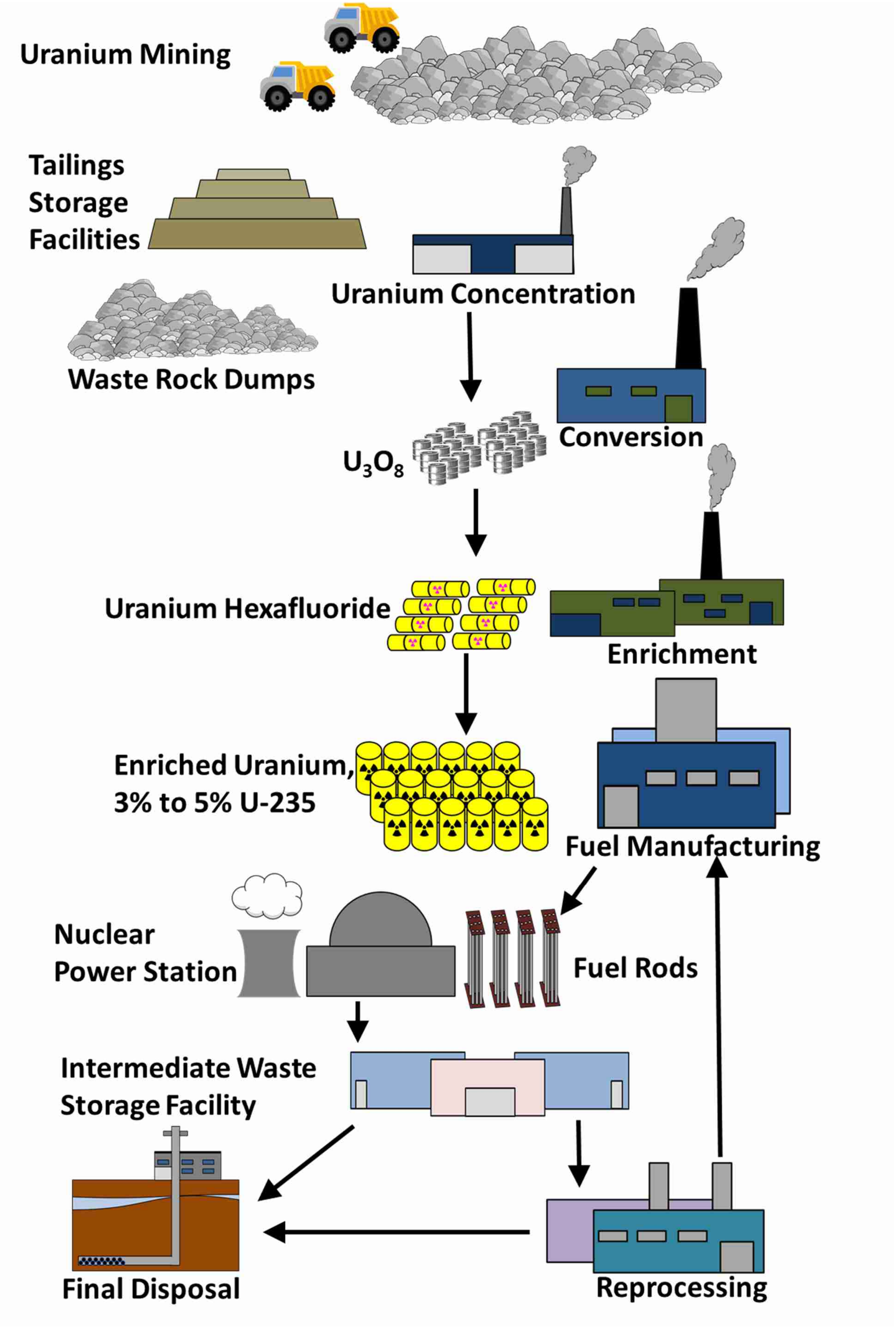


Figure 36: Nuclear fuel chain [8]



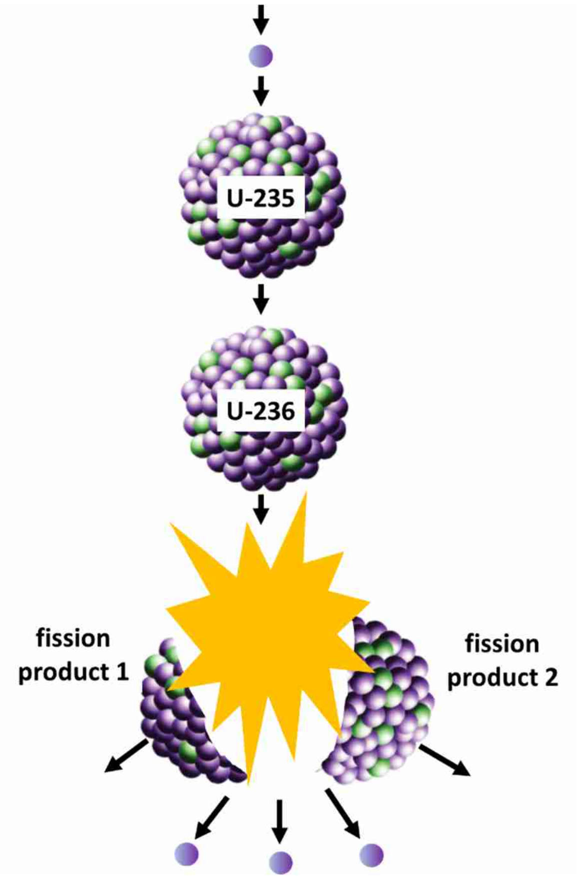
5.6 Fissile Properties of Uranium

U-235 is fissile, which means that it can spontaneously disintegrate into smaller nuclides when such a reaction is triggered.
U-235 is the only naturally occurring radionuclide that has this fascinating property.

Fissile material can start and sustain a nuclear chain reaction when activated with neutrons. As such, fission is a nuclear reaction in which a heavy nucleus splits into two or more constituents, or disintegrates on impact with another particle (such as a neutron), and in the process, releases copious amounts of energy, and one or several neutrons, refer to Figure 37.

It is the fissile characteristic of U-235 that is exploited when enriched nuclear fuel is used in nuclear power plants, or as feedstock in certain types of nuclear weapons. Evidently, U-235's fissile properties are of geopolitical relevance and are of commercial importance.

Figure 37: Induced nuclear fission of U-235 [8]



5.7 Nuclear Chain Reactions

In a neutron-induced nuclear fission reaction, as shown in Figure 37, a uranium-235 nucleus absorbs a neutron. For a brief moment, this results in an excited uranium-236 nucleus, where the kinetic energy of the neutron provides the excitation energy, plus the forces that bind the neutron into the nucleus.

Uranium-236 nuclei, in turn, split into separate fission products. Usually, these are two nuclides of similar mass, and in the process, release two or occasionally three free neutrons. Provided that the concentration of U-235 in the medium is sufficiently high, i.e. exceeding a few percent of U-235, the neutrons released in the fission process trigger additional fission reactions in nearby U-235 nuclei. These, in turn, induce further reactions, thus creating a nuclear chain reaction.

When the energy released in the fission process is used, as is the case in a nuclear power plant, the nuclear chain reaction as described above can be used to harvest considerable amounts of energy, which is available in the form of heat.

In a common boiling water nuclear reactor, as schematically shown in Figure 38, the heat created by the fission reaction is used to convert water to steam. The steam that is generated in this way is channelled to drive a turbine, which is connected to a generator, that produces electricity.

Figure 38: Boiling water nuclear reactor [23]

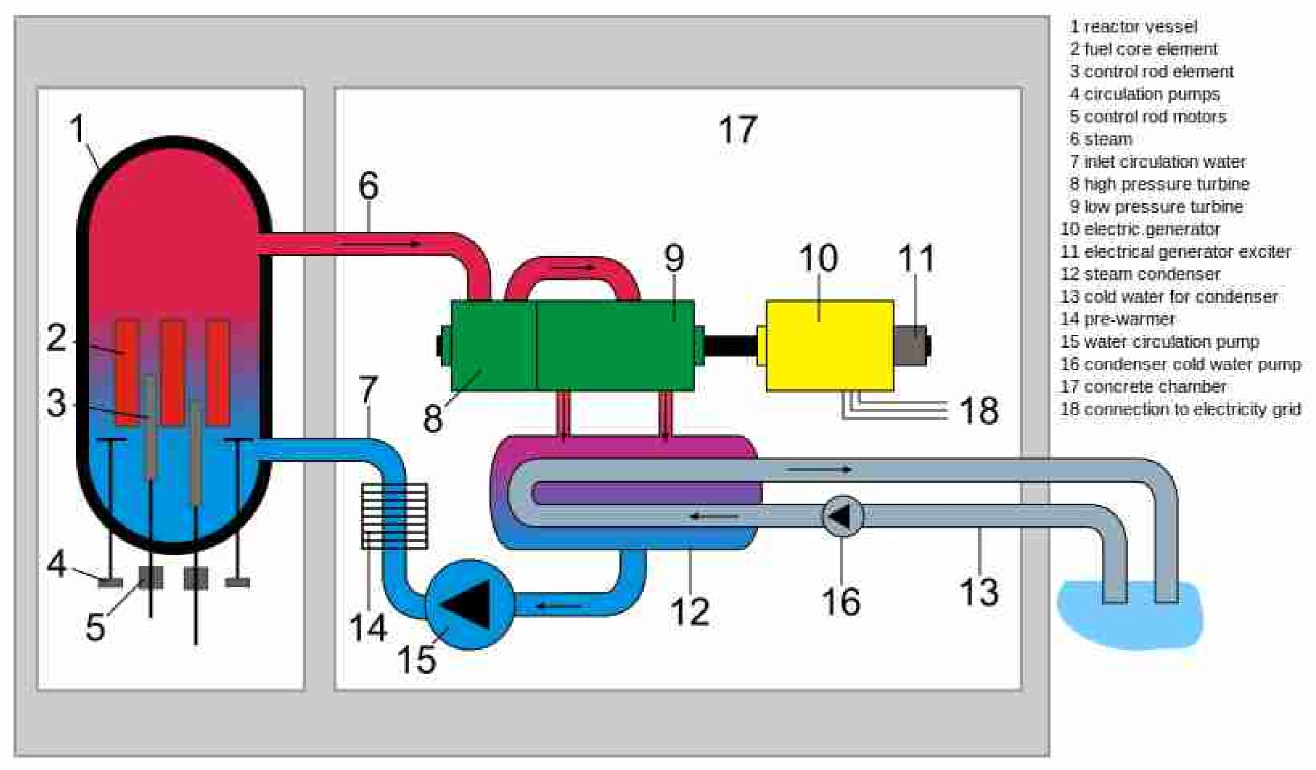


Figure 39: Koeberg nuclear power station in South Africa [24]

Box 16: The story of nuclear fission and Hahn, Frisch, Meitner and Strassmann [25]

Otto Hahn, a German chemist, Otto Frisch, Lise Meitner, an Austrian physicist, an Austrian physicist, and their assistant Fritz Strassmann, a German chemist, collaborated on a variety of topics in nuclear physics at the Kaiser Wilhelm Institut für Chemie at the University of Berlin in Germany.

Towards the end of 1938, experiments were showing that uranium nuclei, when bombarded with neutrons, would disintegrate into lighter elements. Scientists were perplexed by these observations, as initial expectations were that such bombardment would result in elements that were heavier than uranium. Theory and experiment were not aligned.

Hahn and Meitner, who are shown in their laboratory in the picture on the right, set out to explain what was going on. In the process, they developed the concept of *nuclear fission*, a term which they coined. They also developed a theory, which was confirmed by Hahn and Strassmann, that uranium was indeed disintegrating when bombarded with neutrons. It was found that the break-up of uranium would typically result in two similarly sized lighter elements, accompanied by a release of energy, as well as a few neutrons. The discovery laid the foundation for what was later termed the *atomic age*, where it is noted that it would have been more appropriate to call this epoch the *nuclear age,* as the process of fission is a nuclear rather than an atomic phenomenon.

In 1944, Hahn was awarded the Nobel Prize in chemistry, which recognised the discovery of nuclear fission. Although Hahn acknowledged that both Meitner and Strassmann had been instrumental in the discovery of nuclear fission, neither of the latter collaborators were recognised in the Nobel award. Interestingly, Hahn is said to have suggested that the discovery was a feat of experimental chemistry, and it is suggested that he had implied that 'physics had actually hindered the discovery' of fission. *Chemists!*

From left to right: Hahn, Hartmann, Meitner, Heisenberg and Heuss, in 1958

Even though Meitner never received a Nobel prize, she was the recipient of numerous other awards, including the Max Planck Award in 1949, the Enrico Fermi Award in 1966, which she shared with Hahn and Strassmann, and various honorary doctorates, including from Princeton University, Harvard University, and others. In 1982, the radioactive element *meitnerium* was synthesised, and named in honour of Meitner, for her pioneering contributions in the development of our understanding of radioactivity.

5.8 Uranium Mining

Mining uranium is much like that of other minerals. However, a critical distinguishing feature of uranium mining is that the raw material, the final product, and the waste material produced, are *radioactive*.

It is the presence of *radioactivity* that necessitates stringent governance arrangements, and consistent and prudent management, to ensure that current and future generations, as well as the environment, are and remain protected from the potentially harmful impacts associated with the exposure to radiation from uranium exploration, mining, milling, waste disposal, and the decommissioning and closure of such facilities.

It is the primary purpose of this book to equip Radiation Safety Officers active in radiation-relevant work environments, including at uranium mines, with the necessary understanding and tools to competently fulfil their important roles.

5.9 Namibia's Uranium Exploration and Mining Sector

In 1928, Peter Louw discovered uranium in the Namib Desert. In the late 1950s, exploration activities were intensified. Following the discovery of numerous uranium occurrences, Rio Tinto secured the rights to the low-grade Rössing deposit in 1966. Ten years later, in 1976, Rössing Mine commenced with the production of uranium concentrate, being the country's first commercial uranium mining operation. In 2016, Rössing celebrated its 40th year of continuous operations.

Figure 40: Pit and adjacent mining area at the Rössing Mine [26]

In early 2018, Namibia has three uranium-producing mines, i.e. Rössing, Langer Heinrich, and Husab. Jointly, these contributed some 5.9% of the world's annual uranium output in 2016. National production figures are expected to double as operations at Husab are ramped up to design capacity.

The final uranium concentrate product produced is calcined uranium oxide (Rössing and Husab), refer to Figure 41.

Langer Heinrich (and Trekkopje prior to embarking on the current care and maintenance program) sells its produce in form of yellowcake, as shown in Figure 42.

Figure 41: Calcined uranium oxide [27]

Figure 42: Uranium yellowcake [28]

Namibian uranium mines extract uranium from low and very low uranium-bearing ore grades, with a uranium content ranging between 0.01% and 0.1%. Expressed as a uranium concentration in parts per million (ppm), such ore grades contain between 100 and 1 000 ppm uranium.

Uranium mining takes place in sites that exhibit primary and secondary mineralisation of uranium. Examples of primary mineralisation sites in Namibia include Rio Tinto's Rössing Mine, and Swakop Uranium's Husab Mine. Secondary mineralisation occurs when uranium has previously been leached out of its primary mineralisation site and has re-mineralised in a secondary deposit. The paleo-channels mined by Paladin Energy's Langer Heinrich Mine, and those at AREVA's Trekkopje Mine, are examples where deposits are characterised by their secondary mineralisation of uranium.

The chemical process used to extract uranium from the ore involves leaching, using an acid process, as is practiced at Rössing and Husab, and using a pilot plant by Bannerman Resources, as well as an alkaline dissolution media, as used by Langer Heinrich, and prior to commencing with the care and maintenance program, at Trekkopje. Leaching takes place in purpose-built leach tanks, as done at Rössing, Husab and Langer Heinrich, and using heap leaching, as done at Trekkopje and by Bannerman.

Figure 43: Aerial view of the Langer Heinrich Mine [29]

Once in full production, Husab will be one of the largest uranium mines in the world. The mine's potential production exceeds the country's total uranium production capacity and is expected to elevate Namibia to third rung amongst international uranium producers.

Figure 44: Mineral exploration activities at the site of the present-day Husab Mine [30]

Figure 45: Constructing the crusher plant at Husab Mine [31]

Other Namibian uranium projects taking place in the country's Erongo Region include:

- **AREVA Resources Namibia, Trekkopje Mine**

  Trekkopje is a shallow, high-tonnage, low-grade, calcrete surface deposit. The principal uranium mineralisation extends over an area 14 km long, and 3 km wide, which is characterised by very low ore grades. Mining at Trekkopje commenced with a pilot phase, called the MINI and MIDI, resulting in the first production of uranium concentrate in form of sodium diuranate (SDU) in 2011. During the pilot phases, in 2011 and 2012, some 440 tons of SDU were produced, and was used to test and refine the technical aspects of this large-scale alkaline heap leaching operation. Full-scale operations never started at Trekkopje, and in 2013, on-site operations were placed under a care and maintenance program.

Figure 46: The MIDI heap leaching facilities at Trekkopje in 2011 [8]

- **Bannerman Resources Namibia**

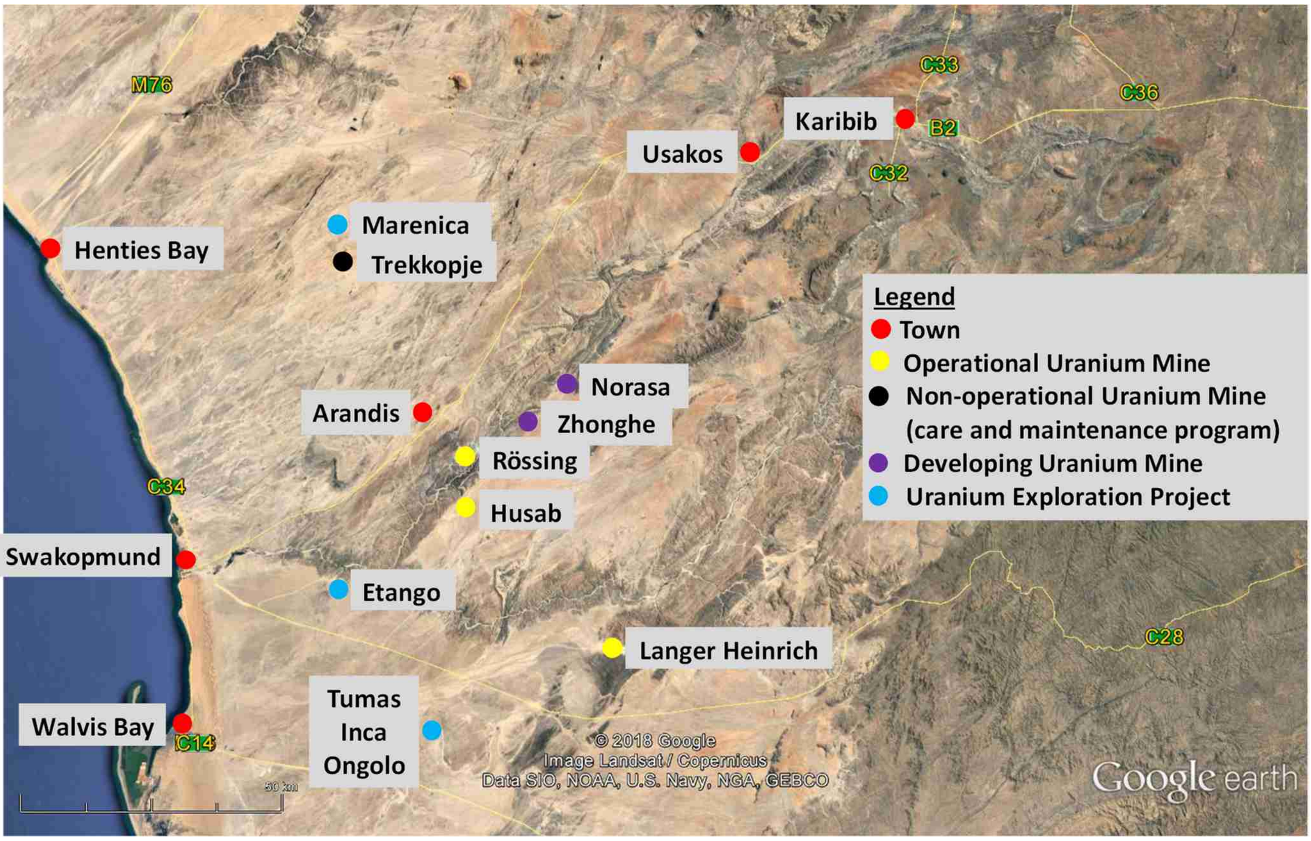
  Bannerman's principal asset is its 95%-owned Etango Project, situated in the so-called moon landscape of the Swakop River valley in Namibia's Erongo Region. Following an extensive exploration phase, Bannerman embarked on a heap leaching demonstration program in 2015, as shown in Figure 47.

Figure 47: Bannerman's heap leach demonstration plant in the moon landscape [32]

Several other potential uranium mining and exploration projects are in various stages of their development, including those by Zhonghe Resources, the Norasa / Valencia project by Forsys Metals, as well as several exploration projects by Deep Yellow Limited's Reptile Uranium, e.g. Tumas, Inca, Ongolo and Marenica.

The locations of the main uranium mining and exploration activities in Namibia's Kunene and Erongo Regions are depicted in Figure 48.

Figure 48: Uranium mining and exploration projects in Namibia's central-western regions [8]



5.10 Strategic Environmental Assessment for the Central Namib 'Uranium Rush'

In 2009, at a time when uranium spot market prices peaked, the Geological Survey of Namibia, in the Ministry of Mines and Energy, and supported by the German Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), initiated a strategic environmental assessment (SEA) for the 'Central Namib 'Uranium Rush'' [33].

The SEA considered the cumulative impacts from uranium mining, and formulated several scenarios that could potentially affect the sector, including a 'boom-bust' scenario where many mines would start up, and close within a short period.

Another outcome of the SEA was the development of a strategic environmental management plan (SEMP), as well as the establishment of a SEMP office in the Ministry of Mines and Energy, as well as the formulation of a set of Environmental Quality Objectives (EQO). Today, compliance with the EQO's is regularly assessed, and forms part of an annual SEMP report published by the Ministry.

In 2016, the Ministry of Mines and Energy commissioned the development of an Air Quality Management Plan (AQMP) for the uranium and other industries in the Erongo region of Namibia. This project is meant as an update of the air quality assessment previously undertaken as part of the SEA. The AQMP aims to establish mitigation measures that can be implemented by the various major role players, to ensure that regional ambient air quality standards are met. Namibia does not yet have air quality standards or emission limits, which are to be developed during the project.

In 2016, and continuing until early 2019, further assessments are undertaken to identify and quantify the contributions of the sources of air pollution in the Erongo Region and determine their significance. Work is supported by an ambient air quality monitoring network, which was established to quantify the regional air quality, and enable the assessment of key air quality indicators, including for ambient dust concentrations, as well as for radon.

5.11 International and Namibian Uranium Production

Namibia's uranium concentrate production between 1976 and 2016 is illustrated in Figure 49, and is based on production figures from Rössing Uranium Limited [34], the World Nuclear Association [35], the Chamber of Mines of Namibia [36], and the Namibian Uranium Association [37].

Figure 49: Namibian uranium concentrate production between 1976 and 2016, in tons per year [8]

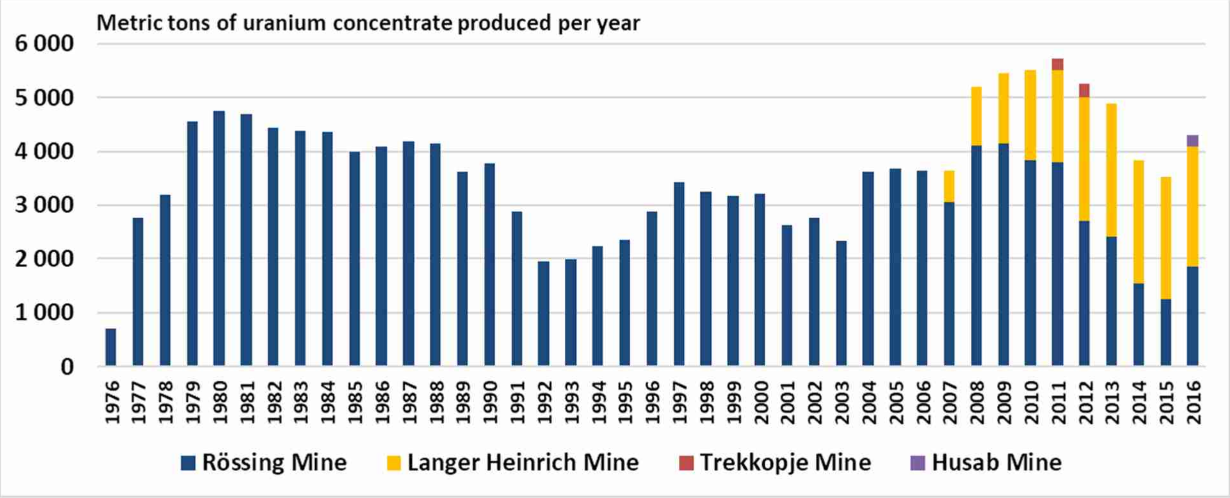


Figure 50 shows the worldwide uranium production (*not* uranium concentrate!) from 2005 to 2016. While uranium is produced in more than 20 countries, about 83.5% of the 2016 production, amounting to some 52 060 tons of uranium, originated in five countries only, with Namibia being the fourth-highest producer in 2016.

Figure 50: World production of uranium between 2005 and 2016, in metric tons [8]

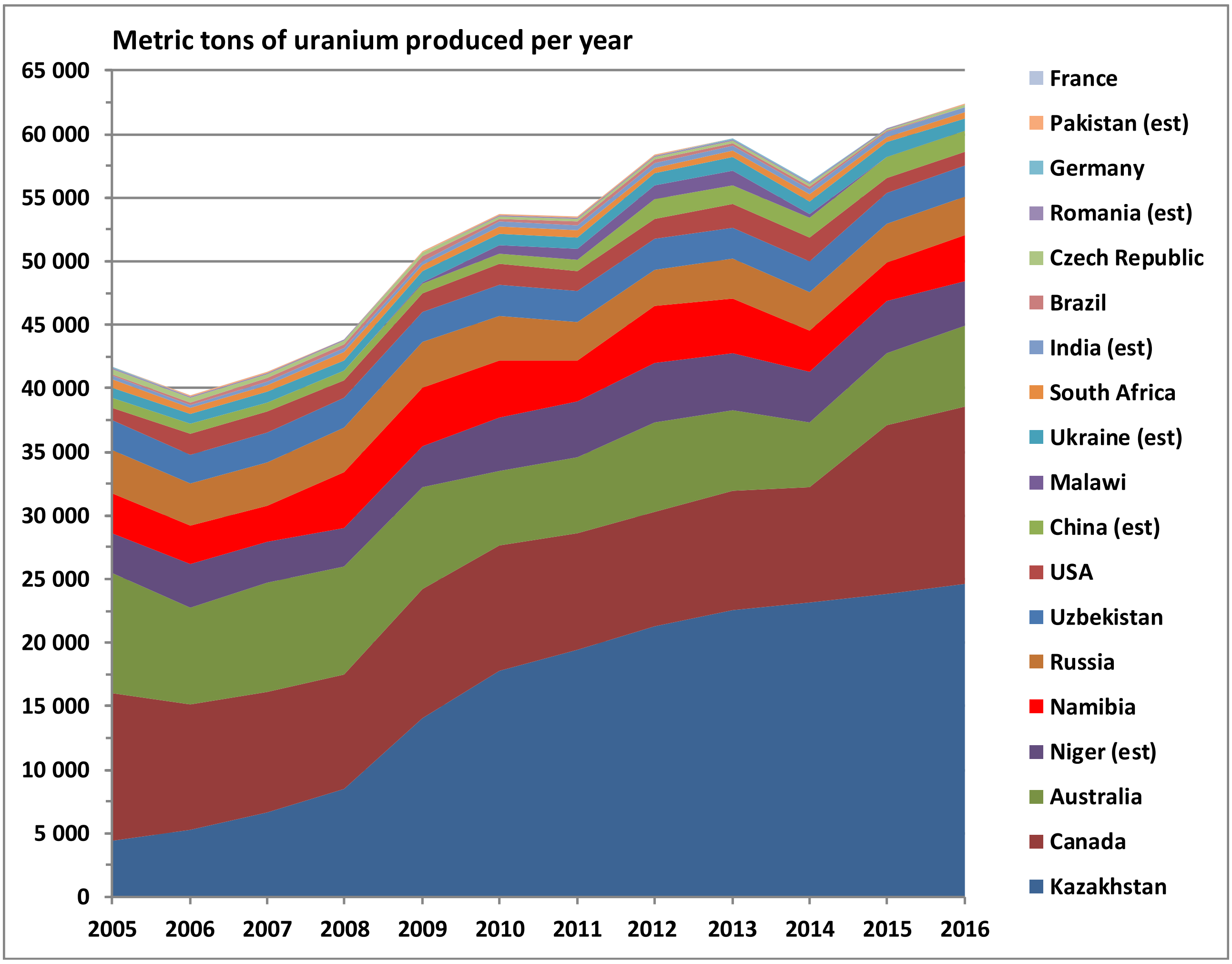
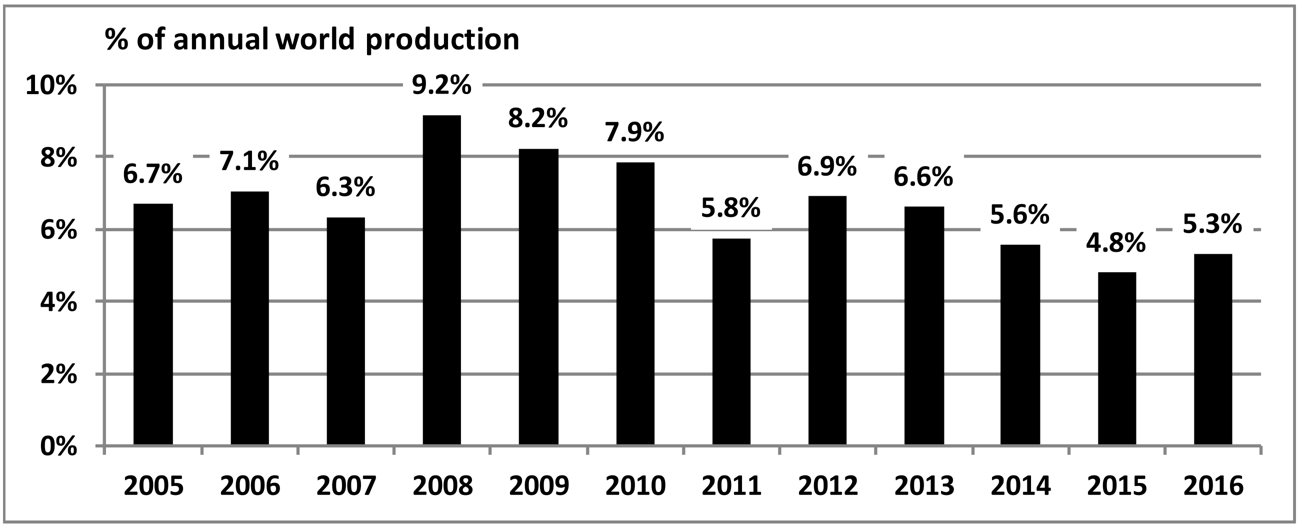


Figure 51 depicts the percentage contribution to the total world production between 2005 and 2016 as made by Namibian uranium producers.

Figure 51: Namibian uranium production as a percentage of the world production [8]



6 Interactions of Ionising Radiation with Matter

This Chapter describes the interactions between ionising radiation and matter, which is essential to the understanding of the impacts of exposure to radiation.

6.1 Ionising Radiation

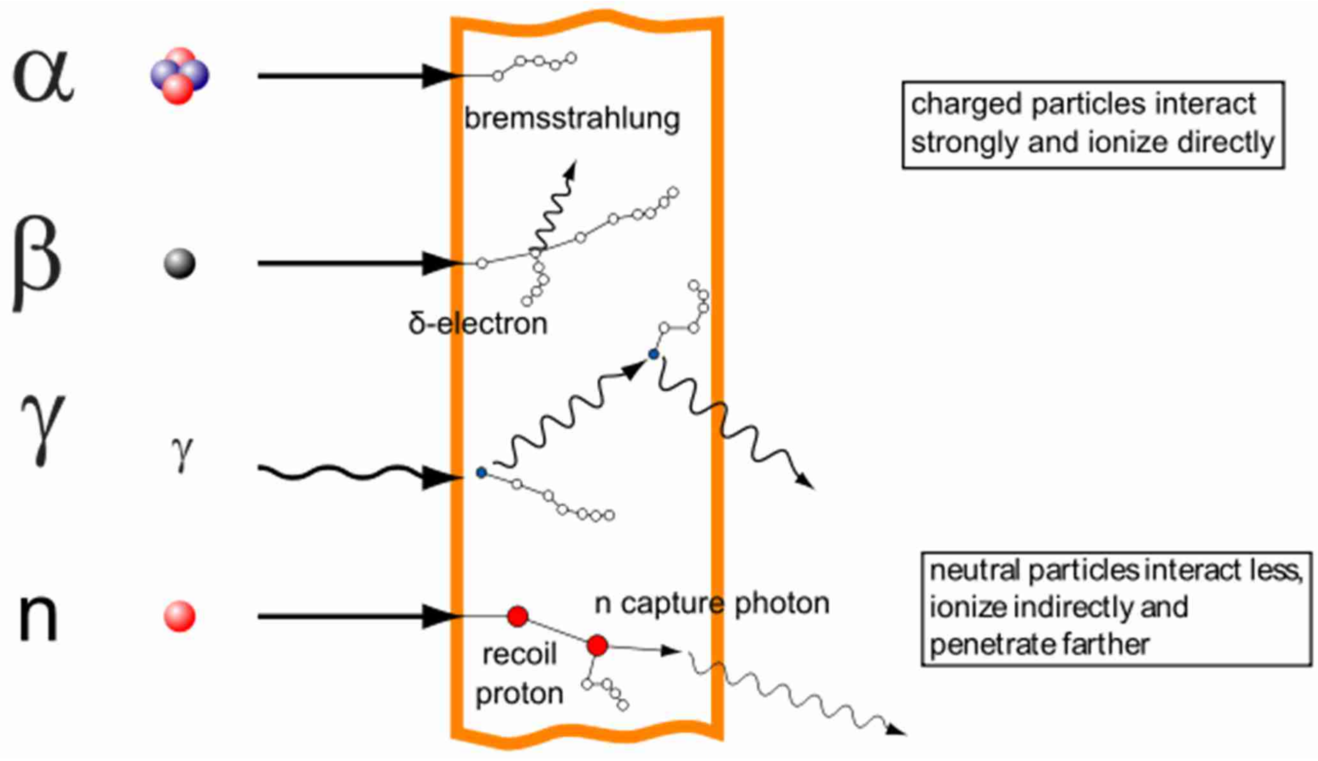
Radiation is called *ionising radiation* if it is sufficiently energetic to strip one or several electrons from an atom. In this process, a previously intact atom is turned into an *ion*. An ion is an atom that is missing one or several electrons, which implies that it is no longer charge-neutral.

Ionising radiation includes higher energy ultraviolet radiation, X-rays, gamma rays, as well as the particulate radiation, such as alpha and beta radiation, as emitted in radioactive decays, as well as neutrons.

Radiation requires an energy exceeding between 10 and 33 eV to be ionising radiation, i.e. able to ionise atoms. The range of ionisation energies is because the energy required to ionise atoms depends on how tightly the electron(s) is/are bound in a specific orbit. For example, the first ionisation energy for hydrogen and oxygen is 13.6 eV, while it is 33 eV for water.

Radiation can be *directly ionising*, or *indirectly ionising*. Charged particles (including alpha and beta radiation) are often directly ionising, because of electromagnetic interactions between charged particles. On the other hand, uncharged particles, including gamma radiation, X-rays and neutrons, do not interact as strongly with matter as their charged counterparts do, because they are charge-neutrality. For these species, ionisation occurs indirectly, through secondary effects.

Figure 52: Interaction of ionising radiation with matter [38]



6.2 Interactions between Radiation and Matter

Radiation that is sufficiently energetic to be ionising interacts with matter either directly or indirectly.

Direct interactions are the result of the electric charge(s) carried by such radiation, as well as the high linear energy transfer (LET) that takes place.

Indirect interactions between ionising radiation include the actions by neutrons, and photons, the latter being the 'particles' of electromagnetic radiation, and include both X-rays and gamma rays.

Photons are associated with a low linear energy transfer, noting that the higher the LET of radiation, the more ionising and the less penetrating it is.

- **Alpha particles** are a highly ionising form of radiation, and interact directly with matter via absorption, and leading to the emission of Bremsstrahlung.

- **Beta particles** may produce Bremsstrahlung, or secondary electrons, when moving through matter, and thereby ionise atoms either directly or indirectly.

- **Gamma radiation** interacts via Compton scattering, pair production, and the photoelectric effect, thereby ionising atoms indirectly.

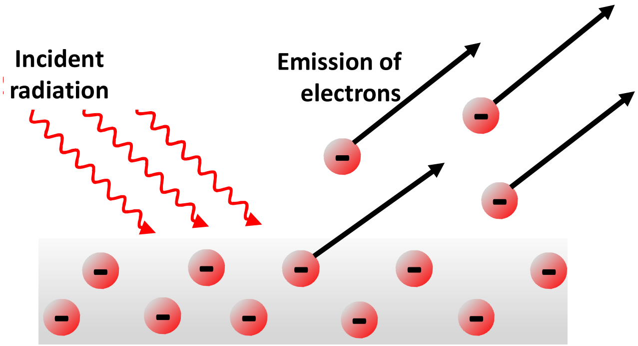
- **Fast neutrons** interact with matter, thereby being 'moderated', i.e. slowed down. Because neutrons are not electrically charged but interact with protons, they can be absorbed by atomic nuclei, which may trigger a fission process, or lead to the emission of protons from the nucleus.

The following subsections briefly describe the various types in which ionising radiation interacts with matter.

6.2.1 Photoelectric Effect

In the photoelectric effect, an electron in an atomic orbit absorbs the energy of the incident photon. If the photon energy is sufficient to break the bond, the electron leaves the orbit, thereby turning a charge-neutral atom into an ion, refer to Figure 53.

Figure 53: Photoelectric effect [8]



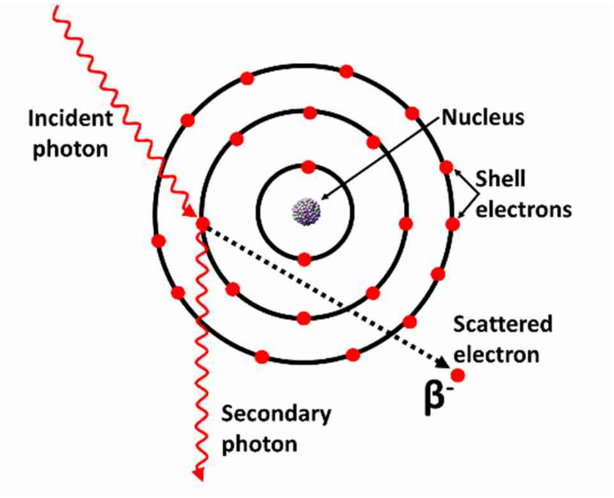
6.2.2 Compton Scattering

Compton scattering happens when the energy of an incoming photon exceeds the binding energy of a bound electron.

In the interaction between the incident photon and an electron, the electron is kicked out of its orbit, and in the process, emits a secondary, lower-energy photon, which continues to travel in a direction different to that of the incident photon.

Compton scattering results in an ion, a free electron, and a lower-energy photon, as illustrated in Figure 54.

Figure 54: Compton scattering [8]



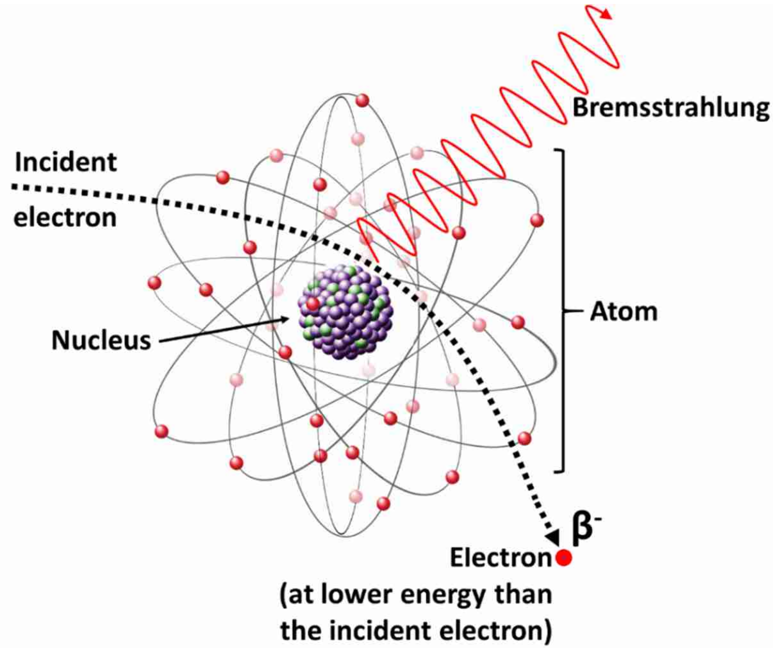
6.2.3 Bremsstrahlung

Bremsstrahlung means 'braking radiation' in German and refers to radiation that is emitted when a charged particle is decelerated when interacting with matter.

To illustrate: a high-speed electron moves through an atom, passing by the nucleus. It is deflected from its original trajectory, because of the attractive force between the positive charge in the nucleus and the electron's negative charge.

The deflection slows down the electron, which leads to the emission of secondary photons, which is called Bremsstrahlung, as shown in Figure 55. Secondary radiation continues to interact with matter and may indirectly ionise additional atoms.

Figure 55: Bremsstrahlung [8]

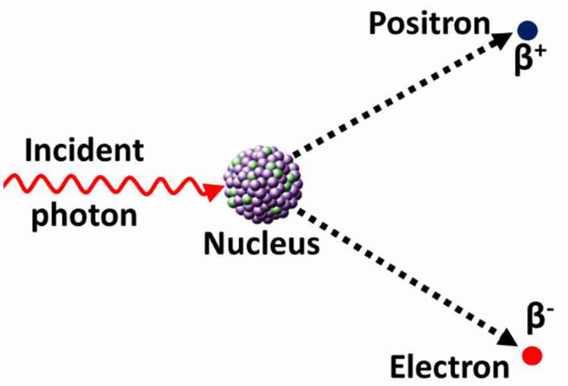


6.2.4 Pair Production

Pair production results when an incoming photon is absorbed by the nucleus of an atom, and the energy absorbed in this way is converted into an electron-positron pair, which is then emitted from the nucleus, as depicted in Figure 56.

The electrically charged particles emitted in this way continue to interact with matter and may cause further ionisation.

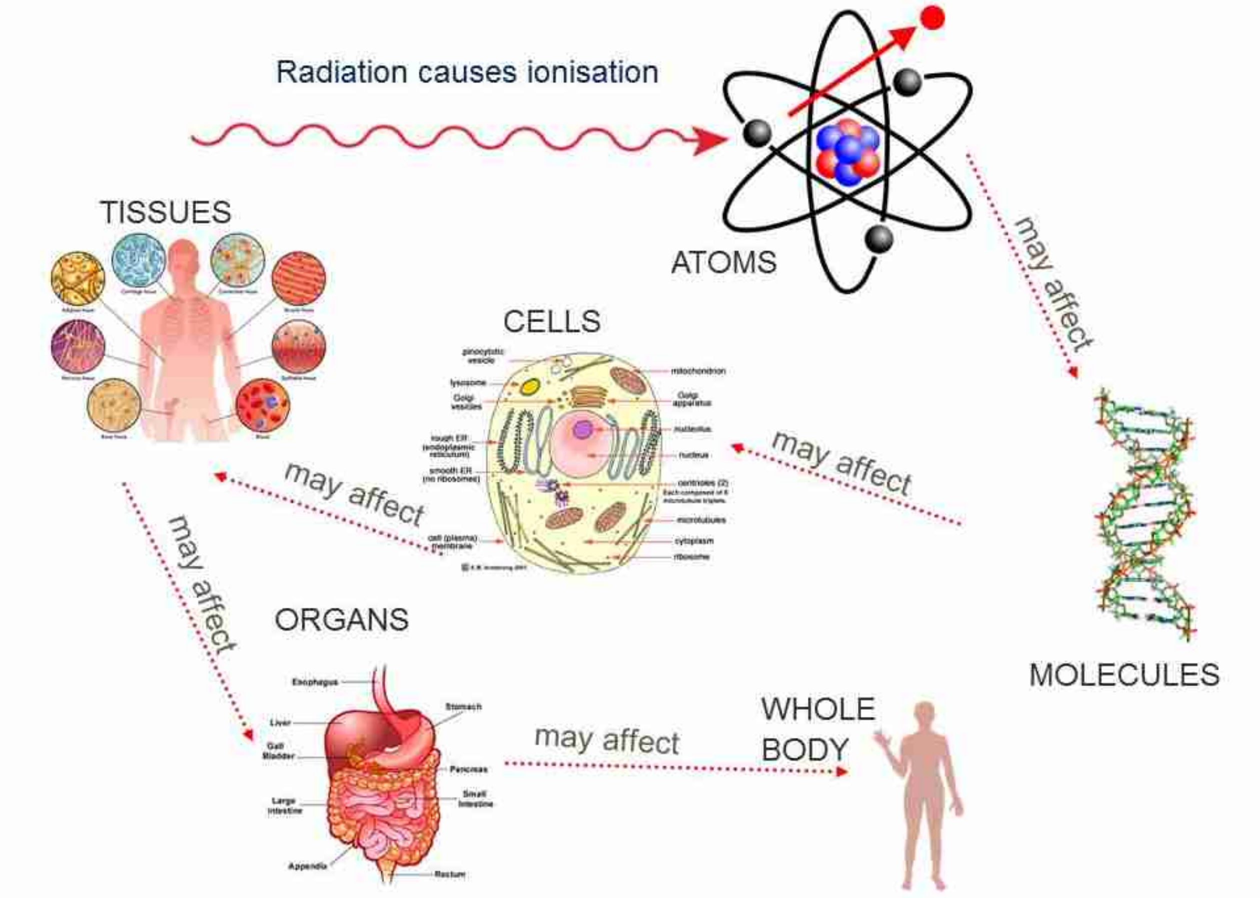
Figure 56: Pair production [8]



6.3 Biological Effects from Exposure to Ionising Radiation

Biological effects and impacts, which are the result of the exposure to ionising radiation, only occur following the ionisation of atoms or molecules. Schematically, the sequence of events, from the exposure to ionising radiation until the effects and impacts arising in tissues, organs or even the whole body, as shown in Figure 57.

Figure 57: Sequence of events leading to biological effects from exposure to ionising radiation [8]



The sequence of events as is depicted in

Figure 57 offers a simplified view of the complex interactions and biological mechanisms at work resulting from the exposure to ionising radiation.

The reader is cautioned that each of the above steps requires a multitude of similar impacts and reactions for the next step in the sequence to occur. For example, the destruction of a single DNA molecule will not simply affect the cell in which it is located, as such an effect only occurs if very many molecules are destroyed at the same time, in proximity to the first event.

The human body consists of an estimated 37 trillion cells (i.e. $3.7 \cdot 10^{13}$), of which some 300 billion cells are replaced each day [39]. This rate of exchange, and the cellular renewal, is equivalent to the replacement of some 8 000 cells per one million cells each and every day - cell replacement works at 8 000 ppm!

Exposure to radiation can affect cells directly as well as indirectly: an indirect impact is the *radiolytic decomposition*, which is the dissociation of molecules resulting from the exposure to ionising radiation. This leads to the formation of a variety of new chemical compounds, including that of peroxide, which is toxic.

Through a complex set of reactions, ionised water molecules form free radicals, which can cause damage to macro-molecules, e.g. DNA molecules.

A direct impact resulting from the exposure of cells to ionising radiation is the absorption of radiation by macro-molecules, such as those forming our DNA, and a variety of essential cell enzymes. If damaged, such macro-molecules may become abnormal, and initiate chemical reactions and trigger changes that may lead to modifications to the biology and biochemistry of cells and organic tissue.

Low exposure doses spread over a prolonged period are unlikely to cause immediate changes. In this context, a low exposure dose refers to one that is less than 100 mSv, when administered over several years. If such low-dose exposure brings about changes, it occurs mostly on the cellular level, and seldom if ever lead to tissue changes. These may therefore not be readily detectable, and if at all, only after many years or even decades following such exposures.

Genetic effects and cancer are the primary health concerns that may result from exposure to ionising radiation, noting that cancer is about five times more likely than a genetic effect. Genetic effects include still births, congenital abnormalities, decreased birth weight, as well as infant and childhood mortality. These effects are often the result of cell mutations in an exposed individual and are then passed on to the offspring. They may appear in the immediate and direct offspring if the damaged genes are dominant, or generations later if the genes are recessive. However, in this context it is important to note that genetic effects have only been observed in laboratory animals exposed to very high radiation doses. No such evidence has yet been found in children born following the nuclear bomb explosions at Hiroshima and Nagasaki (Japan) in 1945.

Cells that reproduce pass on genetic information as is stored in the cellular DNA. If newly created cells are to survive, the information that is passed on cannot be substantially flawed. This insight underpins the approach used in modern radiation therapies, which is for example used to treat certain types of cancer using ionising radiation. As cancerous cells reproduce very quickly, they are particularly sensitive to radiation. Through targeted radiation doses, cancer cells and their rapid growth are negatively affected, causing affected cells to die off, and thereby shrinking the cancerous tumour.

White blood cells, i.e. *lymphocytes*, and other cells that produce blood, are most vulnerable to exposure to ionising radiation. Such cells must reproduce at a high rate, to replenish older ones, and therefore require that the correct DNA information is passed on, which enables the progeny cells to survive. If incorrect DNA information is passed on from one cell to the next, the offspring cells will not be fit to survive, and die. Once the cells responsible to produce blood, and white blood cells, are affected by ionising radiation, their host becomes vulnerable to infections and diseases. In such cases, the most effective treatment includes a transplant of bone marrow, as such marrow contains the cells required to produce blood cells.

On the other hand, muscle and nerve cells are least affected by ionising radiation. This is the result of the slow rate of cell reproduction and renewal. If a radiation dose is sufficiently high, it may affect both muscle and nerve cells. In such cases, the affected person is likely to die, as the brain and muscles may no longer be able to continue controlling the essential bodily functions, including breathing and the continuous circulation of blood.

Cells in the gastro-intestinal (GI) system do not regenerate as fast as blood cells and blood forming cells do. Damage to the GI system is mainly caused when the tissue that forms the organs of the GI system are destroyed. However, once the GI system is damaged or even destroyed by high radiation doses, death is certain.

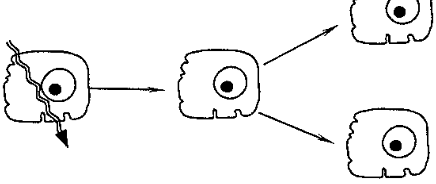
Acute radiation sickness (ARS) is a serious illness that develops when exposed to extremely high doses of radiation. Such exposure doses usually will have to exceed some 2 Sv, and be administered over a short period, for ARS to develop. Initial symptoms signalling the onset of ARS include vomiting, headaches, and/or diarrhoea, and in severe cases, the onset of seizures and/or coma. The leading cause of death from ARS is the destruction of a person's bone marrow, thereby promoting further infections, and triggering internal bleeding. Survivors of ARS may need a few weeks up to some years to fully recover.

Despite the many negative repercussions resulting from the exposure to high doses of ionising radiation, the cells in the human body have a tremendous ability to cope with adversity, and to repair damage that may have occurred. As a result, the effects brought about by the exposure to low-level radiation are usually reversible, and in many instances, cells can completely repair themselves, and continue to function normally thereafter.

One distinguishes between four outcomes resulting from the exposure of living cells to high doses of ionising radiation:

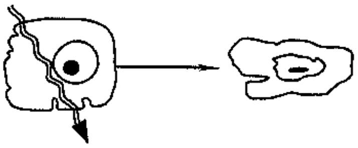
a. As illustrated in Figure 58, ionising radiation exposes and damages a living cell. This triggers the cell's repair mechanisms, thereby mending the damage. Thereafter, the cell produces healthy offspring, that live and procreate.

Figure 58: Cell repair and reproduction [40]



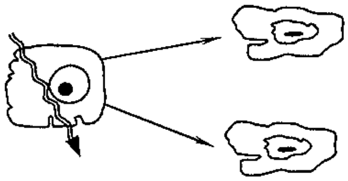
b. Figure 59 illustrates the case where a cell's normal repair mechanisms fail to mend the damage caused by the radiation dose. This renders the cell unable to reproduce, and it eventually dies. Surrounding cells absorb the remaining dead cell material, which is part of the body's normal tissue cleansing mechanism.

Figure 59: Cell repairs fail, cell dies [40]



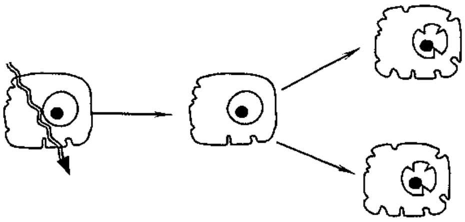
c. As illustrated in Figure 60, ionising radiation damages a living cell, where after cell repairs commence. While such repairs take place, the cell reproduces. Offspring cells produced lack some of the critical life-sustaining components or functions of a healthy cell and die.

Figure 60: Cell repairs fail-offspring dies [40]



d. Figure 61 illustrates how a living cell's repair mechanisms restore some cellular functionality following radiation damage. However, the cell remains partially damaged, but can reproduce. Offspring cells have inherited vital but damaged cell information and are mutant cells. As they reproduce, they perpetuate the inherited mutation, passing on damaged cell information to future cell generations, which could in time lead the formation of a malignant cancerous tumour.

Figure 61: Cell repairs fail-offspring lives [40]



Scenarios a. to c. are part of the everyday cell renewal processes taking place in our bodies, and they leave no biological effect, unless the scale on which such events take place are massive.

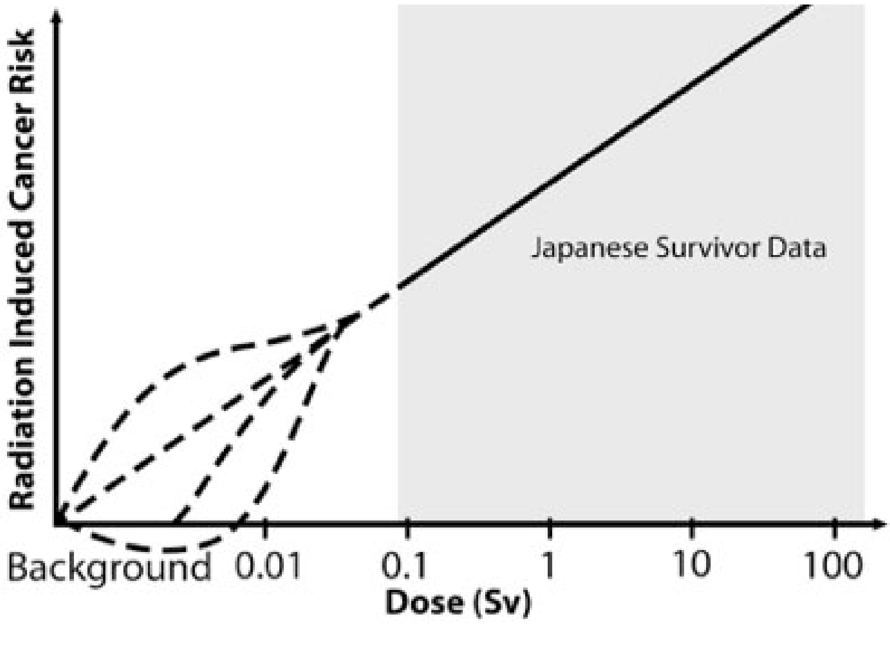
However, a potentially detrimental outcome is the one described in scenario d., where the kernel of a malignant growth, such as a tumour, could be started. In time, it would make itself felt, however only after a very considerable period has passed between the event which triggered the changes, and the detection of such cancerous cells.

6.4 Linear No-Threshold Hypothesis

Most of the information about the risk of exposure to radiation originates from studies of large populations exposed to high doses of ionising radiation.

A common feature of these studies is that they show that the risk associated with the exposure to ionising radiation is directly proportional to the dose. This implies that the risk increases in a linear manner as the exposure increases, and vice versa. This fact is confirmed for exposure doses greater than 0.1 Sv = 100 mSv, as illustrated in Figure 62.

Figure 62: Linear relationship between the risk and dose for high exposures [41]



However, for exposure doses of less than 100 mSv, the data is insufficient to prove that the linear relationship between the exposure dose and associated risk also applies to low-level exposures.

Below 100 mSv, Figure 62 shows several dotted lines, which are associated with various hypotheses that are used to explain the data. These hypotheses – from the dotted line at the top to the lowest dotted line in the graph – have the following characteristics:

- **The low-dose-high-sensitivity hypothesis** suggests that the risk associated with low exposure doses is proportionally higher than is the case at higher doses;
- **The linear no-threshold hypothesis (LNT)** suggests that the linear relationship between the exposure dose and risk holds for high as well as low exposure doses;
- **The threshold hypothesis**, which suggests that there is a threshold dose, below which an exposure to radiation has no effect and therefore without risk; and

- **The hormesis hypothesis**, where the risk associated with an exposure to a low radiation dose is less than that associated with not being exposed at all. This implies that low levels of exposure to radiation is beneficial to the receptor, provided the dose is low.

Today, the hypothesis that is universally accepted, is the linear no-threshold hypothesis, and the ICRP recommendations are based on the application of the LNT [41]. It is emphasised however that a hypothesis is not a proven theory, and that our understanding of the risks associated with low-dose exposures to ionising radiation is not yet proven beyond doubt.

6.5 Radiobiological Effects

Biological effects resulting from the exposure to ionising radiation depend on the exposure dose, and the period over which such an exposure occurred.

Radiobiological effects, i.e. biological effects resulting from the exposure to ionising radiation are differentiated into the so-called *stochastic effects*, and *deterministic effects*. Radiobiological effects on people are called *somatic effects*, those on embryos and foetuses are called *teratogenic effects*, and hereditary effects on offspring are called *genetic effects*. These are introduced in the next subsections.

6.5.1 Deterministic Effects

Deterministic effects arising from the exposure to ionising radiation only occur above a fixed *threshold dose*, which is usually an acute dose, as shown in Figure 63.

The severity of deterministic effects increases with the dose above the threshold. Below the threshold, deterministic effects do not appear.

Examples of deterministic effects include

- Radiation burns (Figure 64);
- Cataract induction (Figure 65);
- Acute radiation syndrome; and
- Radiation-induced thyroiditis.

Figure 63: Deterministic effects only occur above a threshold dose [8]

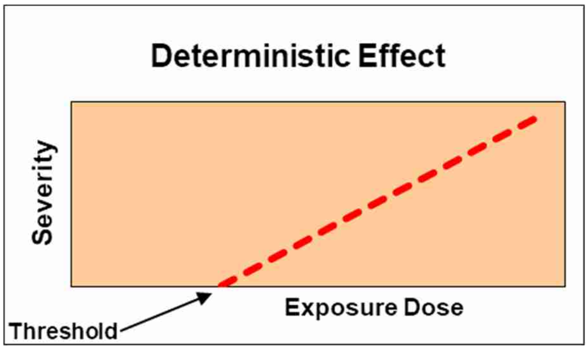


Figure 64: Skin burns through fluoroscopy [42]

Figure 65: Cataract of the eye [43]

6.5.2 Stochastic Effects

Stochastic effects resulting from the exposure to ionising radiation occur randomly, and their probability of occurrence is proportional to the exposure dose, as illustrated in Figure 66.

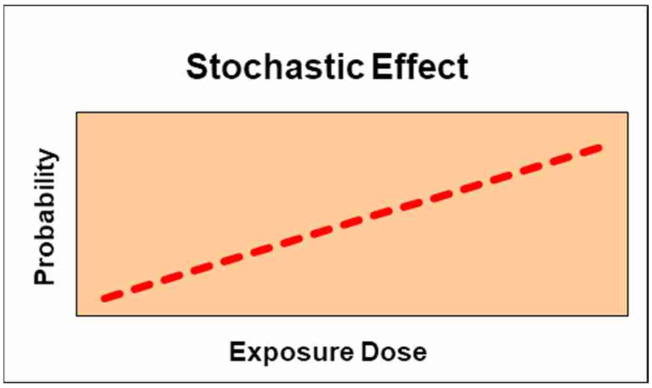
Stochastic effects have no threshold, and there is no certainty as to when they occur, and who will be affected. The likelihood of stochastic effects increases with the dose, noting however that the probability of occurrence is understood to hold for sample sizes comprising of many individuals (i.e. for large populations), and not for individuals.

The ICRP estimates that the risk of cancer incidence has a probability of 5% per accumulated dose of 1 Sv (expressed as 5%/Sv, which is equivalent to 0.005%/mSv). This estimate is based on the linear no-threshold hypothesis, and as such, is a statement of the statistical probability of the risk of exposure to low doses.

Examples of stochastic effects resulting from the exposure to ionising radiation include

- Radiation-induced cancer;
- Teratogenesis;
- Radiation-related cognitive decline;
- Heart disease.

Figure 66: Stochastic effects are probabilistic and linearly increase with the exposure dose [8]



Some effects resulting from the exposure to ionising radiation can be either stochastic or deterministic, and they depend on the dose and exposure period. Examples include the formation of cataracts in the lens of the eye (Figure 65), and radiation-induced injuries of the lung.

6.5.3 Somatic Effects

Radiobiological effects affecting people are *somatic effects*. They result in cell damage which is passed on to successive generations of future cells, which in turn may lead to the modification or impairment of both cells and tissues. Damage to cell membranes, mitochondria and cell nuclei result in abnormal cell functions, and affect cell division and growth, while accelerating their die-off.

Somatic effects include

- Cataracts of the eye (Figure 65);
- Skin cancer (Figure 67);
- Damage to the lining of the gastrointestinal tract, which may negatively affect digestion and absorption;
- Damage to bone marrow, causing anaemia; and
- Cancer.

Figure 67: Skin cancer [44]

The *detriment of radiation exposure*, as determined by the ICRP, includes:

- the probability of inducing a fatal cancer;
- the chance of a non-fatal cancer occurring;
- the chance of severe hereditary effects; and
- the length of life lost if any of the above harm occurs.

Using all these risks, the ICRP estimates that the overall detriment of radiation exposure is 4.2%/Sv for adult workers, and 5.7%/Sv for the population as a whole [45].

6.5.4 Teratogenic Effects

Teratogenesis refers to a prenatal toxicity leading to structural or functional defects in the developing embryo or foetus. Teratogenic effects from exposure to radiation are believed to be a deterministic effect, with a threshold dose below which no such effect occurs. However, there are also stochastic effects affecting the unborn child, including carcinogenesis and mutagenesis, which have no threshold, and which are not classified as being teratogenic.

The development of an unborn child is expressed in terms of its post-conceptional age, and is divided into the three major stages as depicted in Figure 68:

1. **Pre-implantation and implantation stage**, to about the second week after conception;
2. **Organogenesis**, from about the third to the eighth week after conception; and
3. **Foetal development**, from week nine after conception.

Figure 68: Implantation (left), organogenesis and foetal development (right) [46]

During **pre-implantation and implantation**, the principal radiation-induced health effect is abortion, with a threshold dose estimated to lie between 100 and 150 mSv.

Radiation-induced health effects during **organogenesis** include organ malformations, while abnormalities result when cells are killed off by radiation during the active phase of cell proliferation and cell differentiation. Because the embryo is unable to completely replace damaged cells, malformations may occur. The estimated threshold for the occurrence of such abnormalities is between 100 and 200 mSv, with temporary growth retardation taking place at exposure doses estimated to range from 100 to 250 mSv.

During the **foetal stage**, the predominant observable effects of exposure to radiation include growth retardation, microencephaly, and severe mental retardation. These effects have been observed from doses above 500 mSv, but their threshold is believed to be closer to 100 mSv.

In addition to the deterministic effects described above, there are stochastic risks related to carcinogenesis and mutagenesis. Excess cancer because of in-utero exposures has not been demonstrated in the studies of Japanese atomic bomb survivors, even though the population has now been monitored for more than 65 years. However, it is estimated that the associated risk is of the order of 6%/Sv, while the risk for radiation-induced hereditary diseases in humans (mutagenesis) is estimated to be of the order of 1%/Sv.

Table 6 summarises the risks and thresholds for prenatal exposure to radiation and is based on the ICRP publication relevant to pregnancy and radiation [46].

Table 6: Effects from radiation exposure in utero [46]

Gestation age	Stage	Potential effect	Threshold	Risk
0 to 2 weeks	pre-implantation and implantation	abortion	100 -150 mSv	
3 to 8 weeks	organogenesis	organ malformation	100 - 200 mSv	
		growth retardation (temporary)	100 - 250 mSv	
9 to 25 weeks	foetal	mental impairment	100 mSv	
Whole pregnancy		carcinogenesis	none	6% / Sv
		mutagenesis	none	1% / Sv

6.5.5 Genetic Effects

Genetic effects occur when the DNA which encodes the genetic information is damaged, and the damaged genes and chromosomes are then passed from the current to a future generation.

Genetic information is also contained in the chromosomes of germ cells, i.e. the female ovum and male sperm.

While genetic effects because of exposure to ionising radiation have been observed in laboratory animals exposed to very high doses of radiation, no evidence of genetic effects has been seen in children born to the survivors of the atomic bomb blasts at Hiroshima and Nagasaki in Japan.

6.6 Epidemiology

Epidemiology is the study of large groups of people to determine how often and why specific diseases occur.

As for the effects of exposure to radiation, most of our current understanding that links radiation exposure and cancer is based on epidemiological studies of populations that have been exposed to high doses of radiation exposure.

Much of the information about radiation-induced health effects is from the survivors of the atomic bomb explosions at Hiroshima and Nagasaki in Japan, as well as from people who received large radiation doses as part of therapeutic or medical tests. It is found that cancers associated with exposure doses exceeding 500 mSv include leukaemia, as well as cancer of the breast, bladder, colon, liver, lung, oesophagus, ovaries, stomach, and multiple myeloma.

The time between the exposure to radiation and the detection of cancer is the so-called *latent period*. This period can amount to many years, and it is often not possible to identify the exact cause or causes which would explain why cancer developed. In addition to the effects of ionising radiation, there are a large variety of other known and suspected causes that induce cancer, including exposure to chemical and physical hazards, and lifestyle contributors such as smoking, alcohol consumption and poor diet.

Data from highly exposed populations show that high doses of radiation exposure may cause cancer. In this context, a high dose is an exposure exceeding 100 mSv. There is no data that establishes a direct and firm link between cancer and exposure doses that are below about 100 mSv.

Exposure doses exceeding 500 mSv tend to kill cells, which may in turn affect a specific area or tissue type, or even affect one or several organs, which may trigger *acute radiation syndrome*. The higher a radiation dose, the sooner the effects of radiation will appear, and the higher the probability of death.

Many of the survivors of the atomic bomb blasts in Japan experienced the acute radiation syndrome (ARS). Following the accident at the Chernobyl nuclear power plant in 1986, emergency workers reported with symptoms that are referred to as ARS. This is not surprising, as both plant workers and firefighters received radiation doses ranging between 8 to 16 Sv. Of these, 28 died within the first three months following their exposures.

People's responses to high exposure doses are not identical. As a result, and because radiation affects people in a variety of ways, it is not possible to say what exposure dose is fatal. However, statistical evidence suggests that some 50 percent of a given cohort will die within thirty days after receiving a once-off whole-body dose of between 3.5 to 5 Sv. However, individual health outcomes vary between people, even within groups of healthy persons. In addition, the level and response to medical care received immediately after being highly exposed is also of critical importance and plays a crucial role in an exposed person's chances of survival.

Various studies have focused on the health impacts resulting from the exposure to low doses of ionising radiation. Many of the earlier studies focused exclusively on external radiation doses. More recently, several studies have also considered the impacts of internal exposure doses, such as those arising from the inhalation of long-lived radioactive dust, radon and progeny, as well as from the ingestion of radioactive source material. Personal dose monitoring for internal exposures is more complicated than for direct external exposures, and data on the former is therefore sparser than for external exposures.

The following subsections provide a summary of some of the most important studies undertaken and underpin the scientific understanding of the risk of exposure to ionising radiation.

6.6.1 UNSCEAR and BEIR Reports

This series of reports by the US Committee *on the Biological Effects of Ionizing Radiation* (BEIR), and the *United Nations Scientific Committee on the Effects of Atomic Radiation* (UNSCEAR), provides regular updates on the latest scientific research relating to biological effects resulting from the exposure to ionising radiation.

The UNSCEAR reports provide epidemiological evidence for the risk of lung cancer from exposure to radon progeny [47], [48].

The BEIR VI report deals with the health risks from the exposure to radon. It notes that the risk of lung cancer caused by smoking is much higher than the risk of lung cancer caused by the inhalation of indoor radon. Furthermore, there is evidence for a synergistic interaction between smoking and radon, increasing the risk from radon for smokers beyond that of non-smokers.

The BEIR VII report provides an update on the health risks from the exposure to low-LET radiation [49], [50]. In this context, low radiation doses are defined as being low-LET radiation below 100 mSv. The BEIR VII report concludes that – at low exposures to ionising radiation – there is a linear dose-response relationship between an exposure and the development of solid cancers in humans. This is consistent with the ICRP dose-risk estimate [51], and the assumptions underpinning the linear no-threshold hypothesis (LNT), as described in section 6.4. The BEIR VII report also concludes that the risk of adverse heritable effects to children conceived after their parents have been exposed is very small.

6.6.2 Childhood Leukaemia from Background Radiation

A relatively new study undertaken at the Oxford University [52], [53], shows that there is a link between the very low doses of gamma radiation from background radiation, and the development of leukaemia in children.

The study finds that the relationship between a background dose and the risk of developing leukaemia is consistent with the linear no-threshold relationship found in survivors of Hiroshima and Nagasaki, where the latter exposures were higher and over a shorter period than those associated with low-level exposure to natural background radiation.

6.6.3 Cancer from Cosmic Radiation of Airline Crews

A study of 10 000 Nordic cabin crew members [54], using an inferred median cosmic radiation exposure dose for crew members based on information about flight routes and frequencies, found a small excess in the incidence of cancer in the cohort.

The specific cancers for which significant excess risk was identified were breast cancer, cutaneous malignant melanoma, non-melanoma skin cancer, and pharyngeal cancer. The excess in skin cancer could not be explained, as there was no evidence for above-average exposure to ultraviolet radiation.

6.6.4 Correlation between Radon Dose and Chromosome breaks

A study by the National Institute of Public Health in Prague investigated chromosome aberrations in cells from 225 persons exposed to doses between 8 and 3 300 mSv incurred from radon. It reported a statistical correlation between radon dose and chromosome breaks [55].

6.6.5 Connection between Exposure to Radiation and Silica Quartz

Using a cohort of 1 992 uranium mine workers from the WISMUT mining operations in Saxony and Thuringia in the former East Germany [56], the study investigated the suspected link between the exposure of uranium mine workers to silica quartz, radiation and heavy metals, and the development of autoimmune and tumorous diseases. It suggests that a possible connection between exposure to silica quartz and progressive systemic lupus, i.e. an autoimmune disease, may exist.

6.6.6 Lung Cancer Risk from Silica Quartz and Radon

Some studies suggest that there may be an increase of the risk to lung cancer because of a combination of silica quartz and the presence of radon. A study undertaken by the German Federal Government suggests a fourfold increase in the risk of lung cancer for a combination of cumulative exposure to some 4 Sv (i.e. 800 WLM) and > 16 mg/m^3 years [57].

6.6.7 Low Dose Radiation Health Risk

A study by the *German Radiation Protection Association* suggests that the risk factors proposed by the ICRP undervalue the health risk from exposure to low-level radiation by factors ranging between 100 and 2 000 [58].

In addition, and in contrast to the ICRP that suggests that cancer is the only potential effect from exposure to low dose radiation, the *European Committee on Radiation Risk* indicates that a multitude of additional impacts may potentially be caused by exposure to low doses of radiation. The linear no-threshold hypothesis is questioned, also citing a study by Grosche et al [59], which claims to show a proportionately larger health risk for lower doses than would be expected using the LNT.

6.6.8 Applicability of the Pre-1990s Job Exposure Matrix

In the 1970s, area radiation monitoring was introduced in the uranium mining industry. In contrast, personal radiation exposure monitoring only became more common in the 1990s, including at the former East German uranium mining company WISMUT. In the absence of accurate personal exposure doses, it is difficult to quantify the actual risk of exposure incurred in the pre-1990 period. This realisation resulted in the development of the so-called job exposure matrix, to estimate historic radiation doses. It uses average values for radon and dust concentrations, and disregards ingestion doses, which is a short-coming of this method [60], [61], [62].

6.6.9 WISMUT Legacy

The WISMUT uranium mines in former East Germany compiled a detailed register of some 500 000 former workers, including their medical records. The register includes estimates of workplace exposure doses for the period from 1946 to 1955, for which no monitoring data exists, as systematic area monitoring was only introduced in 1964, and select personal monitoring only started in 1971.

Pre-1956, estimates for radon exposure ranges between 150 and 1 500 mSv/a, and 50 to 500 mSv/a from 1956 to 1960, as workplace controls were introduced. Personal monitoring results from 1971 onwards suggest annual exposure doses ranging between 10 and 50 mSv/a, and below 20 mSv/a after 1975 [63].

6.6.10 Uranium Mining and Health Effects

Brugge et al [64] provide a more recent summary of the health effects from uranium mining. It is noted that uranium mining workers face an increased risk from neoplasm of the lung, larynx, and lymphatic tissue. The study also notes that evidence linking internal exposure to uranium and cancer is limited. It also suggests that previous studies failed to assess the impacts of internal exposure to uranium, finding fewer cancers because of poor statistics.

French [65] and Czech [66] cohort studies found that an access risk of lung cancer is correlated with cumulative radon exposure, but could not demonstrate other health impacts, such as kidney cancer.

A study of Colorado Plateau workers [67] found a correlation between lung cancer risk and radon exposure, as well as an elevated risk of silicosis for uranium miners.

Several studies on communities living in close proximity to uranium mines found weak evidence for incidences of elevated lung cancer risk among population subgroups [68] - [71]. However, it is noted that there are suggestions of selection bias / conflict of interest for some of these.

Two uranium legacy studies, [72] and [73], suggest an increased risk of hypertension, diabetes and autoimmune disease for populations living close to uranium mines and associated tailings.

Studies in South Carolina (United States of America) investigating the cancer risk from natural uranium in groundwater suggests dose and risk correlations [74].

A study on reprocessing plants in France found an increase of the risk of lung cancer associated with a decrease of the solubility of uranium products [75].

An increased risk of cancer from contaminated ground water originating at a uranium mine in the Northern Territory of Australia is suggested in [76].

Animal studies link the ingestion of uranium with nephrotoxicity, interference with the reproductive system, genotoxicity, and behaviour-altering influences on the brain [77].

Overall, it is suggested that the toxicity of uranium is a more important and stronger causative agent than the associated radiological effects [78].

6.6.11 Cancer from Internal Exposure to U

Canu et al [79] undertook an assessment of several previously published cohort studies, with the aim to establish potential correlations between the risk of cancer amongst nuclear workers, and internal exposure to uranium. While a low statistical significance renders the study inconclusive, it suggests that there are indications of a correlation between the risk of lung, larynx, lymphatic, and haematopoietic tissue cancers when internal exposure to uranium has occurred.

6.6.12 Cancer from Exposure to Uranium and Radium

A study of 3 000 Cameco uranium processing workers at Port Hope, Canada, focuses on the effects of uranium- and radium-related exposures [80]. Workers that were mainly exposed to radium and uranium were investigated separately. No significant radiation-related risks were found for on-site cancer incidences or as a cause of death. For gamma exposure, the excess risk of mortality from most cancer types was seen to be negative. The study notes a small but insignificant excess risk for lung cancer from exposure to radon progeny.

6.6.13 Cancer Risk from Radon Progeny

A comprehensive study – pooling eleven cohorts of miners – assessed the health outcomes of workers active in the uranium mining and processing industries [81]. The study found an excess relative risk (ERR) for the incidence of lung cancer and mortality, proportional to the exposure to radon progeny, with an ERR of roughly 50% per 100 WLM exposure, but it does not report on any link to other cancers or illnesses. The study noted that the individual risk estimates for workers from different mines differed by up to one order of magnitude.

A French mine workers' cohort study found that an excess directly proportional risk exists due to the exposure to radon progeny, at 71% per 100 WLM [82]. In addition, significant excess risks were observed for kidney cancer and silicosis, but no such risks were found for any other diseases.

A study on a German uranium miners' cohort investigated whether radon in ambient air causes cancers other than lung cancer [83]. Although the number of observed extra-pulmonary cancers showed no excess over national rates, significant excesses were observed for cancers of the stomach and the liver, with a corresponding reduction in some other extra-pulmonary cancers. An overall direct relationship between cumulative exposures to radon and incidences of cancer was observed.

6.6.14 Colorado Uranium Miners Cohort

A cohort of 1 484 mine workers from seven uranium mills in the Colorado Plateau (United States of America) was studied and compared the mortality from all causes to the overall population mortality rates in the United States [84].

The study found that, while overall mortality was less than the US average, significant excesses were observed for non-malignant respiratory diseases. Other non-significant excesses were also observed, including lung cancer. Specifically, a higher lung cancer risk for workers employed before the 1950s was found, attesting to an improvement of health management systems and practices over time.

6.6.15 South African Gold Miners Cohort

A study of South African gold miners investigates the loss of lung function because of exposure to silica dust [85]. It found a significant loss of lung function due to exposure to silica dust, but less than that associated with smoking.

6.7 Exercises

6.7.1 Linear No-Threshold Hypothesis

1. In a laboratory experiment, the continuous exposure of 300 mSv/year was found to kill 6% of the participating laboratory rats within one month. If one assumes that the linear no-threshold hypothesis applies, which of the following statements express the correct conclusions?
   a) 100 mSv/year will kill 2% of rats within two months.
   b) 100 mSv/year will kill 2% of rats within one month.
   c) 600 mSv/year will kill all rats within one month.
   d) 600 mSv/year will kill 12 % of rats within one month.
   e) 600 mSv/year will kill 6% of rats within 15 days.
   f) One cannot determine the mortality from the details provided.

2. In a laboratory experiment, a continuous exposure of 300 mSv/year was found to kill 6% of the participating laboratory rats within one month. If the laboratory staff concluded that 100 mSv/year will not kill any rats, which hypothesis would they have followed?
   a) Linear no-threshold
   b) Cut-off model
   c) Supra-linear
   d) Less than linear

7 Radiation Protection and Radiation Controls

This Chapter presents the foundation that underpins most contemporary approaches used in radiation protection and radiation controls and introduces the radiation risk assessment process.

7.1 International System of Radiological Protection

The International Commission on Radiological Protection (ICRP) provides the framework governing radiological protection [45].

The radiological protection framework is based on three important principles:

1) **Principle of Justification**

   "Any decision that alters the radiation exposure situation should do more good than harm."

   This principle dictates that any exposure to radiation must be assessed, by considering its potential harm and benefit, and that any additional exposures should result in outcomes that have a net benefit.

2) **Principle of Optimisation**

   "The likelihood of incurring an exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable (ALARA), taking economic and societal factors into account."

   This principle dictates that exposure doses must be kept as low as possible under the existing scenario and take relevant social and economic factors into account. To illustrate: it is not reasonable to issue lead clothing to workers to protect themselves from penetrating radiation if this causes undue physical strain and/or discomfort.

3) **Principle of Limitation**

   "The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits specified by the Commission."

   This principle dictates that legal dose limits must always be complied with. Dose limits are specified by the International Atomic Energy Agency (IAEA), refer to [1], and have since also become part of the relevant legal and regulatory frameworks applicable in most countries, including in Namibia [2], [3].

7.2 International Radiation Protection

The risks associated with the exposure to ionising radiation were realised soon after X-rays were discovered by Roentgen in 1895. As early as 1896, X-rays were already used for diagnostic purposes under clinical conditions. Soon thereafter, it became evident that exposed persons were reporting skin burns, hair loss, and a variety of other ailments that are since known to be associated with an exposure to high doses of ionising radiation. In the very early days however, persons exposed to X-rays were unaware that large radiation doses could trigger considerable biological changes and cause serious health hazards. It must also be realised that there were no instruments available to quantify exposure doses or the strength of a radiation field. Instead, the calibration of X-ray tubes was based on how much skin reddening was produced when the operator placed a hand directly into the X-ray beam.

Once it became clear that the exposure to radiation as emitted by X-ray machines and adverse health effects were in fact linked, the first radiation protection limits were pronounced. These were based on preventing the onset of the more obvious effects of overexposure, such as skin ulcerations that appeared following the intense exposure to radiation fields. Such impacts were predictable, which means that the early dose limits were based on deterministic effects.

The first radiation protection dose limit was introduced in 1902, and was based on the harmful effects of X-rays as had been observed: at 10 rad/day, which is equivalent to 100 mSv/day, these dose limits are extremely high when compared to today's occupational exposure dose limit of 20 mSv/a.

In 1941, the first dose limits applying to internal radiation were developed, following the observation of harmful effects by the so-called *radium girls*, who were ingesting radium. This special group of exposed persons were female factory workers who used self-luminous paint to colour in the dials of watches, for example at the United States Radium factory in Orange, New Jersey, in the 1920's. At the time, the paint was considered harmless. However, when ingested, which happened frequently when improving the sharpness of the paintbrushes using the lips, or when beautifying one's fingernails, face or teeth with a substance that would make them glow in the dark, the adverse health impacts could not be overlooked. The ingestion limit suggested at the time was set at 0.1 µg of radium, which was to be understood as the cumulative total over the entire working life and amounts to 3 700 Bq. Interestingly, this limit has remained unchanged to the present day.

Later, exposure limits were based on the premise that delayed effects of exposure to radiation were best to be avoided too. These would include stochastic effects, such as cancer, that had been observed to occur in persons that had been exposed to ionising radiation, particularly from medical exposures to X-rays, as well as exposure to radiation in the atomic bomb blasts at Hiroshima and Nagasaki.

Figure 69: Colouring the dials of watches with radium paint in the 1920s [86]

In 1928, the *International Commission on Radiological Protection* (ICRP) was founded and has since published more than 100 reports on many aspects relating to radiological protection. These include the *international system of radiological protection* as elaborated in section 7.1, as well as recommendations on best practice, dose limits, and many other aspects.

In 1955, the General Assembly of the United Nations established the *United Nations Committee on the Effects of Atomic Radiation* (UNSCEAR). Its mandate, as part of the United Nations, is to assess and report levels and effects of exposure to ionising radiation. Since its inception, UNSCEAR has produced more than 25 major studies, which serve as information base and principal inputs for the work of the ICRP and many others.

In 1957, the *International Atomic Energy Agency* (IAEA) was created, mainly in response to the considerable expectations resulting from the discovery and rapid development in the field of nuclear energy, and to address the fears that arose because of the use of nuclear weapons in the last phases of the Second World War.

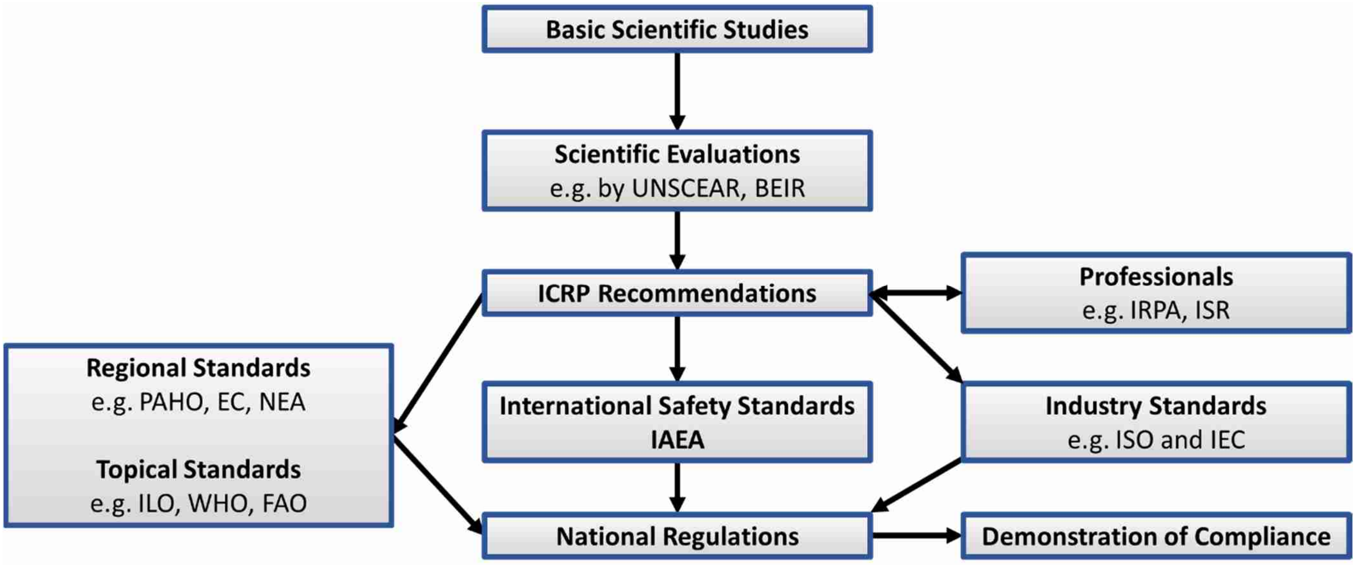
Today, the IAEA promotes the peaceful use of nuclear energy, and attempts to prevent the use of nuclear materials for military purposes, including the use of nuclear weapons.

The IAEA's programs are aimed to encourage the development of peaceful applications of nuclear technologies, providing international safeguards against the misuse of nuclear technologies and nuclear materials, promoting nuclear safety including the application of radiation protection, and advancing international nuclear security standards and their implementation.

Figure 70 illustrates the hierarchy of international organisations of relevance to radiation protection and shows the linkages between the radiation protection principles and the considerable body of regulations that have since been created.

In short, the key activities and responsibilities of the main actors in radiation protection can be summarised as follows: studies and scientific evaluations undertaken by UNSCEAR and others form the foundation on which recommendations are put forward by the ICRP. These in turn serve as input to the work done by the IAEA, who formulates – amongst others – international standards on radiation protection. These serve as guidelines for governments in the formulation of national legislation relating to radiation protection, radiation safety, nuclear safety, and associated topics.

Figure 70: Relationship between international entities and radiation protection [8] based on [87]



7.3 Hazards and Risks

A hazard is a specific cause or causative agent that may harm people. A risk is the chance of an exposure to a hazard leading to a negative outcome. A hazard poses no risk to persons if they are not exposed to such a risk.

An *occupational hazard* is a specific cause or agent that may harm people when at work. Occupational hazards are typically categorised as

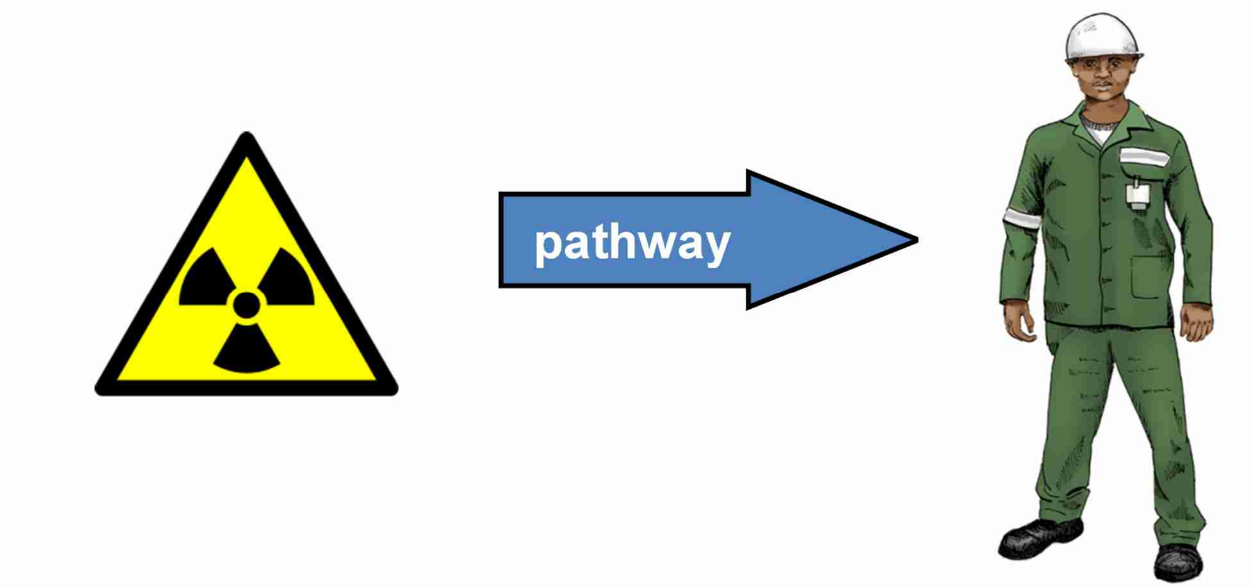
- **biological hazards**, such as infectious diseases and allergens;
- **chemical hazards**, such as excessive airborne concentrations of gases, vapours, or solids, leading to inhalation risks, skin irritation or absorption through the skin;
- **physical hazards**, such as the presence of ionising or non-ionising radiation, noise, vibration and extremes of temperature and pressure;
- **ergonomic hazards**, such as improperly designed tools, procedures or workplaces leading to injuries through repeated motions, or to incidents or accidents; and
- **psychosocial hazards**, including for example emotional stressors, prejudices relating to gender, race, religion, culture, or others.

For each occupational hazard, a suitable standard or occupational exposure limit is selected, and an assessment is undertaken to determine whether controls are needed to limit exposures.

Hazards are evaluated using quantitative measurements. Regarding radiation-related hazards, such measurements include the determination of exposure intensities, exposure frequency, and the duration of such exposure. Once such exposures are quantified, they need to be evaluated in terms of the potential harm they may cause. Often, this is done by comparison to relevant standards, for example those set by a regulating Authority, or international best practices, or internal company standards. Here, *occupational exposure levels* (OEL) may serve as useful standards for such comparisons.

A radiation-related risk is present if three factors come together: a source emitting ionising radiation, a receptor (person) that is potentially exposed to radiation, and an exposure pathway that offers a credible link between the source and the receptor.

Figure 71: Exposure to radiation necessitates a source, a pathway, and a receptor [8]



Once a radiation-related hazard is recognised, and an evaluation has demonstrated that it may result in excessive risk, controls are devised to eliminate or (at least) reduce the risk. Once such controls are established, they are assessed to ascertain whether they effectively mitigate the identified risk(s).

The anticipation, recognition, identification, evaluation, control, and prevention of hazards from work-related activities that may result in injury, illness, or negatively affect the well-being of workers is called *industrial hygiene*, or *occupational hygiene*.

Risk assessments are used to identify, recognise, and describe risks, and risk management practices are employed to control such risks, as illustrated in Figure 72.

Figure 72: Risk assessment and risk management process [8]

7.4 Exposure Controls

Hazards are addressed by way of three types of controls:

- **Engineering controls**, which aim to minimise or eliminate hazards through proper design, or by using engineering specifications regarding their isolation, substitution, and ventilation;

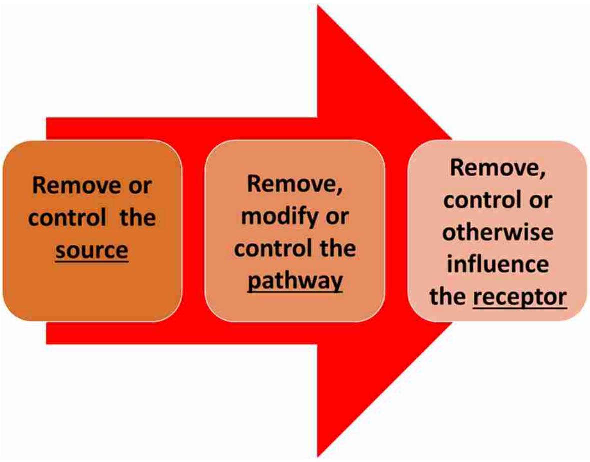
- **Administrative controls**, which include imposing rules on the performance of jobs, reducing the working time in affected areas, and providing training to recognise and prevent hazards; and

- **Personal protective equipment** (PPE), in the form of protective clothing and work gear worn by employees, to protect them from workplace hazards.

Regarding radiation-related risks, and framing the risk as a relationship between the source, pathway and receptor, controls are applied to any or all of the three ingredients, as illustrated in Figure 73.

It is noted that the most effective controls are applied at the source, while the least effective controls are those applied on the receptor side.

Figure 73: Prioritisation of controls, from the source, via the pathway to the receptor [8]



Controls are chosen to ensure their maximum effectiveness. It is better to use controls for the source(s) rather than using controls for the pathway, and the latter are preferred over the controls applied to receptors.

A variety of control measures exist. Their usefulness depends on how effective they are applied. The following examples illustrate the types of controls along the source-pathway-receptor chain:

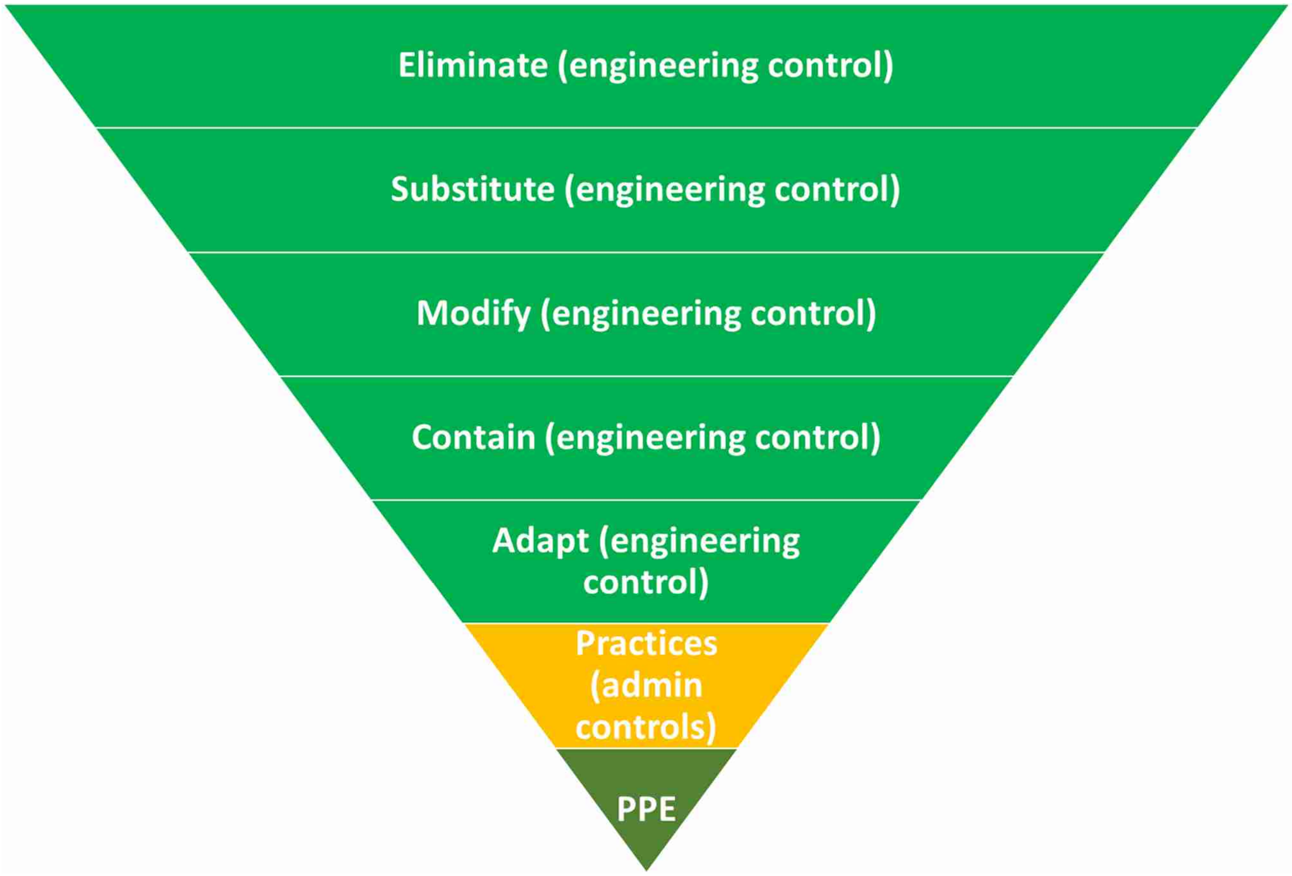
- **Source:**
  - Eliminate the source
  - Substitute the source with a less hazardous source
  - Change the process
  - Adapt the process, e.g. by enclosure, ventilation, or other means
  - Ensure that the source(s) is/are maintained

- **Pathway:**
  - Improve housekeeping, e.g. limit contamination
  - Apply ventilation, e.g. to dilute
  - Apply administrative controls, e.g. time, distance and shielding
  - Set area alarms
  - Apply an adequate area maintenance program

- **Receptor:**
  - Induct and train affected persons
  - Rotate shifts
  - Create area enclosures
  - Modify area conditions, e.g. by air conditioning
  - Issue personal monitoring devices, e.g. with pre-set alarms
  - Issue PPE, e.g. dust masks or positive pressure respiratory protection.

Controls are best designed around their effectiveness to accomplish a given task. This is expressed in the so-called *hierarchy of controls*, as depicted in Figure 74. It is noted that the effectiveness of controls decreases from the top to the bottom of the hierarchy of controls.

Figure 74: Hierarchy of controls [8]



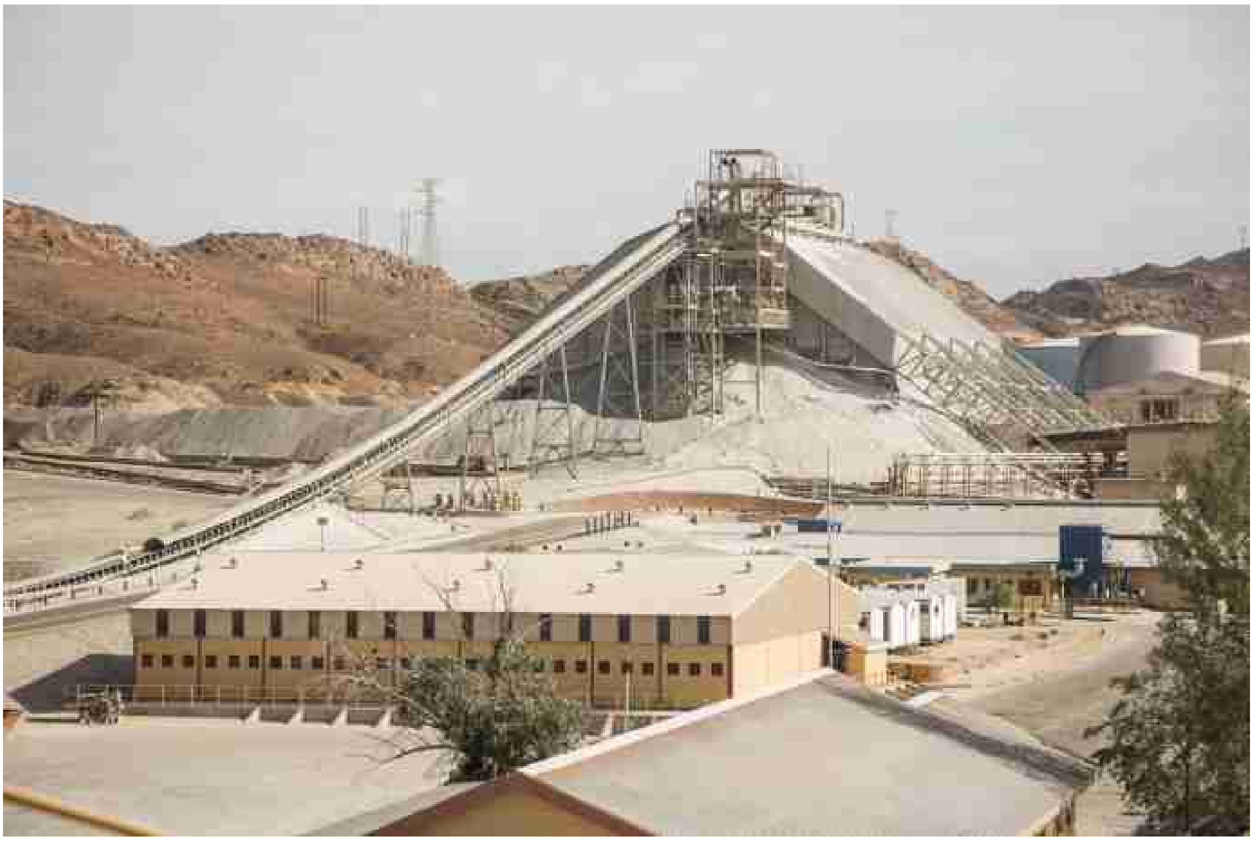
7.4.1 Engineering Controls

Engineering controls should always be at the top of to-be-applied controls. As such, they form the top layers of the hierarchy of controls, as shown in Figure 74.

This implies that, if possible, engineered solutions should be used to control and thereby limit exposures, such as for example an exposure to radiation. This is achieved, for example, by applying appropriate designs that take radiation-related requirements into account, and by ensuring that procedures are such that plant, equipment, and work processes can optimise the application of radiation protection.

To illustrate: dust emissions can be reduced by avoiding or minimising dusty processes, covering dusty areas, wetting dusty surfaces, and/or using dust extraction. Specifically, processes that create dust that contains radioisotopes, such as those arising as part of the mining, milling and concentration of uranium, and as part of the drying, roasting, and drumming of uranium concentrate, are best physically separated from other work areas, for example by using purpose-built enclosures. An example of this is a shed covering the fine ore stockpile at a uranium mine, as shown in Figure 75.

Figure 75: Covered fine ore stockpile at Rössing [34]



7.4.2 Area Access Controls

If an area requires radiation-related supervision and control, access controls are required, as shown in Figure 76. Zoning specific work areas as supervised or controlled areas allows for area-specific rules, including access controls, which are linked to area-specific induction, training, monitoring and control activities.

Figure 76: Radiation-related area zoning [34]

7.4.3 Worker Classification

Classifying workers into exposure groups allows the implementation of worker-specific controls, such as those pertaining to specific physical protection requirements, work- and/or area-specific induction and training, work- and/or area-specific monitoring, and others.

7.4.4 Ventilation

To control ambient concentrations of radon, ventilation is most effective. In offices and buildings, natural ventilation is readily achieved by opening doors and/or windows or using air conditioners. Forced ventilation may be needed in constrained spaces, such as poorly ventilated storage areas containing radon-exhaling materials, as well as in underground mines.

7.4.5 Hygiene

People working in areas which are radioactively contaminated must follow special hygiene measures, as contamination of people with radioactive materials is likely. In such cases it is essential that proper washing facilities are available, enabling contaminated staff to clean-off contaminants, as shown in Figure 77.

Work areas which are contaminated must be separated from clean areas in which people consume food, and smoke. In addition, suitable facilities to clean contaminated work gear, including clothes and shoes, must be provided on site, to limit the spread of contamination from dirty to clean work areas, as will occur if contaminated clothing can be removed from dirty work sections, or the work premises.

Figure 77: Washing facilities for employees to limit the spread of contamination [8]

7.4.6 Contamination Controls

Contamination with radioactive materials occurs when such materials settle on exposed surfaces. Surface-contaminated objects pose a radiation-related risk, as contaminants can become airborne, be inhaled, and/or ingested by people, or settle uncontrollably in the environment.

Local rules and supervision must include a systematic monitoring process which can detect the presence of surface contaminants, as well as the detention of radioactively contaminated objects in areas which are specially designated for use with radioactively contaminated objects.

Figure 78: Measuring surface contamination on uranium drums at Rössing [34]

7.4.7 Administrative Controls

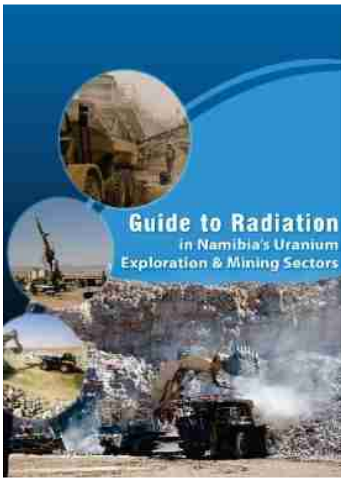
Administrative controls include safe work procedures that are implemented for keeping radiation doses ALARA. It is essential that such procedures are thoroughly communicated throughout the affected workforce, and form part of the induction and training curricula of all persons who will or may have to apply them.

Figure 79: Safe work signage at Rössing [34]

7.4.8 Radiation-related Induction

New employees must be made aware of the risks they face in a workplace and must understand the actions they need to take to ensure that they are and remain protected, in compliance with the ALARA principle. Workplace inductions must include an awareness session about radiation protection and applied radiation safety. Easy-to-read guidelines are an essential feature of awareness raising at the workplace (Figure 80).

Figure 80: Example of a guide to radiation [88]



7.4.9 Radiation-related Training

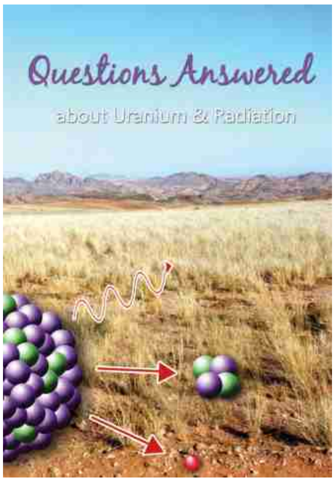
While exposure to ionising radiation in the workplace is a risk to the workforce, a larger risk is posed by a workforce that is unable or unwilling to put risks in general, and specifically radiation-related risks, into proper perspective, and is either dismissive of risks, or unnecessarily afraid of them. It is therefore essential that the workforce is adequately and professionally informed about radiation-related risks, about suitable controls, and how to implement these in the workplace.

The objective of radiation-related training must be to empower the workforce, and ensure that risks are neither trivialised, nor that staff is immobilised with fear. Effective and regular radiation-related training is best achieved in an environment where suitably qualified and experienced radiation safety professionals explain the do's and don'ts, focusing on facts.

Figure 81: Hands-on training of RSOs [8]

In this context, it is important that responsible managers are made aware of the risks in the work areas under their control and are empowered to make decisions promoting radiation safety. Suitable training and guidance material must be made available to them, as illustrated in Figure 80, Figure 81, Figure 82 and Figure 84.

Figure 82: Radiation information for managers [89]



7.4.10 Emergency Drills

In a work environment in which radiation-related risks exist, the preparation for emergencies relating to radiation safety is essential, refer to Figure 83.

Figure 83: Emergency spill drill [34]

Such preparation must include the compilation of suitable and adequate emergency response plans, and their regular testing by way of emergency drills. To this end, site-wide risk assessments that identify the scenarios in which radiation sources can be involved in an incident or accident are essential.

To illustrate: at a uranium mine, the spill of uranium concentrate, breakage of tanks containing uranium-bearing liquids, fires in areas with contaminated plant and equipment, and accidents involving sealed radioactive sources are all possible, and therefore necessitate the development and adequate practice of response measures.

Figure 84: Participants of a radiation-related course at the Namibian Uranium Institute [90]

7.4.11 Personal Protective Equipment

As shown in the hierarchy of controls as are depicted in Figure 74, personal protective equipment (PPE) is the measure of control of last resort and should only be used when all other control options have been investigated and found to be insufficient to ensure the adequate protection of workers.

To illustrate: the atmospheric concentrations of radionuclides in some work areas may be such that respiratory protection is needed, despite all other control measures, including engineering and administrative controls, having been applied.

Respiratory protection, such as the use of dust masks or respirators, must be underpinned by a clean-shaven policy, and include fit-testing, to ensure that such measures can be effective in their use.

Figure 85: Respirators must be used correctly and serviced regularly [34]

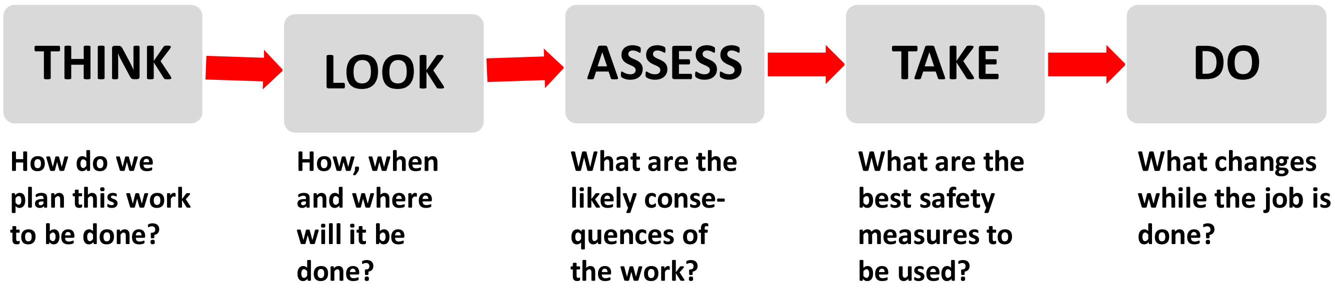
In addition, while procedures and checks are needed to ensure that respirators are properly worn, it is also important that such PPE is regularly serviced and cleaned and remains free of contaminants (Figure 85).

7.5 Risk Assessment

A risk assessment is used to identify and recognise hazards, and to formulate relevant controls to address them. Depending on the work environment, the level and depth of a risk assessment can take various forms. The following risk assessments are frequently used:

- **Pre-task work assessment**, which usually includes an assessment of the work environment and the potential hazards that may be present in the work environment. A pre-task risk assessment, referred to as a *take 5 assessment*, is shown in Figure 86.

Figure 86: Example of a pre-task risk assessment [8]



How do we plan this work to be done?

How, when and where will it be done?

What are the likely consequences of the work?

What are the best safety measures to be used?

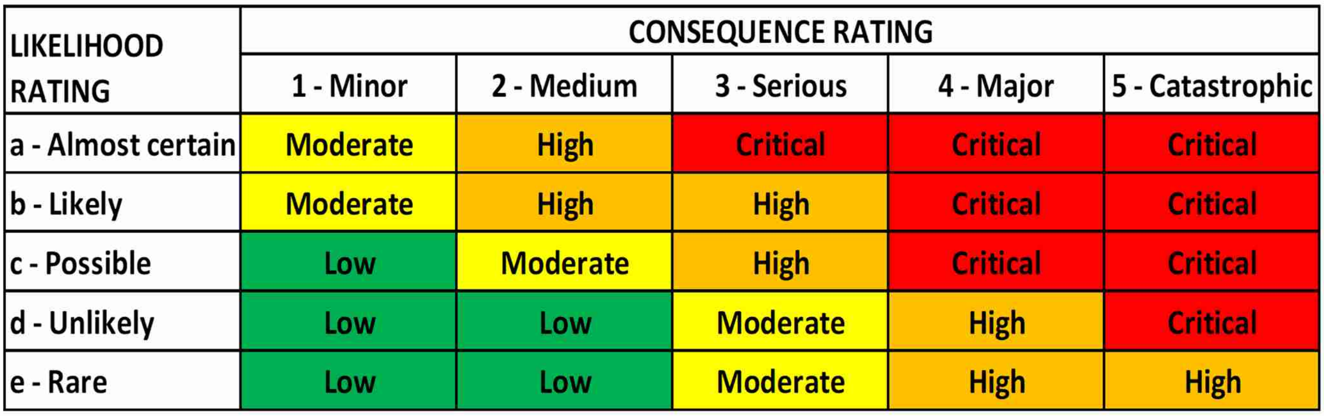
What changes while the job is done?

- **Qualitative risk assessment**, which rates the risks according to the severity and the likelihood of the outcome, which is then used to decide whether the risk is a priority risk, and how it is best managed.

  Qualitative risk assessments are often undertaken using risk assessment tables, which list the severity and probability, and a colour coding indicating which combination of severity and probability constitutes a critical risk, as shown in Table 7.

  Alternatively, qualitative risk assessment tables describe the consequences, which in turn enable the risk assessor to classify the risks which are considered, as shown in Table 8.

Table 7: Qualitative risk matrix in which the criticality of a risk is indicated in colour [8]



LIKELIHOOD RATING	CONSEQUENCE RATING				
	1 - Minor	2 - Medium	3 - Serious	4 - Major	5 - Catastrophic
a - Almost certain	Moderate	High	Critical	Critical	Critical
b - Likely	Moderate	High	High	Critical	Critical
c - Possible	Low	Moderate	High	Critical	Critical
d - Unlikely	Low	Low	Moderate	High	Critical
e - Rare	Low	Low	Moderate	High	High

Table 8: Example of consequence descriptors for risks relating to health and safety

Minor	Medium	Serious	Major	Catastrophic
Reversible health effects of little concern. May require first aid treatment, at most. Includes minor irritations of the eyes, throat, nose and/or skin, or minor unaccustomed muscular discomfort.	Reversible health effects, which typically result in medical treatment. Includes temperature effects, travel effects, stress as well as sunburn.	Severe but reversible health effects, which typically result in lost time illness. Includes acute/short-term effects associated with exposure to extreme temperatures, or musculoskeletal effects, vibration effects, nervous system effects, as well as some infectious diseases.	Single fatality or irreversible health effects or disabling illness. Includes effects of suspected carcinogens, mutagens, teratogens and reproductive toxicants, as well as progressive chronic conditions and/or acute/short-term high-risk effects.	Multiple fatalities or serious disabling illness to multiple people. Includes effects of known human carcinogens, mutagens, teratogens and reproductive toxicants, as well as life-threatening respiratory sensitisation and falciparum malaria.

Box 17: Example of a qualitative risk assessment

Use the 5x5 risk matrix and consequence descriptors in Table 7 and Table 8 respectively to assess the risk associated with radon concentrations in an office exceeding 600 Bq/m^3. It is noted that the given radon concentrations exceed the action levels recommended for such work places.

The consequence of an elevated radon concentration is lung cancer. Even in a large open plan office, one would not expect more than a single irreversible health case or fatality, hence the consequence is **major** (not catastrophic). The likelihood for this to happen is **rare**, but that still implies a **high risk**, which implies that controls are definitely needed.

- **Semi-quantitative and quantitative risk assessments** quantify the exposure response to a risk and predict specific outcomes as result of such an exposure. Using a (semi-) quantitative risk assessment, the risk assessor can take or recommend decisions, for example whether and how much to spend on mitigation or controls to manage a given risk. A simple quantitative risk assessment is illustrated in Box 18.

Box 18: Example of a quantitative risk assessment

Quantify the risk of exposure to the Namibian population because of the natural background radiation, assuming that – on average – the exposure from natural radiation sources result in an exposure dose of 2 mSv per year, noting that 2 mSv/a = 2 / 1 000 Sv/a.

The ICRP estimates that the risk of stochastic effects from ionising radiation amounts to 5%/Sv (i.e. 5 / 100 per Sv), when averaged over large populations [45]. Using this risk estimate, one determines the number of people who will be affected by exposure to natural background radiation. Noting that Namibia has a population of approx. 2.3 million persons, the number of affected persons is computed as follows:

$$\text{Number of persons affected per year } = (5/100) \cdot 2\,300\,000 \cdot (2/1\,000) = 230 \text{ persons per year.}$$

Note that the above risk estimate is for comparative purposes only, as the ICRP explicitly cautions against the use of the collective dose for epidemiological risk assessments.

7.6 Risk Perception and the Communication of Risk

Although the risk of exposure to ionising radiation has been quantified long ago, the relationship between any actual risk of exposure and its impacts on health, and the perceived risks of exposures are often challenging to explain to people. This is speculated to have several reasons: some persons may not have a well-developed understanding of what numbers mean, or how one applies probabilities in practice.

The concept of exposure to radiation is often viewed with suspicion, and possibly even fear, as has been expressed before: "Nuclear energy was conceived in secrecy, born in war, and first revealed to the world in horror. No matter how much proponents try to separate the peaceful from the weapons atom, the connection is firmly embedded in the public" [92].

In some ways, the intrinsic connection between the use of nuclear weapons and the risk of exposure to nuclear or radioactive materials has contributed to skewing the perception that people have when thinking about the risks posed by radiation.

While the exposure to radiation from uranium exploration and mining activities are often low, some people remain fearful of them, even when actual exposure doses are low or very low. In contrast, exposure doses resulting from natural background sources, frequent flying, smoking or medical procedures involving an exposure to X-rays are often seen as benign, or not worth worrying about, even if they are higher than incurred in uranium mining.

Because of potential anxieties, fear, prejudice and/or pre-conceptions, communication about radiation must be cognisant of the fact that the public perception and acceptance of exposure to radiation is frequently determined by the context in which such exposure doses are incurred.

Figure 87: Engaging with key stakeholders at a display of the Namibian Uranium Association [34]

Past approaches to address the fear of radiation by ridicule, or using comparisons which linked unrelated probabilities to one another, are ill advised, and counterproductive. In the same vein, using numbers but omitting their units, or using units that lead to very large numerical values, is regarded as a tell-tale sign of poor communication.

In contrast, empowering people to be able to apply their own cognitive functions to arrive at their own opinion on a matter is always preferred. In this context, it is important to realise that in many cases, limited knowledge about radiation will lead to greater fear in people than no knowledge at all. This is expressed by Alexander Pope, who famously stated that "a little learning is a dangerous thing" – although it must be emphasised that this was not said in the context of radiation protection or industrial hygiene [93].

The ICRP has put forward the following cautionary statement, expressing the linkage between risk and exposure doses: "Collective effective dose is not intended as a tool for epidemiological risk assessment, and it is inappropriate to use it in risk projections. The aggregation of very low individual doses over extended time periods is inappropriate, and in particular, the calculation of the number of cancer deaths based on collective effective doses from trivial individual doses should be avoided" [45].

It is therefore most helpful to put exposure doses from ionising radiation and their estimated risks into perspective. For example, comparing medical and occupational exposures to each other may result in a meaningful comparison, as all such exposures are quantified in the same way and expressed by the same unit, i.e. in Sievert or milli-Sievert, hence expressing equal biological risk in terms of the same numerical value.

It is also important to describe specific contextual elements related to exposure situations, including the contributing factors such as the source(s), the exposure pathway(s), and the magnitude of the exposure dose, and expressing these using sensible units.

7.7 Exercises

7.7.1 The ICRP Principles

1. Identify the statement(s) which correctly summarise(s) the main intentions of the international system of radiological protection:
    a) no practice involving exposure to radiation should be adopted unless its benefits to the government of a country outweigh the risks;
    b) the limitation of exposure doses applies solely to persons active in the nuclear and other industries;
    c) radiation doses and risks should be kept as low as reasonably achievable, and take economic and social factors into account;
    d) the exposure of individuals should result in appreciable exposure doses to be meaningful;
    e) the justification of practices using radiation sources is the sole domain of a government of a sovereign nation;
    f) the principle of optimisation, when applied to the administration of medical exposure doses, is to ensure the effective treatment of tumours;
    g) the exposure of individuals should be subject to dose or risk limits below which the radiation risk is deemed unacceptable.

7.7.2 Application of the Risk Matrix

Using the 5x5 risk matrix and consequence description elaborated in this chapter, estimate the likelihood, and use the consequence table to assess the following risks for a radiation worker who has an exposure dose of 5 mSv per year due to the inhalation of radon, inhalation of radioactive dust, and exposure to gamma radiation.

8 Radiation-Related Legal and Regulatory Requirements

This Chapter introduces the radiation-related legal and regulatory requirements as are applicable in Namibia.

In Namibia, the legal, statutory, and regulatory requirements relating to radiation protection and radiation safety are governed by the Atomic Energy and Radiation Protection Act, Act 5 of 2005 [2], and the Radiation Protection and Waste Disposal Regulations, No. 221 of 2011, which are the Regulations under the Act [3].

All entities that handle, own, transport, dispose, import, and export sources of ionising radiation, including naturally occurring radioactive minerals such as uranium, thorium, or potassium, as well as instruments and equipment emitting ionising radiation, are subject to the stipulations of the Act, and the Regulations under the Act.

8.1 Atomic Energy and Radiation Protection Act [2]

The Act came in operation on 16 January 2012, and comprises of six chapters, which lay down the framework that underpins how radiation-related activities are governed and regulated [2].

The object of the Act, amongst others, is to ensure that people and the environment are protected against the harmful effects of radiation and provide for the establishment of an *Atomic Energy Board* (AEB), and a *National Radiation Protection Authority* (NRPA).

The AEB is the national advisory body on all matters relating to radiation sources. The NRPA is the country's radiation-related regulatory Authority, i.e. the Regulator, and must ensure that all role-players are (and remain) compliant with the provisions of the Act and the Regulations under the Act. The NRPA – as a body established under the Act – is charged with its administration. It is headed by the Director-General, who is supported by Radiation Protection Officers (RPOs). The RPOs may take samples of materials, undertake inspections and audits, and interview people, if these activities are deemed necessary to carry out the provisions of the Act.

The NRPA's duties include, amongst others, the regulation and control of the production, processing, handling, use, holding, storage, transport, and disposal of radioactive materials as well as of ionising and select non-ionising radiation sources.

8.2 Radiation Protection and Waste Disposal Regulations [3]

The Namibian Regulations comprise of twelve chapters, which are organised into 78 regulations [3]. The following are key elements of relevance for RSOs:

A. **Exemption Levels for Radioactive Materials**
   Amongst others, the Regulations provide exemption levels for radioactive materials. These are expressed as a combination of a threshold or maximum activity (expressed in Bq), and a threshold specific activity or activity concentration (in Bq/g).

   Provided that the properties of a given radioactive material are such that both its activity and its activity concentration do not exceed the exemption levels provided in the Regulations, such material is not subject to the provisions of the Regulations. This implies that a radioactive substance with either an activity or activity concentration (or both) below the specified exemption levels is exempted from the requirements of the Regulations.

It is important to note that most sealed radioactive sources, as are frequently used in mineral exploration, mining, and milling operations, are characterised by activities and activity concentrations which exceed the exemption level(s) of their constituent radionuclide(s) and are therefore subject to regulatory oversight. In other words, most sealed radioactive sources are above the exemption thresholds, which implies that they are subject to the provisions of the Regulations.

Table 9 provides a summary of exemption levels in the form of their activities and activity concentrations of radioactive materials that are typically dealt with in the exploration and mining sector in Namibia. It is noted that the exemption levels do not apply to waste material, and that separate waste-specific clearance levels apply.

It is noted that the exemption levels as are provided in Table 8 for natural uranium and natural thorium apply to the leading element of the relevant decays chain only, i.e. to U-238 and Th-232 respectively. The radioactivity of the remaining decay chain members is implicitly accounted for in these levels and is therefore not considered separately.

Table 9: Activity and activity concentration exemption levels for select radioactive materials [3]

Radionuclide	**Activity** [Bq]	**Activity concentration** [Bq/g]
Potassium K-40	10^6	10^2
Uranium – natural *	10^3	1
Thorium – natural †	10^3	1

* Uranium U-238 in secular equilibrium with its progeny Th-234, Pa-234m, U-234, Th-230, Ra-226, Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, and Po-210.

† Thorium Th-232 in secular equilibrium with its progeny Ra-228, Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Tl-208 (0.36), and Po-212 (0.64).

B. Exemption Levels Electrical Instruments Emitting Ionising Radiation

Instruments that emit ionizing radiation, including for example cathode ray tubes, and X-ray and X-ray fluorescence (XRF) analysers, are exempted from the provisions contained in the Regulations if they operate at a potential difference below 30 kV, if they do not cause a radiation dose rate exceeding 1 µSv/h at a distance of 0.1 m from any accessible surface of the apparatus under normal operating conditions [3].

C. Dose Limits

The annual effective exposure dose limit for members of the public is 1 mSv/a above the exposure dose due to natural background radiation.

For persons who are occupationally exposed to ionising radiation, an average effective dose of 20 mSv/a (when averaged over a 5-year period) is the annual effective exposure dose limit. The maximum effective dose in any single year is 50 mSv/a [2].

D. Notification

The Act specifies that any person who intends to possess, import, export, transport, or dispose of any radiation source or nuclear material must notify the NRPA of this intention, and provide the following details [2]:

1. Name and address of the person making the notification;
2. Name and address of the person or entity that the person making the notification represents;
3. Name and address of the manufacturer or producer of the radiation source or the nuclear material concerned;
4. Nature of the intended practice; and
5. All relevant details of the intended practice and identification of each radiation source or nuclear material.

E. Authorisation

Conveyors, importers, and exporters of radioactive or nuclear material must submit a written notification to the NRPA, and submit the required details in the prescribed application form together with a Transport Plan prior to the Regulator considering an authorisation [2].

F. Registration of Sources and Facilities

The Act stipulates that any person who intends to possess, use, operate, or in any manner engage in an activity involving a non-exempt radiation source must ensure that the radiation source(s) or facility where such source(s) is/are to be used is registered. An application for the registration is made in writing, and must contain the following information [2]:

1. Particulars of all relevant licences as well as licences, permits, registrations, or similar permissions under any other law that have previously been issued to the applicant;
2. Particulars of the source and the facilities where the source will be installed;
3. Purpose for which the source will be used;
4. Description and classification of the potential receptors, including members of the public, workers, patients, or other persons who may be exposed to radiation emitted by the source;
5. All relevant information required to assess the doses of radiation to which each receptor class identified in (d) will be exposed; and
6. Risk identification to enable the regulator to assess the risks relating to the disposal of the source.

G. Licenses and Licensing

The Regulations identify several specific classes for which the NRPA may grant licenses, including [2]:

1. Instruments to search persons or detect the presence of objects/substances;
2. Gamma-ray equipment to produce images for diagnostic purposes;
3. Gamma rays or radionuclides to produce images for diagnostic purposes;
4. Equipment using radionuclides, X-rays, or gamma rays for therapeutic purposes;
5. Sealed sources for density measurements, level detection, thickness control, moisture measurements and control, examination of components/products, and similar industrial uses;
6. Radioactive or nuclear material produced in form of minerals in exploration, mining, or milling;
7. Import and export of nuclear material and radiation sources; and
8. Transport and waste disposal of radioactive material.

Applications for licenses are submitted to the NRPA using a completed license application form, which is available from the website of the AEB (http://aebofnamibia.org/) and specify the class of licence applied for, and particulars of all other licences/registrations granted by other public bodies in relation to the activities relating to the practices and use of sources.

In most cases, the NRPA requires an applicant to submit a Radiation Management Plan (RMP) together with the license application. For conveyors of radioactive materials, a *Transport Plan* is required.

The RMP forms part of the toolkit at the disposal of the Authority for monitoring the applicant's ability and capability to fulfil the various requirements under the Act and Regulations. As such, the RMP is a prerequisite for most registrations and licenses issued under the Act. Because of its importance, the next section provides a high-level description of the generic content of an RMP.

8.3 Radiation Management Plan

The Radiation Management Plan (RMP) is an applicant's statement of intent regarding all matters relating to radiation protection and applied radiation safety and must provide a comprehensive description of how radiation-relevant activities and processes are to be undertaken. As such, the RMP is how the Regulator is informed about an applicant's intended radiation-related activities, and in this way, forms the basis from which the risks associated with such activities are assessed. In addition, the RMP is one of the Regulator's instruments for monitoring the applicant's compliance with the stipulations and provisions of the Act and the Regulations and is an integral part of all future assessments of the applicant's operations.

An RMP should be a document with clear, concise, and action-oriented messages. It must provide all necessary information relating to the radiation sources that will be handled, transported, disposed of, imported, and exported as part of the operations of the applicant. In addition, it must provide sufficient detail to allow the NRPA to form an opinion of all relevant radiation hazards and associated risks.

As per the NRPA's guidance document for RMPs [95], these must comprise of the following sections:

a. **Introduction and Business Profile:** as the introduction to the RMP, this section should provide detailed background information which describes the technical nature of the intended business or operation. It must include a description of the physical plan of the business site or premises, the sources of radiation, type(s) of radioactive or nuclear material(s) to be used, overview and assessment of the key radiation hazards, and a description of the principal exposure pathways arising from the activities of the intended operation.

b. **Pre-Operational Safety Assessment:** this section must summarise the main results and outcomes of all assessments carried out prior to the intended operations, including those of radiation impact assessments, risk assessments, environmental impact assessments, remediation/rehabilitation assessments, risk management plans, and Environmental Management Plans, if available. It is of importance that the results of the pre-operational assessment are consistent with the exposure pathways identified in the RMP's first section, i.e. the Business Profile, and provide realistic potential dose estimates to the critical group identified along each exposure pathway, if these have been quantified in any of the pre-operational assessments that were undertaken.

c. **Organisational Arrangements:** this section describes the main responsibilities within the organisation, and the assignment of responsibilities to different management levels throughout the organisation, including the organisational processes which enable the efficient and effective functioning of organisational arrangements.

The section is to include relevant organisational charts, and must identify the organisation's legal person, and the designated Radiation Safety Officer (RSO), and other RSOs, if relevant. The section must identify and specify the functions and responsibilities of the RSOs, and describe the role and profile of the RSOs, consistent with the requirements of the Act, and the latest stipulations by the AEB and the Regulator.

d. **Occupational Radiation Protection Programme:** specifies programmes and actions to be taken to monitor and protect workers in the occupational setting. It is to describe the approaches and methods that are to be adopted for optimising the protection of workers.

   An occupational radiation protection programme must be aligned to the exposure-related risks arising from the activities of the organisation, and should address the following:
   1. types of radiation hazards;
   2. work areas that are to be delineated as controlled and supervised areas;
   3. methods of dose assessment (external dose, radon, and radon progeny concentrations, radioactive dust concentration, and others, as relevant);
   4. local rules and supervision;
   5. dosimetry service provider (if applicable);
   6. equipment to be used for routine monitoring;
   7. protective equipment to be issued;
   8. group of workers to be monitored on an individual basis, including frequency of monitoring;
   9. work areas to be monitored, including frequency of monitoring programme;
   10. radiation-related induction programme, differentiated to address work area-specific radiation risks;
   11. education and training programme;
   12. engineered and administrative controls;
   13. health surveillance programme; and
   14. management of exposure dose records.

e. **Medical Exposure Control:** such a section is only required if occupational exposure doses result from medical practices taking place at the to-be-licensed entity. Its aim is to identify and describe how the operator intends to optimise any patient exposure doses, by for example administering such minimum exposures as are required to reach the desired image quality or targeted therapeutic dose. The section must also describe the engineering, administrative and other measures to minimise exposures of individuals who are not medical personnel or patients.

f. **Public Exposure Monitoring Programme:** this section identifies the programmes and methods to identify all relevant public exposure pathways and minimise any public exposures due to normal releases caused by operations, as well as those resulting from incidents or accidents. It must describe the programme for monitoring radiation exposure along each pathway that affects relevant members of the public, as well as potential exposures of the environment. Such a monitoring programme must include descriptions of the following topics:
   1. description of exposure pathways;
   2. identification and description of the critical group(s);
   3. types of radiation of relevance to the identified exposure pathways;

4. control of visitors;
5. identification and description of the external sites that are to be monitored;
6. monitoring techniques to be applied, including for example area monitoring, selective grab sampling, approach to radiation measurements, monitoring frequency, and related topics; and
7. management of records from the public exposure program.

g. **Safety and Security of Radiation Sources:** this section describes the controls and measures to ensure the safety of radiation sources. It must include a description of the procedures to prepare and undertake source inventories. The section must also describe how the licensee intends to prevent and detect any potential leakage from sources of radiation. It must also provide a high-level description of the controls to be used to prevent and detect any unauthorised access to the operational site, as well as any attempt to remove or divert radioactive material and/or radiation sources.

h. **Transport Plan:** this section specifies protection and shielding of radioactive materials during transport. As the transport of radioactive materials to and from a site is governed by the latest version of the IAEA Regulations for the Safe Transport of Radioactive Material, this section must describe how the licensee intends to package, shield, mark, placard and label any consignment of radioactive materials which are to be conveyed to or from the organisation's operational site. The section must identify and describe the main characteristics of the materials to be transported and provide a summary of the emergency procedures to be applied during transport, if these are different to those emergency preparedness and response activities described in the next section. In describing to-be-applied emergency measures, it is useful to provide descriptions of those emergency situations that are considered likely to arise during the conveyance of radioactive materials.

i. **Emergency Preparedness and Response:** this section describes the emergency management plan enacted after an incidental or accidental exposure situation, which caused the unplanned exposure of one or several persons. To this end, an emergency plan that is appropriate for the source(s) and associated risk of exposure must be prepared. It must identify, characterise, and describe the content, features, and extent of potential emergency situations. This section must also describe the methods, procedures, and instruments to be used to assess and mitigate incidents and/or accidents involving sources of ionising radiation and provide a description of the main consequences and repercussions of such potential emergency scenarios.

j. **Waste Management Programme:** this section describes the management of radioactive waste (both in form of sealed or unsealed radioactive sources), contaminated material(s), and effluent(s) arising from operations, including the management of tailings.
The waste management programme must include a description how sealed radioactive sources used by the licensee are to be managed and monitored.
A description of the potential exposure pathways along which effluents are intended to be discharged is to be provided. If operations result in radioactive tailings, the characteristics of such tailings must be specified. A detailed description on how such tailings are to be managed – from the date where any waste generation commences to the decommissioning of the facility – must be provided.

The waste management section must include a description of how waste rock dumps are to be managed, provided that their activity concentration exceeds 1 Bq/g (for uranium-bearing tailings and those resulting while producing concentrated uranium).
The radioactive contamination of tools, equipment and persons which may arise from the routine or accidental activities undertaken by the licensee must be identified and described. This is to include a description of the activities and procedures to be used to manage contaminants, and waste material that is radioactively contaminated, arising from the treatment and de-contamination of tools, equipment and effluent that the licensee intends to produce as part of the intended operations.

If the NRPA does not approve the RMP, or if a licensee's annual reporting requirements are not met, new licenses or permits, or extensions of existing licenses will not be issued by the NRPA. As for any updates of the RMP, these must be approved the Regulator.

8.4 Transport Plan

No radioactive or nuclear material may be offered for conveyance by rail, ship, aircraft, or road vehicle unless it is packed, shielded, marked, and labelled in accordance with the latest version of the IAEA Regulations for the Safe Transport of Radioactive Material [96], [97]. This implies that all conveyors, importers, and exporters of radioactive or nuclear material must submit a Transport Plan, as well as a relevant license application forms, to the NRPA prior to being considered for an authorisation. In this context, the authorisation is a pre-requisite and critical requirement before an operator commences with the conveyance of radioactive or nuclear material into or out of Namibia.

A Transport Plan must take cognisance of and address specific local requirements and circumstances. As the contextual setting changes in time, a Transport Plan is best to be regularly updated, to take the changing operational realities into account.

A Transport Plan usually comprises of the following [94]:

a. **Background:** this section describes the technical nature of the operation(s), sources of radiation, type(s) of radioactive material(s) used, overview and assessment of radiation hazards, and description of the principal exposure pathways during transport.

b. **Responsible Parties:** this section describes the main responsibilities within the conveyor's organisation, as well as other entities participating in the transport undertaking. It also identifies and describes the functions and responsibilities of the designated Radiation Safety Officer(s).

c. **Occupational Radiation Protection:** this section specifies the programmes and activities to be taken to protect workers in the occupational setting. It is to identify the workers who will be involved with the handling, storage, and transportation of the material, supported with an assessment of the potential magnitude of their exposure due to handling, storage, or transportation.
This section also details the appropriate induction and training relating to radiation protection, including the precautions to be observed to restrict the occupational exposure and the exposure of other persons who might be affected by their actions.

d. **Public Radiation Exposure:** this section identifies the storage site(s) along the transport route that might be occupied by members of the public and provides an estimate of their potential radiation exposure.

e. **Security:** this section describes the measures to secure the product during storage and transportation to prevent or minimize any unauthorized removal or other malicious acts.

f. **Emergency Preparedness and Response:** this section describes the emergency provisions to allow the conveyor to respond to accidents or unexpected incidents during storage and transport of radioactive material, including a description of the scale and scope of any potential emergency, and a description of the response plan.

g. **Packaging:** this section provides a detailed description, supported with illustrations where applicable, of the transport vehicle(s), type of packaging used, labelling, marking, placarding, and documentation required, as per the latest version of the IAEA Regulations for the Safe Transport of Radioactive Material [96].

8.5 Radiation Safety Officer and Radiation Safety Assistant

The Regulations stipulate that every licensee must appoint a Radiation Safety Officer (RSO), who is technically competent in all matters relating to radiation protection (also refer to [95]). A licensee may decide to subdivide operations into several separate sections, in which case each section could be placed under the responsibility of a separate RSO, if this is desirable.

The RSO is not the legal person for the site. This implies that the legal responsibility for any omissions, errors or legal transgressions relating to radiation protection lie with the legal person who is responsible for the licensee. However, the RSO may be held responsible for wilful acts of wrongdoing.

The RSO is the person who is responsible for

- advising management on all matters pertaining to radiation protection;
- maintaining, updating, and implementing the RMP;
- communicating radiation- and RMP-related matters with the Regulator;
- developing, assessing, and ensuring the implementation of all relevant radiation safety rules applied by the licensee;
- devising, implementing, and managing the occupational and public exposure doses arising from the lice see's operations;
- providing reports on all radiation-related matters to the Regulator; and
- applying for all necessary licenses, permits and authorisations, as required under the Regulations.

The Authority has grouped the requirements of RSOs into separate categories, namely those for

- X-ray facilities used for medical purposes;
- radiotherapy facilities;
- industrial radiography;
- analysis laboratories;
- uranium exploration; and
- uranium mining.

For medical facilities, including those using dental X-ray machines, for analysis laboratories, for operations using X-ray scanners for persons, portal, and baggage scanners, XRF units and veterinary X-rays, for uranium storage facilities, and for transport and storage agents, the RSO must be designated, but does not need to be employed by the licensee, or to be working permanently at the site.

For radiotherapy facilities, the designated RSO must be a full-time employee of the licensee.

For businesses providing industrial radiography services, as well as those using density, moisture, level or flow gauges, and in diagnostic radiology, nuclear medicine and the field of uranium exploration, the designated RSO must be a full-time employee, and must be on site whenever the source(s) is/are used, and is to be the person who is responsible for the routine use of the source(s).

For uranium mines, a full-time designated RSO is required. The RSO must hold a position of sufficient seniority to take decisions, and be able to intervene immediately, if unsafe acts relating to radiation protection arise. The designated RSO is the main contact person who liaises between the licensee and the Regulator and must be supported by a well-resourced and trained team of other RSOs.

The AEB specifies that the minimum qualification of an RSO should be a tertiary-level education, which is relevant to the practice for which the person is to be certified as RSO. The designated RSO must have a good understanding of the practice for which he/she is responsible, must possess a good knowledge of the principles of radiation safety, as well as radiation sources, the interactions between radiation and matter, as well as some radiation biology. The AEB considers a BSc degree in physics, engineering, chemistry, geophysics, geology or equivalent as the minimum tertiary qualification for an RSO who wishes to work in the uranium production sector.

Licensees often have more than one RSO. This is the case as one person is in many instances not able to single-handedly undertake the multitude of activities that must be accomplished. In such cases, persons who have some minimum technical expertise, for example to perform routine radiation-related tasks (including but not limited to monitoring, contamination control, issuing of clearances, and others), support the designated RSO and other RSOs as Radiation Safety Assistants (RSAs).

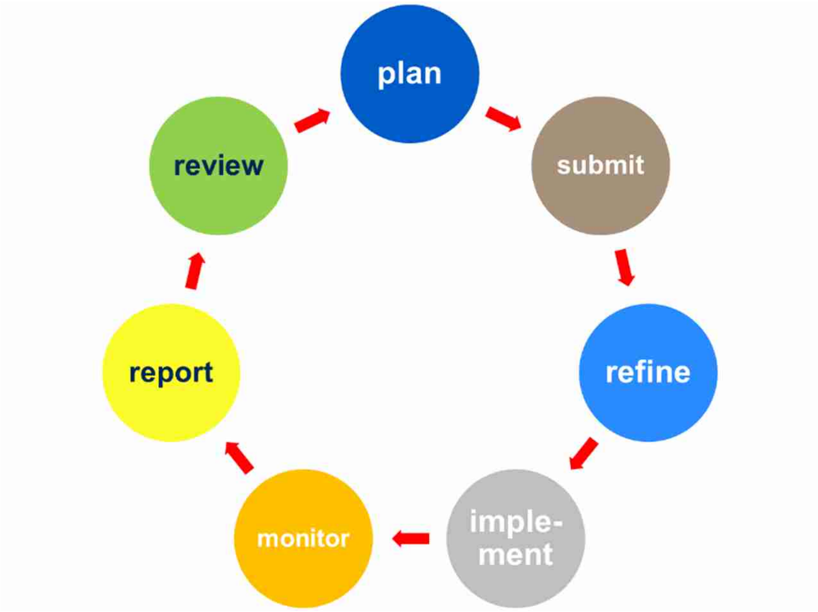
8.6 Implementing the RMP

In Namibia, every entity that wishes to handle, own, transport, import, or export sources of ionising radiation must have an RMP, or Transport Plan. However, the mere existence of such a plan is no guarantee that such a n entity employs all the necessary radiation-safe practices. One way to assess whether radiation safety provisions are consistently, effectively, and timely implemented is to use the RMP / Transport Plan as the basis for an audit.

It is useful to depict the process underpinning the implementation of the RMP/Transport Plan as a continuous interactive process, as shown in Figure 88, which shows a schematic implementation process map. The process commences at the planning stage, which sees its finalisation when the RMP or Transport Plan has been drafted. Once complete, the document and associated license application forms are submitted to the Regulator, who will scrutinise them, and provide feedback to the applicant. This also enables the licensee to further refine the RMP/Transport Plan, as may be required by the Regulator.

Once the Plan is accepted, implementation commences. As part of the implementation process, various key indicators are monitored, which form the basis of the annual or semi-annual report to the Regulator, as well as other reports that are generated for management.

Figure 88: Implementation process of an RMP/Transport Plan [8]



Reporting to the Authority is by way of a narrative report, detailing how the RMP/Transport Plan was implemented. This must be accompanied by a populated spreadsheet containing dose records of all employees, as well as providing details about the radiation sources which were used, imported, and exported by the licensee. Specifically, the spreadsheet database submitted with the report includes

- monthly and total staff exposure doses from penetrating radiation, the inhalation of ore dust, the inhalation of uranium concentrate dust, as well as the inhalation of radon and its decay products;
- a summary of exports and imports of radioactive materials;
- an inventory of sealed radioactive sources (with serial numbers, source type, and their radionuclide activities), and summary of safety tests, integrity tests and/or leak tests undertaken; and
- an inventory of hazardous waste.

Reports to the NRPA form the basis of regular review activities of the RMP/Transport Plan and may lead to further planning or re-planning.

As required, the RMP/Transport Plan is updated as and when necessitated by changes to the operational realities and/or as radiation-specific requirements change and must be approved by the Regulator. Updates must also be reported and approved. At the same time, the licensee (if not done before) applies for all relevant permits and licenses. Some of such licenses are issued on an annual basis, for example the export licenses for uranium concentrate as well as transport authorisations, while others may be issued for two or more years at a time.

To comply with the Regulations, a regular monitoring program is required. It is left to each licensee how such a monitoring program is structured. It is important to realise that it is not necessary to monitor all workers all the time, as the regulatory requirement stipulates that a dose assessment is undertaken for each occupationally exposed person, but not necessarily by way of individual monitoring.

Dose assessments may be based on area monitoring, or random sampling of similar exposure groups. It is however important that a dose assessment program complies with the following basic principles underpinning the science of monitoring:

- monitoring results must be statistically valid over the period of an entire year. This implies that specific conditions that affect the work environment and therefore potentially the exposure of persons, for example whether afternoon/night shifts take place or whether work is done only during the day, as well as seasonal and process-related variations at the workplace, must be considered when exposures are assessed.
- monitoring instruments must be calibrated as per the manufacturer's specifications, and such calibration must be undertaken by an accredited calibration facility;
- radiation risk assessments form the basis of how individuals and/or groups of exposed persons are monitored, and how the priority of their monitoring from amongst all exposed persons is determined;
- appropriate sample sizes are to be used for each group that is separately monitored. While being specific to the context in which monitoring is to be done, and the associated risk level, the minimum sample size for each group should comprise of at least six persons.
- If the monitoring results for a given group are consistently below 25% of the applicable dose limit for a given work area, the frequency at which monitoring is undertaken can be reduced, provided that the prevailing exposure conditions remain unchanged.
- If a site has adopted a specific dose limit for a given work area, the 25%-rule applies to that dose limit. For example, if an operation has adopted a site-wide dose limit of 5 mSv/a, all exposed persons are subject to this dose limit, and the exposure monitoring program must be designed to assess this self-imposed dose limit.

8.7 Addressing Implementation Issues and Challenges

The implementation of the RMP/Transport Plan seldom proceeds as has initially been planned. A considerable number of issues and challenges can arise, both in the run-up and during the implementation of an RMP/Transport Plan. Some of the main aspects are summarised in Table 10, and cover some of the best-practice approaches that are of relevance to exploration, mining, and processing activities of radioactive minerals.

Table 10: Issues and challenges encountered during implementation of the RMP/Transport Plan

Issue / Challenge	Description	Mitigation measure(s)
Role of management	Management is unaware of their roles and responsibilities *vis-à-vis* on-site radiation safety	Management must have a hands-on involvement in all matters pertaining to radiation safety
Who is responsible for what?	Radiation-related roles and responsibilities are unclear	An implementation plan that spells out the roles and responsibilities of all parties involved in the roll-out of the RMP/Transport Plan
Allocation of tasks, frequency of tasks	Tasks and activities are insufficiently described, and their timing is uncertain	An implementation plan must include a schedule of activities, and describe who will be responsible for what
Access to human resources	Trained and experienced personnel are unavailable	Applied radiation safety – and by implication the compliance with national regulations – hinges on having the necessary human resources to implement the RMP/Transport Plan
Access to technical resources	Technical resources, such as instruments required to undertake workplace and individual dose monitoring, are unavailable	The implementation of radiation safety provisions hinges on having access to the required technical resources
Induction and training of workers	Induction and training is not supported by management, and is not taken seriously by staff, and is therefore generally unsuccessful	Radiation-related induction and training is necessary and must be undertaken in regular intervals as part of the implementation of the RMP/Transport Plan (Figure 89)
Monitoring of worker exposure doses	Monitoring of worker exposure doses is not regularly undertaken, and is not statistically significant or valid	Radiation safety is underpinned by empirical data that is statistically valid for the specified time interval
Data collection, measuring and monitoring	Radiation risks are not mitigated through the systematic collection of data, and the interpretation of data is inadequate	Radiation-related risks are best reduced or mitigated if they are based on empirical data rather than theoretical projections
Regular reporting	Radiation-related data/information is not reported to management	Management can best contribute to radiation safety when regularly informed about issues/developments
Contractor management	Duties and responsibilities are not adequately communicated between employers and contractors	Clear contractual specification of roles and responsibilities relevant to radiation protection
External auditing and value-addition	The following statement illustrates the issue: "*Radiation safety measures must be kept confidential, and external review will unnecessarily disclose what we do.*"	An external independent specialist regularly reviews all radiation safety functions

8.8 Other Legal Requirements

Most jurisdictions have a variety of legal and regulatory requirements for entities dealing with sources that emit ionising radiation. These fall beyond the scope of this book, but a few examples of additional regulatory requirements as they apply in Namibia are summarised below, for illustration purposes:

1. exploration and/or mining license, under the relevant mineral laws, where applicable;
2. additional legal requirements when dealing with strategic minerals;
3. specific import and export licensing requirements of select minerals, incl. uranium, as part of the safeguards agreement with the IAEA;
4. labour law;
5. environmental legislation;
6. licensing for water abstraction;
7. use of explosives and hazardous substances; and others.

Figure 89: The end of a professional development course at the Namibian Uranium Institute [90]

8.9 Exercises

1. Regulatory oversight in the uranium mining sector is applied to
   a) minimise occupational exposures of radiation workers
   b) provide justification for damaging environmental practices which occur in uranium mining
   c) control the transport of uranium oxide through populated areas
   d) ensure that workers, members of the public and the environment are protected against the potentially harmful effects of ionising radiation.

2. Monitoring of potential exposures of members of the public is
   a) a regulatory requirement which is accomplished by the strict application of engineering control measures
   b) a voluntary part of a mine's overall monitoring program
   c) undertaken to build a case against arguments by environmental activists and pressure groups
   d) a regulatory requirement which relies on the identification and monitoring of critical groups of members of the public.

3. Monitoring of the occupational exposure of radiation workers is
   a) a regulatory requirement undertaken by systematically monitoring all relevant exposure pathways
   b) a regulatory requirement provided that pregnant females are members of staff
   c) a regulatory requirement to ensure that the potential ingestion and inhalation of radionuclides is minimised and kept ALARA
   d) a regulatory requirement to protect foetuses and other vulnerable members of the public.

4. Public exposure doses as reported to the regulator
   a) must include the prevailing background radiation levels to ensure that exposures can be kept ALARA
   b) must be lower than 1 mSv/a even if no critical groups were monitored
   c) must be expressed as a percentage of the gamma contribution to the population weighted gamma background radiation
   d) are derived from monitoring critical groups of members of the public.

5. Occupational exposure doses as reported to the Regulator
    a) must exclude the prevailing background radiation levels to ensure that exposures can be kept ALARA
    b) must be lower than 20 mSv/a and expressed as a percentage of the gamma contribution to the total dose
    c) are derived from monitoring select groups and individual members of staff
    d) are interpolated from the results of measurements undertaken in near-by communities.

6. Your immediate line manager suggests that "the Namibian legislation does not require us to have an RMP as we are not a uranium mine". What are the determining factors that need to be considered before deciding whether an RMP is required for an operation other than a uranium mine?

7. You work at a zinc mine, and in discussions with some of the mine's staff it is suggested that "our mine can definitely operate without having to apply for licenses from the NRPA". Under what circumstances will a license from the NRPA be required?

9 Exposure to Radiation and Exposure Doses

This Chapter introduces how relevant exposure pathways are identified and presents the foundation required to assess and quantify exposures and exposure doses due to ionising radiation.

9.1 Exposure Pathways

Radiation can enter the human body in several ways, and these different exposure routes are called *exposure pathways*.

One distinguishes the following main exposure pathways:

1) **External exposure:**
Direct external exposure to penetrating radiation is the result of exposure to gamma radiation and X-rays. In addition, external exposure to radiation can result from exposure to beta radiation, which only penetrates a short distance into the skin, and thereby gives rise to a so-called *skin dose*.

2) **Internal exposure:**

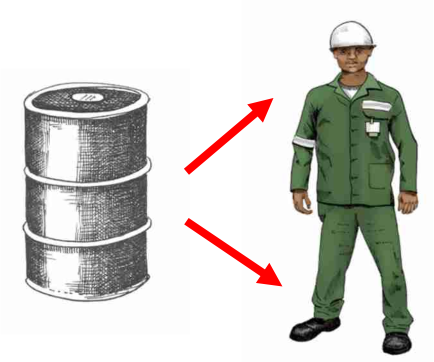
   a. **Inhalation of long-lived radioactive dust (LLRD):** naturally occurring radioactive elements, such as uranium and thorium, have very long half-lives. The radioactive decay of these elements, and their long-lived decay products often takes longer than their dissolution and excretion from the body. This implies that exposures resulting from the inhalation of dust containing long-lived radionuclides must take the duration that these nuclides remain in the airways or lung into account.

   b. **Inhalation of radon and radon progeny:** radon is a radioactive noble gas and does not readily attach itself to surfaces. As a result, the inhalation dose associated with the inhalation of ambient atmospheric radon is small, as such radon does not remain in the lung for long after being inhaled. On the other hand, the radon decay products are solids that readily attach themselves to surfaces and particulate matter in air. Exposure from radon gas is therefore principally due to radon progeny that is present in air, and which will remain in the air ways and the lung once inhaled. In this context it is important to note that the immediate decay products of radon are short-lived, which implies that the decay of radon progeny in the lung will usually occur long before such radionuclides would dissolve and be excreted from the body.

   c. **Ingestion of radionuclides:** radioactive materials can be accidentally swallowed, for example when not applying proper hygiene practices, or when inadequate respiratory protection is used. This may result in the accumulation of radioactive dust in the mouth and throat, which is then swallowed. Also, radionuclides can be ingested when consuming radioactively contaminated food and liquids, or when food that contains radionuclides (e.g. vegetables that have taken up radionuclides from the soil and water through the roots, or by drinking contaminated water) is consumed.

Table 11 provides a graphical illustration of the main exposure pathways by which radiation enters the human body.

Table 11: Main exposure pathways by which radiation enters the human body [8]

External	Internal
Direct: penetrating radiation entering the human body from the outside 	**Inhalation:** long-lived radioactive dust (LLRD) 
	Inhalation: radon decay products 
	Ingestion: radionuclides contained in or on food or liquids 

9.2 Exposure to Radiation

The human response to exposure to radiation follows an exposure response curve. Often, this response is linear, which means that an increase in the exposure dose leads to a proportional increase in the response, and vice versa – although it is important to note that this is not always the case.

One of the first persons to realise that a relationship between a given exposure dose and the associated response exists was the medieval doctor Paracelsus (Philippus Aureolus Theophrastus Bombastus von Hohenheim, 1493–1541, a Swiss-German philosopher, who laid the foundation of modern toxicology). Paracelsus is quoted to have observed that "*All things are poisons, for there is nothing without poisonous qualities. It is only the dose which makes a thing poisonous.*"

Figure 90: Paracelsus highlighted the link between exposure dose and response [98]

The human response to hazards other than ionising radiation is beyond the scope of this book, and the reader is referred to literature on industrial hygiene and toxicity.

The human response to radiation exposure has been studied extensively. The most well-known studies in this field are those on the survivors of the nuclear explosive devices set off over Nagasaki and Hiroshima in 1945. More recently, such studies include cohorts of workers at nuclear facilities, underground uranium miners, and persons exposed to the fallout from the nuclear accidents at Chernobyl in 1986, and Fukushima in 2011.

Principally, exposure to ionising radiation causes two types of biological effects: those called *deterministic*, and *stochastic* effects, as has been covered in section 6.5. Deterministic effects occur if an exposure exceeds a given dose threshold, while stochastic effects occur without a dose threshold. While there continues to be much debate about stochastic effects resulting from the exposure to radiation, the LNT hypothesis is generally accepted to hold, refer to section 6.4. The LNT hypothesis suggests that the response to low doses of radiation is linear, and that even small exposure doses have a small but finite risk associated with such exposures [41].

Soon after the discovery of X-rays it was realised that exposure to radiation has definite impacts on the human body. It was observed that X-ray technicians presented symptoms that seemed to be correlated with their exposure to this type of radiation. Exposed persons experienced symptoms ranging from mild to most severe, and especially those parts of the body that were most exposed to X-rays and therefore associated with the highest exposure doses, i.e. the hands, were often affected, as shown in Figure 91.

Figure 91: An X-ray technician's response to radiation exposure [100]

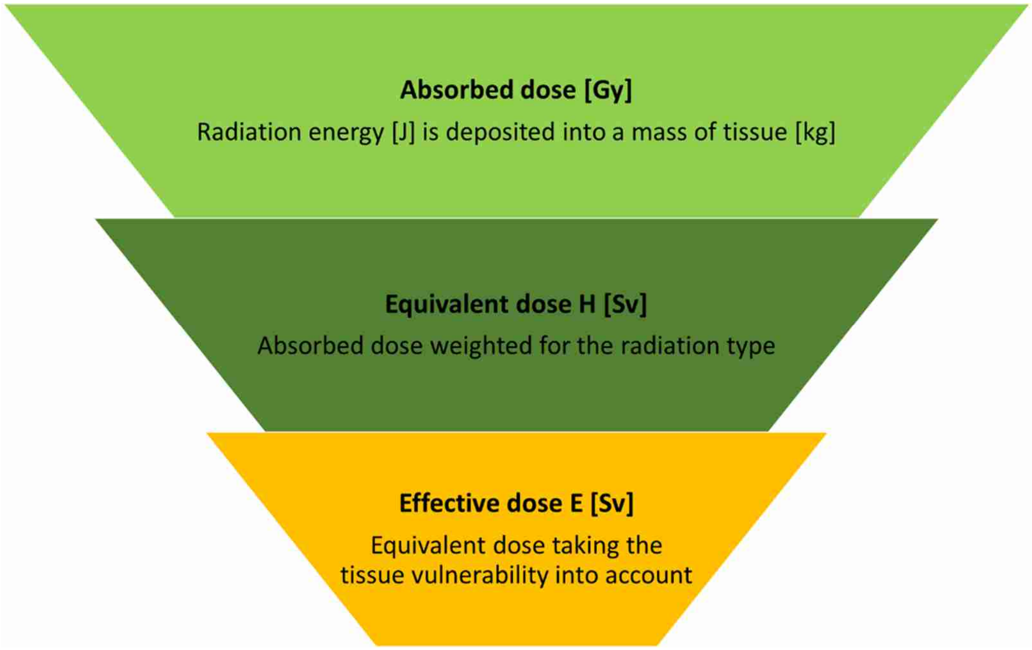
9.3 Exposure Doses

How much exposure to ionising radiation damages the body? To answer this question, one needs to consider the type of radiation, the exposure pathway, and the exposure dose.

An exposure dose provides a measure of the amount of radiation that a receptor was exposed to. Here it is noted that a radiation dose is slightly different to a more common dose, as may for example be used in the field of medicine, where the mass or volume of a medicinal drug can readily be measured before it is administered to a patient. In the case of a radiation dose, the effect that such an exposure has on living tissue is how such an exposure dose is quantified. Considering that tissue effects often only arise after a considerable time has lapsed between an exposure event and the emergence of a discernible impact, the quantification of the detriment of radiation impacts on the body is often complicated.

Exposure to ionising radiation is quantified using a *hierarchy of exposure doses*, namely the absorbed dose, the equivalent dose, and the effective dose, as shown in Figure 92. These different types of exposure doses are further elaborated in the subsections below.

Figure 92: Hierarchy of exposure doses [8]



9.3.1 Absorbed Dose

The *absorbed dose* is a measure of the radiation energy that is absorbed by tissue. It is used to quantify the impact that an exposure has on a specific tissue, for example the potential biochemical changes because of an exposure to ionising radiation.

The unit for the absorbed dose is the Gray [Gy], where one Gray corresponds to one Joule of energy absorbed by one kilogram of tissue:

1 Gy = 1 J/kg.

In the USA, the unit *rad* remains in use, where

1 rad = 10 mGy.

9.3.2 Equivalent Dose

The *equivalent dose* quantifies the impact of a given radiation dose on tissue, including a weighting factor for different radiation types.

The unit for an equivalent dose is the Sievert, which is abbreviated Sv. One Sv is equivalent to one Joule of photon energy deposited into a tissue having a mass of one kilogram.

Mathematically, the equivalent dose $\boldsymbol{H_T}$ is expressed as follows:

$$\boldsymbol{H_T = \sum_R W_R \cdot D_{T,R}}$$

where

H_T is the equivalent dose on tissue T;

W_R is the weighting factor for radiation of type R; and

$D_{T,R}$ is the dose from radiation of type R that is absorbed by tissue T.

The following weighting factors $\boldsymbol{W_R}$ are used:

$\boldsymbol{W_R} = \mathbf{1}$ for photons, i.e. for X-rays and gamma rays;

$\boldsymbol{W_R} = \mathbf{1}$ for electrons, i.e. beta radiation;

$\boldsymbol{W_R} = \mathbf{2}$ for protons; and

$\boldsymbol{W_R} = \mathbf{20}$ for alpha radiation, nuclear fission products, and heavy nuclei.

For neutrons, W_R depends on the specific neutron energy in question.

The above weighting factors imply that for both gamma and beta radiation, the equivalent and the absorbed dose are numerically identical. On the other hand, alpha radiation is 20 times more effective in delivering an exposure dose than beta and gamma radiation.

9.3.3 Effective Dose

The *effective dose* is a measure of an exposure dose that takes the absorbed dose to all organs of the body, the relative harm level of the radiation, as well as the specific organ sensitivities to radiation into account.

The unit for the effective dose is the Sievert (Sv). In USA, the unit *rem* remains in use, where

1 rem = 10 mSv.

Mathematically, the effective dose $\boldsymbol{E_T}$ is expressed as follows:

$$\boldsymbol{E_T} = \sum_{\boldsymbol{T}} \boldsymbol{W_T} \cdot \boldsymbol{H_T}\,,$$

where

W_T is the weighting factor for tissue type T, as summarised in Table 12; and

H_T is the equivalent dose on tissue T.

The effective dose is the sum of all equivalent doses in all specified tissues and organs of the human body and is the applicable metric in exposure situations in which the body has not been uniformly irradiated.

When referring to exposure doses as they are incurred in the exploration, mining, milling, and processing of radioactive minerals, for example, one uses the effective dose as the measure for the exposure dose to radiation. Such an exposure dose is meant to refer to the **effective whole-body dose**, as one often assumes that the whole body is uniformly exposed, rather than select organs only, or limited to specific tissues in the body.

In many medical radiation exposure applications, uniform whole-body irradiation is seldom used. This necessitates that weighting factors are used for each affected tissue type [45], as summarised in Table 12.

Table 12: Tissue weighting factors [45]

Organ/tissue	Tissue weighting factor
Gonads	0.08
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Breasts	0.12
Bladder	0.04
Liver	0.04
Oesophagus	0.04
Thyroid	0.04
Skin	0.01
Bone surface	0.01
Salivary glands	0.01
Brain	0.01
Remainder of body	0.12
Total	**1.00**

9.4 Exposure Dose Calculations

An *exposure dose* quantifies a specific exposure event. In contrast, an *exposure dose rate* is an expression of the risk of exposure and quantifies how quickly an exposure dose occurs.

The unit used to express both equivalent and effective exposure doses is the Sievert (Sv). It is an expression of the biological risk associated with an exposure to ionising radiation, regardless of the specific exposure pathway and the radiation type.

When an exposure dose is expressed in units of Sievert, the risks associated with different exposure doses can be directly compared to one another.

To illustrate: the exposure dose incurred from the exposure to cosmic radiation during an intercontinental flight is equivalent to eating 600 bananas, although the former is an external exposure event, while the latter is the result of internal exposure resulting from the ingestion of food which contains radioactive K-40.

Dose rates are conveniently measured in terms of a dose per unit of time and are often expressed in units such as a milli-Sievert per hour, which is abbreviated mSv/h or mSv.h^{-1}, in micro-Sievert per hour, which is abbreviated µSv/h or µSv.h^{-1}, or in nano-Sievert per hour, which is abbreviated nSv/h or nSv.h^{-1}.

At a dose rate of 1 mSv/h, it takes just one hour to reach the annual public dose limit of 1 mSv. This implies that a dose rate of 1 mSv/h is a high dose rate.

To illustrate: a dose rate of 1 mSv/h may occur close to an open sealed radioactive source, or close to an X-ray source as used for non-destructive testing purposes.

Dose rates of the order of 1 mSv/h do not commonly occur in the uranium exploration and mining sectors when dealing with uranium-bearing source material such as uranium-bearing ore or uranium concentrate only.

At a dose rate of 1 µSv/h, it takes 1 000 hours to reach the annual public dose limit of 1 mSv. This implies that such a dose rate should not occur in places where members of the public regularly spend time, unless of course that it is due to the natural background radiation in a specific area.

A radiation worker whose exposure must remain below 20 mSv/a could spend an entire working year, i.e. some 2 000 working hours, in a radiation field with a dose rate of 1 µSv/h without exceeding the occupational dose limit.

In the uranium mining sector, areas that typically have dose rates of several µSv/h include those at or close to ore stockpiles, on tailings storage facilities, and in processing and concentration plants. Several tens of µSv/h are reached on contact with drums filled with uranium concentrate, and shipping containers loaded with such drums, and next to or inside tanks and pipes that contain radium-rich scales (jarosite), or on contact with certain pregnant liquids and processing solutions.

A dose rate of 1 nSv/h implies that it takes one million hours to reach the annual public dose limit of 1 mSv.

To illustrate: the natural background radiation from terrestrial and cosmic sources is usually associated with a dose rate of the order of 0.1 µSv/h, which is 100 nSv/h, noting however that the natural background radiation field is highly variable from one location to another.

If the dose rate ***DR*** is known, for example by way of a dose rate measurement, and the duration t_e of such exposure is known, the exposure dose is calculated using the following mathematical formula:

Dose = duration multiplied by dose rate, i.e.

$$\textit{Exposure dose} = t_e \cdot DR.$$

Box 19: Annual exposure dose of a radiation worker

For 3 months of a year, a radiation worker is active in the product recovery area, which results in a total whole-body dose of 1.2 mSv for this period. Thereafter, the person is transferred to an office, where the annual exposure dose has been determined to amount to 0.8 mSv per annum.

What is the annual exposure dose of this person?

The total annual exposure dose is therefore the sum of the exposure dose while in the product recovery area, plus the dose incurred while working in the office environment.

During the 9 months spent in the office environment, the person incurred an exposure of

$$0.8 \text{ mSv/annum} \cdot (\text{ 9 months / 12 months/annum }) = 0.6 \text{ mSv.}$$

The total annual exposure dose is therefore computed as follows:

$$\text{Dose}_{\text{total}} = \text{Dose}_{\text{product recovery}} + \text{Dose}_{\text{office}} = 1.2 \text{ mSv} + 0.6 \text{ mSv} = 1.8 \text{ mSv.}$$

9.5 Natural Background Radiation

Radiation is all around us and originates from natural as well as man-made sources.

The radiation field that we are immersed in is called *background radiation*, and more specifically, *natural background radiation* when it refers to naturally occurring origins of the radiation only.

The subsections below provide a brief description of the different types of natural background radiation that exist.

9.5.1 Terrestrial Radiation

Terrestrial radiation is emitted by radionuclides that occur in the environment. This type of radiation causes direct external exposures. It originates in minerals, rocks, water, and the air in the environment. The radionuclides which contribute to this radiation field are mainly uranium and thorium and their various decay products, as well as the radioactive isotope of potassium, i.e. K-40. On average, the above radionuclides contribute to terrestrial radiation in similar parts [101].

The worldwide average annual effective exposure dose from terrestrial radiation is 0.48 mSv/a. Individual country averages are mostly in the range between 0.3 to 0.6 mSv/a [101]. In Namibia's Erongo Region, the exposure dose from terrestrial radiation is of the order of 0.55 mSv/a [33].

Local variations from the worldwide average can be substantial. Table 13 provides examples of locations which are known for their high natural gamma background field [101].

Table 13: Examples of high natural gamma background fields in select parts of the world [101]

Area	Average dose (mSv/a)	Local characteristics
Iran, Ramsar	Average up to 150	Spring waters
China, Yangjiang	3.2	Monazite particles
India, Kerala	16	Monazite sands
Brazil, Mineas Gerais	Average up to 25	Volcanic intrusions

Note: these gamma background radiation doses include terrestrial and cosmic radiation.

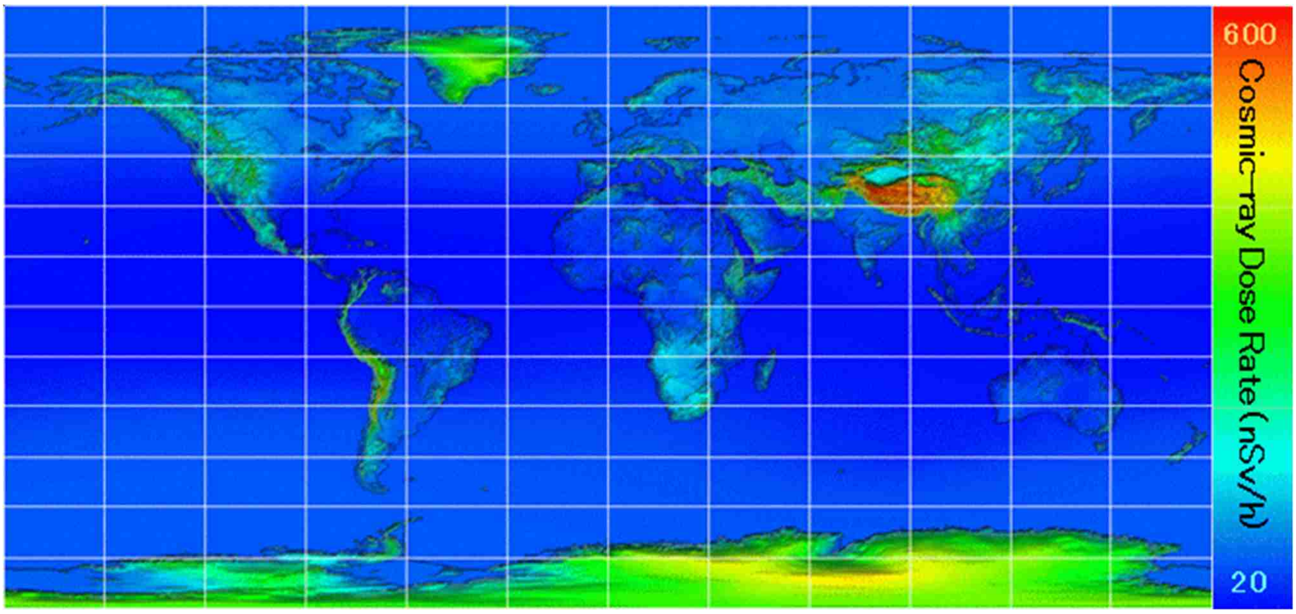
9.5.2 Cosmic Radiation

Cosmic radiation originates mostly from beyond the solar system and consists of very high energy radiation. Most of this radiation is absorbed in the Earth's atmosphere. Charged cosmic rays are deflected towards the poles by the Earth's magnetic field. When the so-called primary cosmic rays hit the top layers of the Earth's atmosphere, secondary particle showers are produced, as illustrated in Figure 93.

Figure 93: Artist's impression of primary and secondary cosmic ray shower [102]

The Earth's atmosphere provides some protection from cosmic radiation. Because the Earth's magnetic field deflects charged cosmic radiation towards the poles, cosmic radiation levels are lowest at the equator, and increase as one moves closer to the poles. Also, the levels of cosmic radiation are lowest in coastal regions, and highest in the mountains, as is illustrated in Figure 94. Man-made structures such as buildings shield cosmic radiation, which implies that the actual exposure to cosmic radiation depends on the amount of time one spends outdoors, and the level of shielding provided by the buildings in which one spends time.

Figure 94: Dose rate from cosmic radiation, in nSv/h, from 20 nSv/h (blue) to 600 nSv/h (red) [103]



The population-weighted world average exposure dose which can be attributed to cosmic radiation amounts to 0.38 mSv/a [101]. In Namibia's Erongo Region, the population-weighted average cosmic radiation dose is approx. 0.35 mSv/a [33].

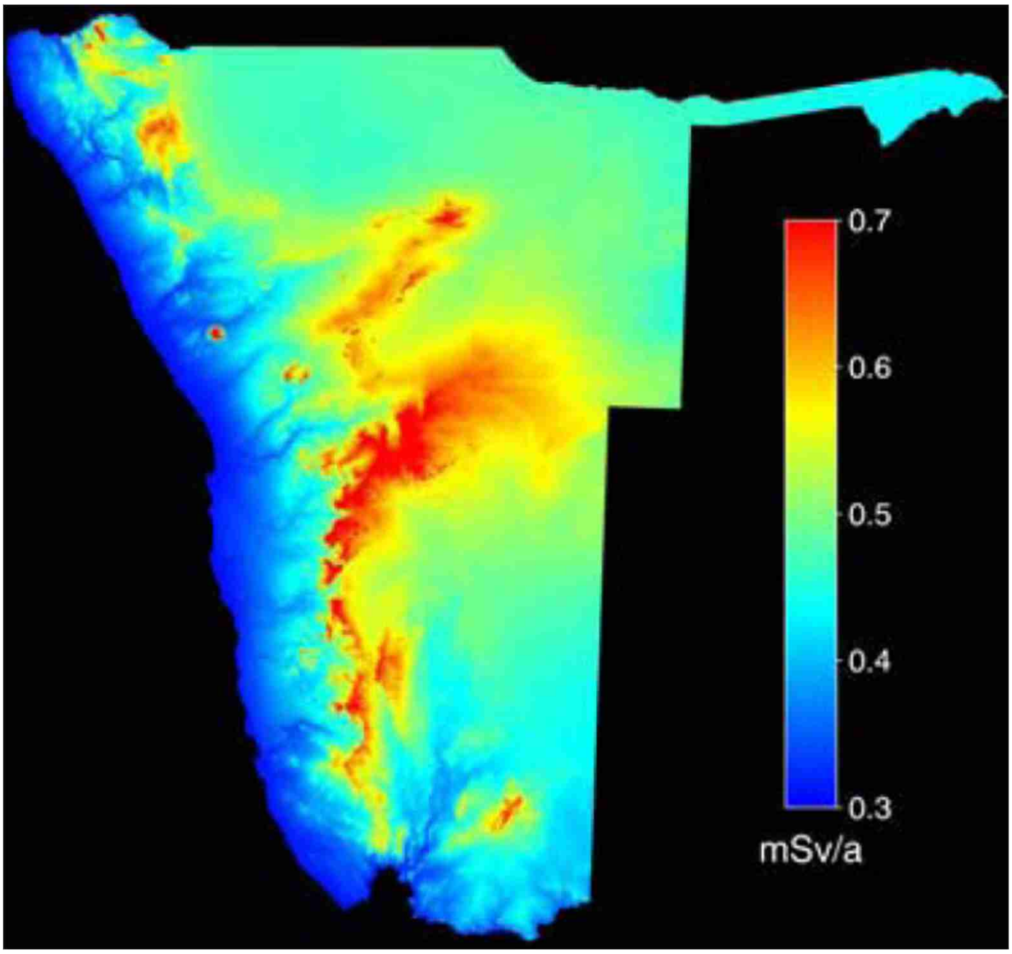
For an aircraft flying at between nine and twelve kilometres above mean sea level, the effective dose rate from cosmic radiation ranges between 5 and 8 µSv/h. This implies that one incurs an exposure dose of some 60 µSv from cosmic radiation when flying between Windhoek and Frankfurt. Airline staff incur an annual dose from cosmic radiation which typically ranges between 3 and 9 mSv/a.

Table 14 provides examples of typical cosmic radiation doses in select localities around the world.

Table 14: Examples of cosmic radiation doses in select parts of the world [101]

Area	Approximate dose (mSv/a)
Sea level	0.32
World average	0.38
Windhoek (1 700 m)	0.72
Tibet (4 000 m)	1.9
Kilimanjaro (5 895 m)	7.1
Mount Everest (8 800 m)	42

Figure 95: Contribution of cosmic radiation in Namibia, in mSv/a [104]



9.5.3 Ingestion Dose

Radionuclides are everywhere, including in food and water. Food which is characterised by elevated radionuclide concentrations include those high in potassium, such as bananas and green foods, as well as mussels and shellfish, which feed on nutrients which they filter from the environment in which they live.

The world average exposure dose from the ingestion of naturally occurring radionuclides in food and water is of the order of 0.31 mSv/a, of which some 0.17 mSv/a is due to the presence of potassium-40, and 0.14 mSv/a is due to radionuclides from the uranium and thorium decay chains [101].

Table 15 provides examples of sources of radionuclides as are found in common foods.

Table 15: Radionuclide concentrations in some common foods [105], [106]

Food	Bq/kg from K-40	Bq/kg from Ra-226
Bananas	130	<1
Brazil nuts	200	260
Carrots	125	<1
Potatoes	125	<1
Red meat	111	<1
Beer	14	<1
Water	0	0.007

9.5.4 Inhalation Dose from Atmospheric Dust

The ambient air we breathe contains dust, which inevitably contains traces of radionuclides that occur in the environment.

The world average exposure dose from the inhalation of radioactive dust in air amounts to some 6 μSv/a. This is a small exposure dose when compared to the other contributions to the natural background radiation field [101].

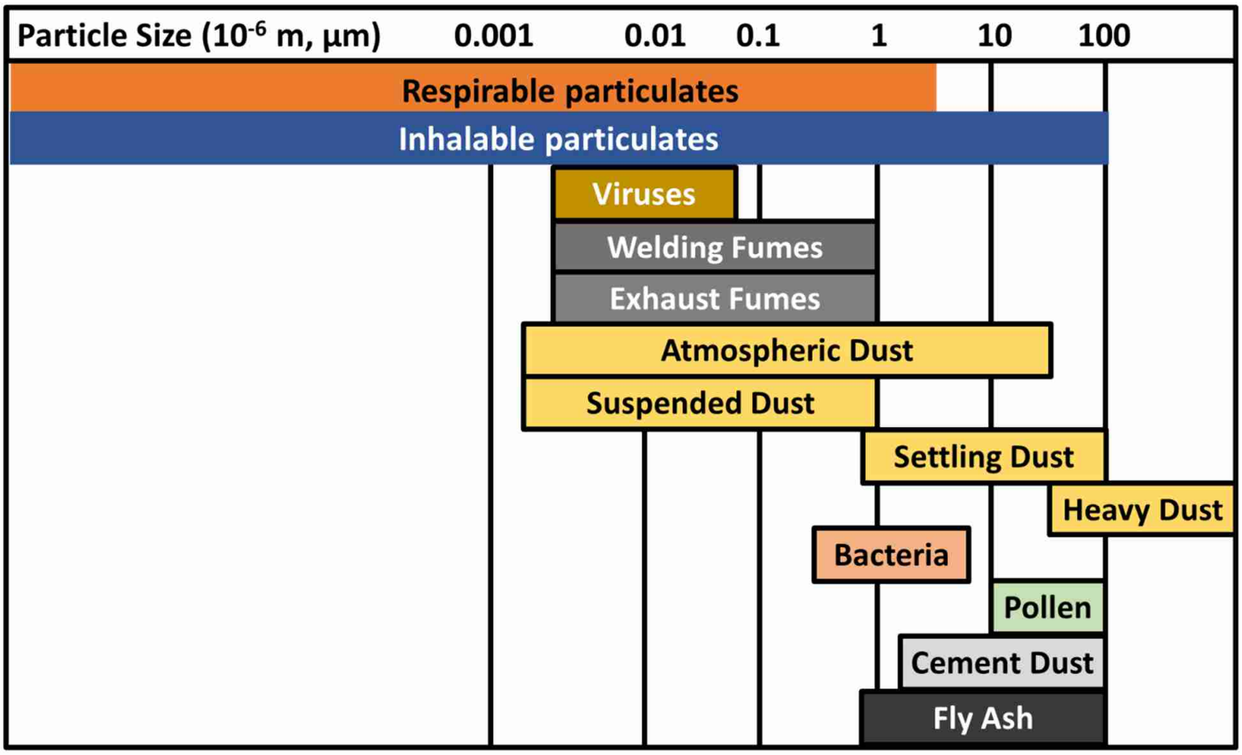
Examples of the types of dust found in a work environment include:

- mineral dust, such as that containing free crystalline silica (e.g. quartz), coal and cement dust;
- radioactive minerals, such as uranium and thorium;
- metallic dust, such as that containing lead, cadmium, nickel, and beryllium;
- chemical dust, as contributed by many bulk chemicals as well as pesticides;
- organic and vegetable dust, such as that of flour, wood, and pollen;
- Fibrous dust, such as asbestos; and
- biohazardous dust, such as from viable particles, moulds, and spores.

Dust can have a variety of different impacts on humans. These depend, amongst others, on the size of the individual dust particles that one is dealing with. The smaller such dust particles are, the deeper they can penetrate the airways of the lung, and the more hazardous they are likely to be.

Some typical particle sizes of common atmospheric pollutants are summarised in Figure 96.

Figure 96: Some typical particle sizes of common atmospheric pollutants [8]



A measure that is used to quantify the size of dust particles, which is of relevance to industrial hygiene, is the *particle aerodynamic diameter*. It must be realised that airborne particles have irregular and often widely varied shapes. To capture this variety and associated aerodynamic behaviours of dust particles, one uses the diameter of an idealised spherical particle, known as aerodynamic diameter, which is defined as *the diameter of a hypothetical sphere of density of 1 g/cm^3 having the same terminal settling velocity in calm air as the particle in question, regardless of its geometric size, shape, and true density.*

Dust is classified depending on the region of the respiratory tract it penetrates:

- **Inhalable particulate fraction** includes the fraction of dust that can be breathed into the nose or mouth. The inhalable fraction of dust includes particles of up to 100 micron (µm) in diameter, with 77% of it being less than 10 µm in diameter. Inhalable particulate dust is sampled by collecting the PM$_{10}$ portion of dust, i.e. the fraction of particulates which are smaller than 10 µm in diameter.

- **Thoracic particulate fraction** is the dust fraction that can penetrate the head airways and enter the airways of the lung. It includes dust which is smaller than 25 µm, with 50% of it being smaller than 10 µm.

- **Respirable particulate fraction** is the dust fraction that can penetrate beyond the terminal bronchioles into the gas-exchange region of the lungs. Examples of such dust, for which the respirable fraction offers the greatest hazards, include quartz and similar sources containing free crystalline silica, and others. It includes dust which is smaller than 10 µm, with about 90% of it being smaller than 2.5 µm. Respirable particulate dust is sampled by collecting the PM$_{2.5}$ portion of the dust, i.e. particulate matter which is smaller than 2.5 µm.

Measurable quantities relating to dust in air include the following:

- **Total particulate matter in air**, TPM, which is measured in mg/m^3 or µg/m^3;

- **PM$_{10}$** or particulate matter up to 10 microns in size, in µg/m^3;

- **PM$_{2.5}$** or particulate matter up to 2.5 microns in size, in µg/m^3;

- **Dust deposition rate**, which is measured in mg/m^2/day; and

- **Activity concentration of LLRD**, which is measured in Bq/m^3.

Figure 97: PM$_{10}$ dust monitoring at Rössing [34]

The World Health Organisation (WHO) has issued guidelines on outdoor air quality relating to particulate matter [107]. The following is an incomplete summary of the main guideline values:

- **for $PM_{2.5}$:** annual average value of 10 µg/m^3, with a 24-hour average value of 25 µg/m^3; and
- **for PM_{10}:** annual average value of 20 µg/m^3, with a 24-hour average value of 50 µg/m^3.

The WHO guidelines for indoor air quality identify specific hazardous substances, such as formaldehyde, naphthalene, nitrogen dioxide, polycyclic aromatic hydrocarbons, radon, and trichloro-ethylene [108]. These do not specifically include a general standard for the concentration of indoor particulates, except for those arising during the combustion of some of the typical fuels used in a household.

The inhalation dose from radionuclides in ambient atmospheric dust in Namibia's Erongo Region was previously estimated at approximately 0.04 mSv/a [33]. However, as this estimate was based on extrapolations from numerical atmospheric dust dispersion models, and these models predicted average dust concentrations of up to three times higher than measured values, the previous inhalation dose determined for the Erongo Region is considered to overestimate the actual inhalation dose from LLRD in ambient air in the Erongo Region. However, it is noted that the Region is naturally dusty, which is exemplified on days with strong east-wind conditions, as shown in the satellite image depicted in Figure 98.

Figure 98: Dust from the Namib is blown into the Atlantic Ocean by winter east winds [109]

9.5.5 Exposure Dose from Radon

Worldwide, radon is a significant source causing internal exposure to ionising radiation. Atmospheric radon concentrations depend on the uranium and thorium content of the soil. However, the exposure of people to radon and its progeny depends – to a large extent – on the degree of ventilation of homes and offices, as well as on the foundation and building materials used in such structures.

Radon is the element with symbol Rn and atomic number 86. It is a radioactive, colourless, odourless, tasteless noble gas, and occurs naturally as a decay product of radium. Its isotopes are members of the decay chains of U-238, U-235 and Th-232. Radon's most stable isotope, Rn-222, which originates from the uranium decay chain, has a half-life of 3.8 days. Rn-220, which is called thoron, and originates in the thorium decay chain, has a half-life of 55 seconds, and is therefore much less significant than Rn-222. Rn-219, from the actinium chain, has a half-life of 4 seconds, and is insignificant as an inhalation risk.

Radon is one of the densest substances that remains a gas under normal atmospheric conditions. As a noble gas, it does not form molecules, and occurs in form of monatomic particles in air. Radon is also the only gas that has no stable isotopes under normal conditions. This means that all radon found in air, regardless of its origin, is radioactive. All radon isotopes are alpha emitters.

Because of its density, noting that radon is about 8 times denser than the Earths' atmosphere, radon sinks to the ground, provided that atmospheric conditions are still. However, any movement of air, such as through convection and the wind, readily mixes radon with fresh air. Radon also readily diffuses through most materials, because it is monatomic, and its particles are small compared to those of most other materials.

Because radon is a noble gas, it is chemically inert, which means that it does not form chemical bonds, and does not readily attach itself to any surfaces, with charcoal being a notable exception. Radon is moderately soluble in cold water, and is found in many ground water sources, from where it is exhaled into the ambient air when such water is used in homes.

Unlike radon itself, all its progeny are solids, which can attach themselves to particles in the air, as well as the airways when inhaled. Exposure to radon is therefore primarily because of the decays of radon progeny, and not from radon itself. The ratio of radon in air to its progeny is called the *equilibrium factor*, and ranges between 0.2 and 1. An average value of 0.4 is often used in dose calculations.

For radon in buildings, the WHO guidelines for indoor air quality propose a reference level of 100 Bq/m^3, and indoor reference levels not exceeding 300 Bq/m^3 [108].

9.5.5.1 Brief History of Radon

For most parts in human history, the mining of minerals was associated with many risks. Working conditions were often poor, and frequently resulted in casualties and work-related injuries. Underground mining often took place in narrow and unstable tunnels, with minimal lighting and poor ventilation, and little regard for the risks associated with working in confined and polluted spaces, as illustrated in Figure 99.

Five centuries ago, it was already known that underground miners in the Erzgebirge in Europe, where silver was mined, often died of lung disease. In the 1500s, Paracelsus described the lung disease found in miners as the "pestilence of the air". Life expectancy of underground miners was low – often less than 30 years. In 1879, Haerting and Hesse identified the lung disease of these miners as bronchial cancer.

Radon was the fifth naturally occurring radioactive element discovered, after uranium, thorium, radium, and polonium. In 1899, Pierre and Marie Curie had noticed that a gas emitted by radium remained radioactive for a month, and in 1900, the German physicist Friedrich Dorn discovered that radium-bearing compounds release a radioactive gas, which he named 'radium emanation'.

Figure 99: Today, many historical mining practices are considered unsafe [110]

In the early 1930s, studies suggested that radon caused lung cancer in miner cohorts working in the Schneeberg and Joachimsthal mines, which originally produced silver. The word 'dollar' stems from the word 'Thaler', as the coins minted from the pure silver of Joachimsthal were called 'Joachimsthaler' or, abbreviated, 'Thaler'.

Between 1876 and 1938, some 60 to 80% of all miners working in these mines developed a deadly disease, called the *Bergkrankheit* (mountain sickness), or *Schneeberg Krankheit*. Certain regions of the mines were known as 'death pits', where all workers got sick. As a result, lung cancer affecting miners was recognised as an occupational disease, and in turn entitled miners to be compensated.

Initially it was thought that chemical constituents of the ore produced, most notably arsenic, might be the causative agent of such lung cancers, but there were also early suspicions that 'radium emanation' could be the main culprit. In 1924, the German physics journal *Zeitschrift für Physik* confirmed that the air of these underground mines was characterised by radon concentrations of up to a million Bq/m^3 [111].

Following the discovery of radium as a medical cure, it was mined at the Erzgebirge, the same region in which uranium was mined for the Soviet nuclear weapons program starting in the late 1940s.

In 1949, it became evident that radon decay products were responsible for most of the alpha radiation exposure to the lung. Pre-1956, radon exposure doses of occupationally exposed persons in these underground mines ranged between 150 and 1 500 mSv/a [63]. Only when ventilation was introduced did radon concentrations and their associated doses decrease.

The connection between lung cancer and smoking was discovered at about the same time as that between lung cancer and exposure to radon. In the 20th century, the incidence of lung cancer rose steeply, due in parts to the increase of cigarette smoking across large sections of the population, as well as due to the increase of air pollution caused by the fuel sources powering the industrial revolution, such as coal, diesel, and petrol. In the late 1940s and early 1950s, cigarettes were finally recognised as the leading cause of the lung cancer epidemic.

Today, lung cancer kills more than 1.5 million people per year and is the leading cause of cancer deaths worldwide. As such, lung cancer is a significant risk, and has considerable socio-economic impacts and repercussions. It is accepted that cigarette smoking is the main causative agent leading to lung cancer.

9.5.5.2 Radon Concentrations in Air

The UNSCEAR report on background radiation provides some estimates for the worldwide average radon concentration in air, suggesting that it amounts to some 40 Bq/m^3 indoors, and 10 Bq/m^3 outdoors [101]. The population-weighted average exposure dose for such an average radon concentration is quoted as 1.095 mSv/a. It is important to note that this exposure dose is based on assumptions about the equilibrium factor, the average time spent in- and outdoors, and the specific dose conversion factor used.

Radon has a half-life of 3.8 days, while thoron has a half-life of about one minute. Because of the difference of these half-lives, the opportunity for thoron to escape from soils and rocks before it decays is much smaller than it is for radon. The world average effective dose from thoron is therefore much lower than the one from radon and is estimated to be of the order of 0.09 mSv/a, which is associated with an average in- and outdoor thoron concentration of some 10 Bq/m^3 [47].

In Namibia's Erongo Region, the population-weighted average exposure dose resulting from the inhalation of radon and radon progeny is estimated to be of the order of 0.46 mSv/a [33].

Atmospheric radon concentrations vary significantly from one location to the next and fluctuate considerably over time. This is the result of a variety of environmental factors that influence the atmospheric radon concentration, including the uranium content of the underlying mineral and soil substrate, the permeability and moisture content of the soil substrates, as well as the degree of natural and forced ventilation. Typically, ambient radon concentrations are lowest near the shores of the oceans, and highest in areas underlain by granites and other uranium-bearing minerals.

Table 16 provides a summary of some typical atmospheric radon concentrations, and their associated exposure dose for adult members of the public, if 7 000 hours per year are spent indoors, and the remaining 1 760 hours per year are spent outdoors, and an equilibrium factor of 0.4 for indoor and outdoor radon concentrations.

Table 16: Examples of some typical atmospheric radon concentrations [47]

Area	Outdoor radon concentration in air [Bq/m³]	Indoor radon concentration in air [Bq/m³]	Average public exposure dose for adults [mSv/a]
Underlain by granites	100	140	2.8
World average	10	40	0.7
Namibia (Erongo)	20	20	0.4
Small islands	1	10	0.2

Ambient radon concentrations can be particularly high in unventilated underground areas, such as underground mines and tunnels. In such locations, radon is continuously exhaled from soils, and in this way, leads to a steady build-up. One way of managing high radon concentrations is by exchanging air volumes regularly, or by reducing the radon concentration by way of forced ventilation. Before it was realised that radon exposure causes lung cancer, underground mines were seldom ventilated, which meant that such work places were characterised by extremely high radon concentrations, often exceeding one million Bq/m³.

Figure 100 provides a graphical summary of some typical ambient radon concentrations. Corresponding public exposure doses resulting from such radon concentrations are shown in Figure 101, if an adult member of the public spends a full year in each location.

Figure 100: Some typical atmospheric radon concentrations [8]

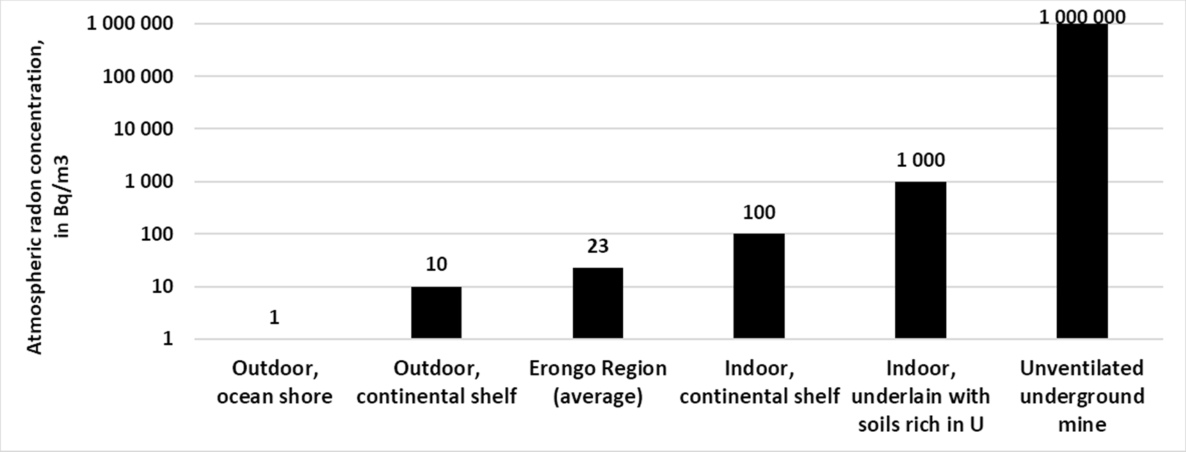
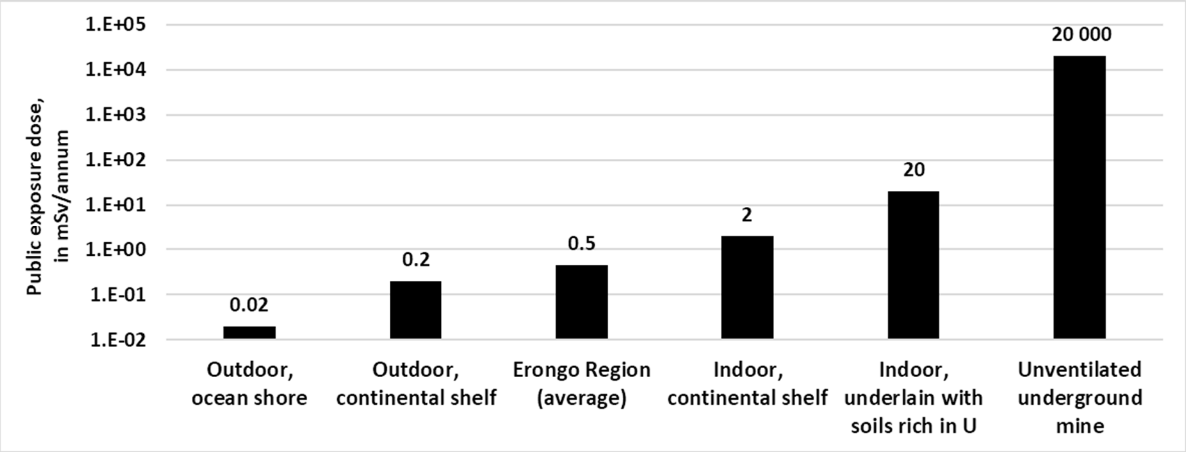


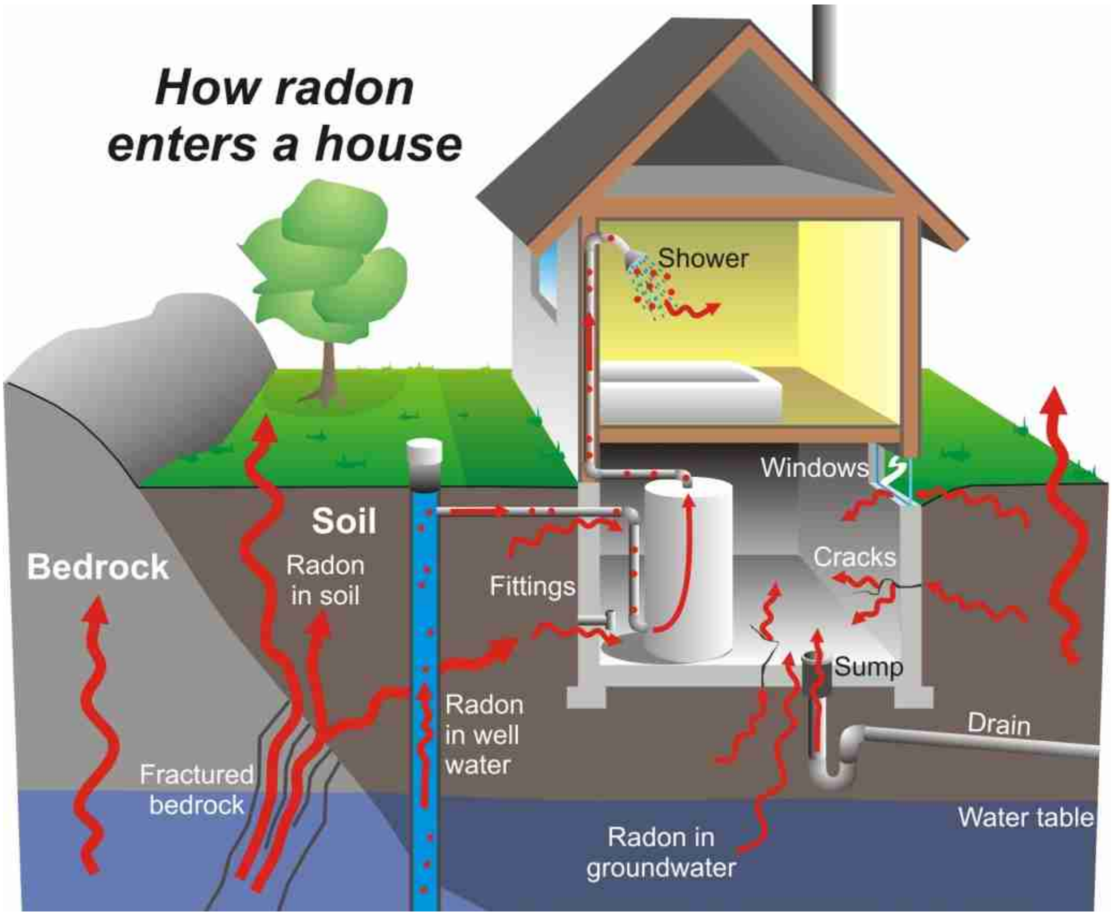
Figure 101: Public exposure doses from select radon concentrations [8]



Radon is formed in the soil, in radium-bearing substrates, from where it is readily exhaled to be diffused into the air. In addition, radon is formed in some building materials, such as granites and marbles, as well as in foundations and cement containing uranium, as illustrated in Figure 102. Such radon, in addition to the fraction that penetrates a home from the outside, may lead to a steady accumulation and increase of indoor radon concentrations.

The emission rate of radon from the soil depends on the uranium and thorium content of such soil, its permeability and moisture content, and on the degree of ventilation above the ground level. As a result, houses with cellars tend to have higher radon concentrations, because all underground areas are exposed to uranium-bearing soils, and because of the limited ventilation applied in most cellars and similar underground spaces.

Figure 102: Sources of radon entering a home [112]



9.5.6 Radiation Exposure Doses from Medical Procedures

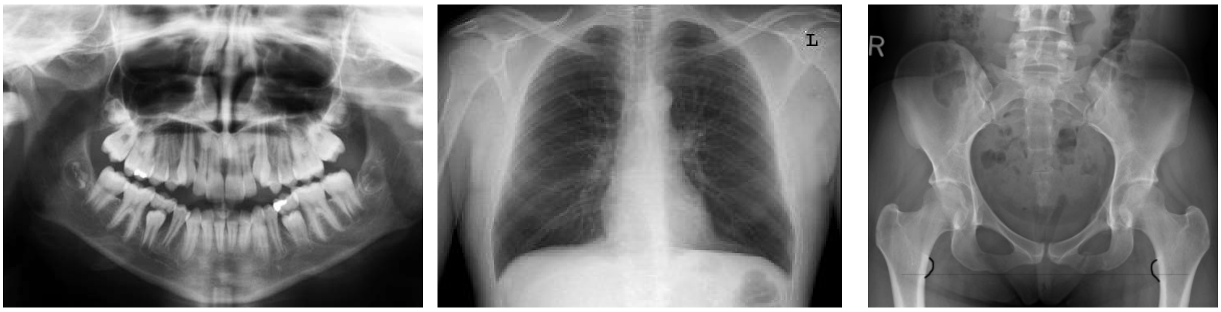
Worldwide, most medical radiation exposures are from diagnostic X-rays. As the technology used in modern X-ray machines has improved dramatically in the past one hundred years, the exposure doses from individual procedures have been successively decreasing. However, at the same time, the application and use of X-rays is steadily increasing, which leads to increasing cumulative exposure doses from diagnostic procedures using X-rays.

In addition to X-rays, medical radiation exposures also result from radiation therapy, where tumours are exposed to intense radiation to kill off tumour cells. Also, the diagnostic administration of radio-pharmaceuticals is another source of medical exposures. A few examples of medical procedures and their typical exposure doses are shown in Figure 103.

For the period between 1991 and 1996, UNSCEAR provides estimates of medical exposure doses. Today, these historical exposures are outdated, but they remain instructive. UNSCEAR reports that the average worldwide exposure from medical procedures amounted to some 0.4 mSv from diagnostic X-rays, and approx. 0.03 mSv from diagnostic nuclear medicine, therapeutic exposures are not provided.

In Namibia, no reliable data is available for exposure doses from diagnostic X-ray procedures. However, as the country's health care category is in level III - IV, the average per person diagnostic X-ray doses are expected to be of the order of 0.02 mSv/a [101]. While exposure estimates from diagnostic radio-pharmaceuticals and therapeutic procedures do not exist, population-weighted exposure doses from these is expected to be negligible.

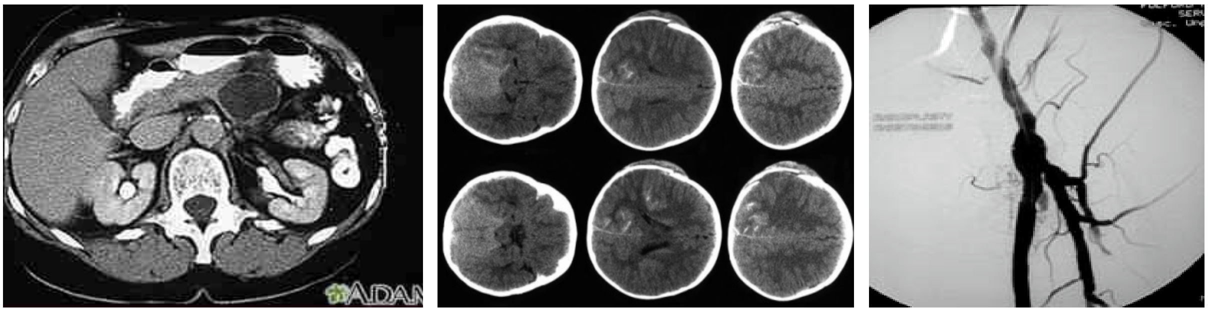
Figure 103: Typical medical procedures and their approximate exposure doses, in mSv



Dental X-ray (panoramic), 0.09 mSv [113]

Diagnostic chest X-ray, 0.1 mSv [114]

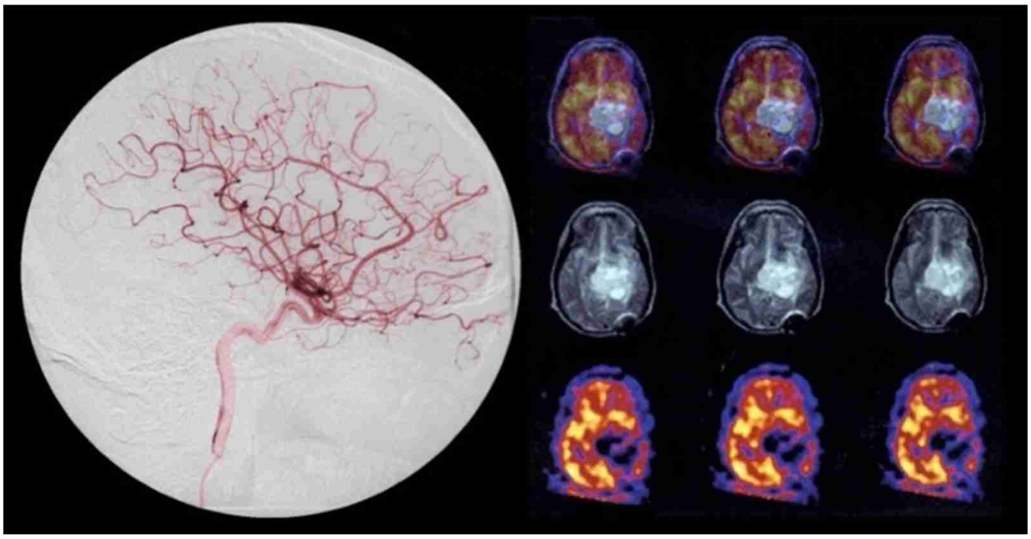
Diagnostic pelvic X-ray, 0.7 mSv [115]



Abdominal CT scan, 10.0 mSv [116]

Head scan using CT, 2.0 mSv [117]

Angioplasty (heart study), 7.5 to 57 mSv [118]



Nuclear medicine scan, as used in the treatment of tumours, 18.5 mSv [119]

9.5.7 Exposure Doses from Man-made Sources

Man-made sources of radiation other than from medical exposures include

- Smoking (up to 15 mSv/a);
- Consumer products (~0.06 mSv/a);
- Security applications, such as X-rays (a few µSv/a);
- High-altitude flights (a few mSv/a);
- Fallout from testing and the production of nuclear weapons (~1.7 µSv/a ingestion, and ~0.0008 µSv/a inhalation);
- Nuclear fuel cycle activities (mining, conversion, fuel production, nuclear power plant operations (~0.2 µSv/a); and radioisotope production and use.

In the above list, the numbers in brackets provide the average exposure doses for world-wide exposures. Where no average value is given, these are either very small, or may not be meaningful. A case in point are exposure doses from smoking, which often cause large internal exposures. To illustrate: smoking one pack of cigarettes per day is estimated to result in an average annual internal exposure dose of some 13 mSv/a [120]. While select dose calculations for smoking have reduced this estimate (see for example [121]), the scientific consensus that smoking is a significant health risk, both the toxicological as well as from the radiological perspective, remains a given.

Some exposures, such as those attributable to the fallout from nuclear weapons testing, do not occur uniformly across the globe, and most of this fallout occurs in the northern hemisphere.

Exposure doses from consumer products are a function of the average financial wealth of a population, which determines (to some degree) how many sources of radiation exposure can be afforded. The average exposure dose from consumer products, as provided in the above list, applies for the USA. For this reason, it is assumed that the equivalent average in Namibia is likely to be lower than the values provided above.

9.5.8 Exposure from Natural Background Radiation – World Average and Erongo Region

Background radiation comes from both natural as well as man-made sources. Doses to people are given as averages over entire populations, although individual doses can vary significantly. This implies that such average doses are only useful as reference levels. Figure 104 depicts the most important contributions to the world average exposures due to natural background radiation, while Figure 105 shows those as apply for the Erongo Region in Namibia.

Figure 104: Population-weighted world background exposure dose, in mSv/a [8]

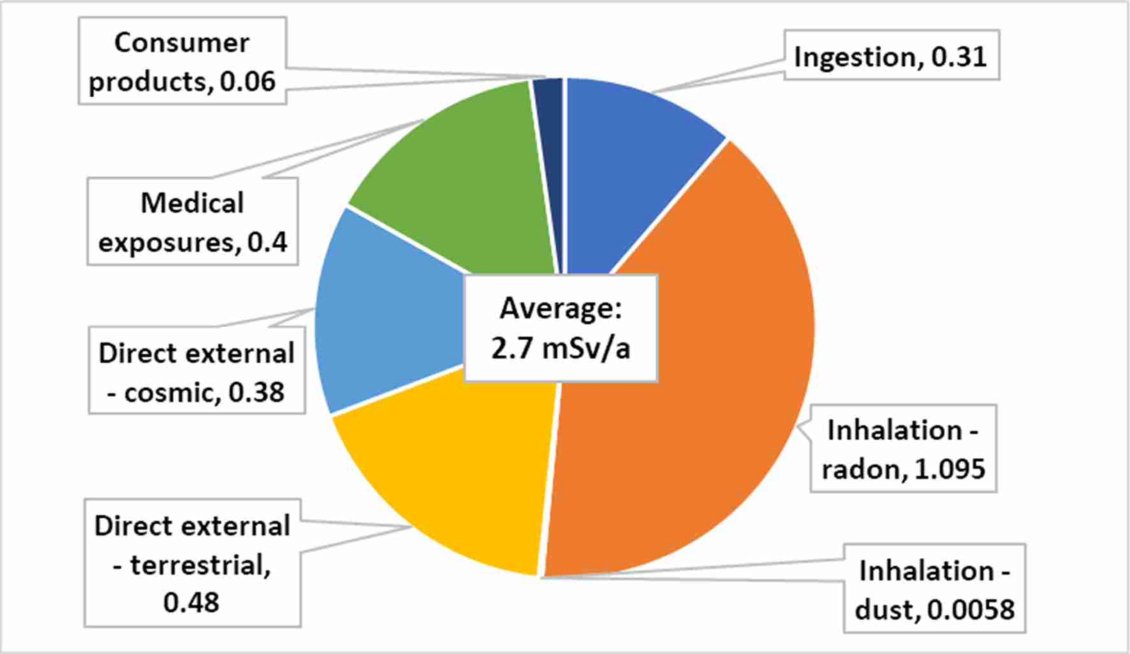
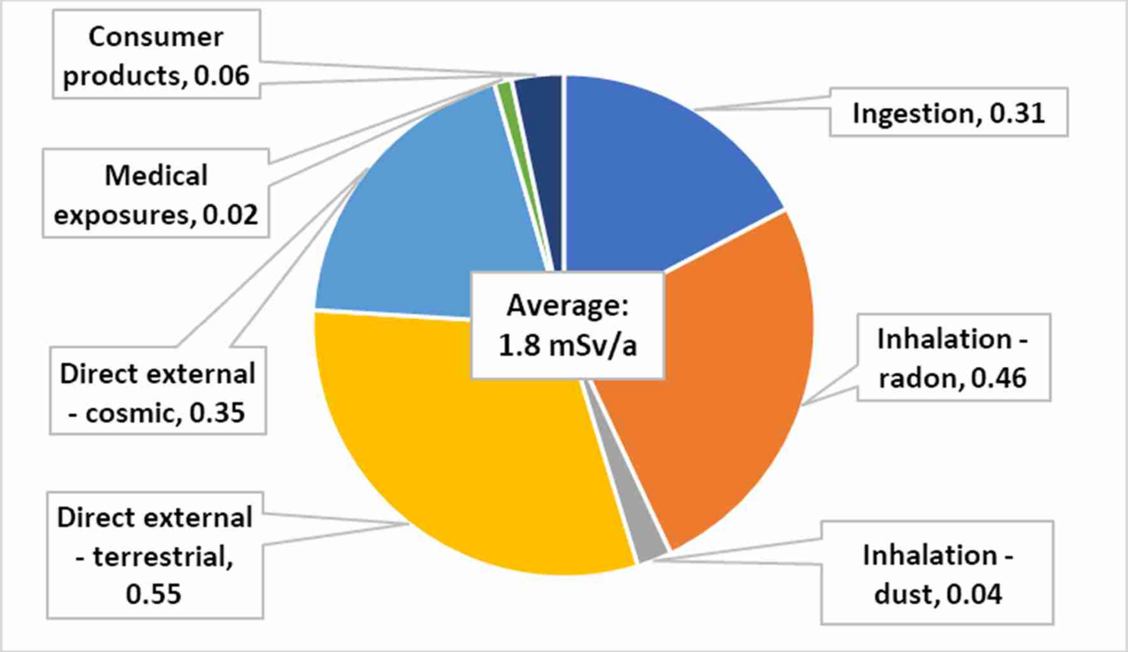


Figure 105: Population-weighted background exposure dose, Erongo Region, in mSv/a [8]



9.6 Exposure Dose Limits

Exposure dose limits are suggested by the International Atomic Energy Agency (IAEA) [1], and are based on the recommendations of the International Commission for Radiation Protection (ICRP).

The Namibian exposure dose limits for persons who are occupationally exposed to ionising radiation, and for members of the public, are laid down in the Regulations under the Atomic Energy and Radiation Protection Act, Act 5 of 2005, refer to [3].

For easy reference, the IAEA's occupational exposure dose limits are provided in Box 20, and the corresponding Namibian limits are summarised in Box 21. The corresponding public dose limits as put forward by the IAEA are summarised in Box 22, while Box 23 shows the public dose limits as apply in Namibia.

Box 20: Occupational exposure dose limits as suggested by the IAEA [1]

For occupationally exposed persons above the age of 18 years, the exposure to ionising radiation is subject to the following limits:

a) an effective dose of 20 mSv/a, averaged over five consecutive years (i.e. 100 mSv in 5 years), with a maximum of 50 mSv in any single year;
b) an equivalent dose to the lens of the eye of 20 mSv/a, averaged over five consecutive years (i.e. 100 mSv in 5 years), with a maximum of 50 mSv in any single year; and
c) an equivalent dose to the extremities (e.g. hands and feet) or to the skin of 500 mSv/a.

It is of note that the dose limit for the lens of the eye as referred to in Box 20, paragraph (b), has recently been changed, from the previous dose limit of 150 mSv/a, to 20 mSv/a. This change is not yet part of the Regulations as they apply in Namibia [2], refer to Box 21. The IAEA's amendment came in light of observations by the ICRP, recognising that the lens of the eye is significantly more sensitive to radiation damage than had previously been thought to be the case.

Box 21: Namibian occupational exposure dose limits for adult workers [3]

The occupational exposure of any (adult) worker must be so controlled that the following limits are not exceeded –

a) an effective dose of 20 mSv per year averaged over five consecutive years;
b) an effective dose of 50 mSv in any single year;
c) an equivalent dose to the lens of the eye of 150 mSv in a year; and
d) an equivalent dose to the extremities (hands and feet) or the skin of 500 mSv in a year.

Box 22: Public exposure dose limits as suggested by the IAEA [1]

For public exposure to ionising radiation, the exposure dose limits are:

a) an effective dose of 1 mSv/a;
b) under special circumstances, a higher value of effective dose in a single year could apply, provided that the average effective dose over 5 consecutive years does not exceed 1 mSv/a;
c) an equivalent dose to the lens of the eye of 15 mSv/a; and
d) an equivalent dose to the skin of 50 mSv/a.

Box 23: Namibian public exposure dose limits [3]

The estimated average doses to the relevant critical groups of members of the public

that are attributable to practices may not exceed the following limits –

a) an effective dose of 1 mSv in a year:
Provided that in special circumstances, an effective dose of up to 5 mSv in a single year may be approved:
Provided further that the average dose over five consecutive years does not exceed 1 mSv per year;
b) an equivalent dose to the lens of the eye of 15 mSv in a year; and
c) an equivalent dose to the skin of 50 mSv in a year.

For the public exposure dose limits, as summarised in Box 22 and Box 23, the IAEA's recent changes entail the adjustment of the dose limit to the lens of the eye, from the previous value of 50 mSv/a, to 15 mSv/a. In this case, the Namibian Regulations reflect the updated dose limit [2], as illustrated in Box 23.

For the mineral exploration and mining sectors, applicable exposure dose limits always relate to effective whole-body doses. Given the above, the dose limits as specified for the lens of the eye are not relevant for typical exposure situations as they occur in the exploration, mining, milling, and processing of radioactive minerals, for example when producing uranium, thorium, or some rare earth minerals.

For penetrating radiation, i.e. exposures to X-rays and gamma rays, it is always assumed that the whole body is uniformly irradiated, unless explicitly stated otherwise.

As for internal doses, the dose calculations described in this book refer to whole-body exposures unless explicitly indicated, and thus not limited to specific organs.

9.7 Occupational Radiation Exposure Doses

Occupational exposure to ionising radiation is the exposure of people resulting from the work they do.

While people at work are also exposed to natural background radiation, it was shown in section 9.5 that exact values for local natural background radiation are usually not accurately quantified, and vary significantly from one location to the next. As a result, occupational radiation exposure doses often include the contribution of natural background radiation.

If occupational exposure doses are to exclude the background contribution, a sensible proxy for the prevailing natural background exposure must be identified and is subtracted from occupational doses. This is sometimes challenging, as the background radiation field is both time- and location-dependant and may lead to occupational exposure doses that are lower than the average value used for the natural background in the area.

While the exact number of working hours per year depends on a company's leave policy, attendance on site as well as personal behaviours, it is good practice to assume that the entire workforce is at work for the same number of hours in the year. In this way, occupational exposure doses for individuals are comparable to one another, both within a specific workplace, and amongst different practices.

As per the recommendation by the ICRP, it is often assumed that the annual number of total working hours amount to 2 000 hours per year, unless special considerations apply [45]. It is emphasised that, when the exposure dose due to the natural background radiation field is included in the occupational exposure dose, it only applies to exposures incurred during working hours, and not for the entire year.

Typical occupational exposure doses, for example in an open pit uranium mining setting in a dry climate, such as at Rio Tinto's Rössing Uranium Mine in Namibia, range from background radiation doses to some 6 mSv/a, provided that the working environment benefits from suitable engineering and administrative controls, and that the use of relevant PPE is compulsory.

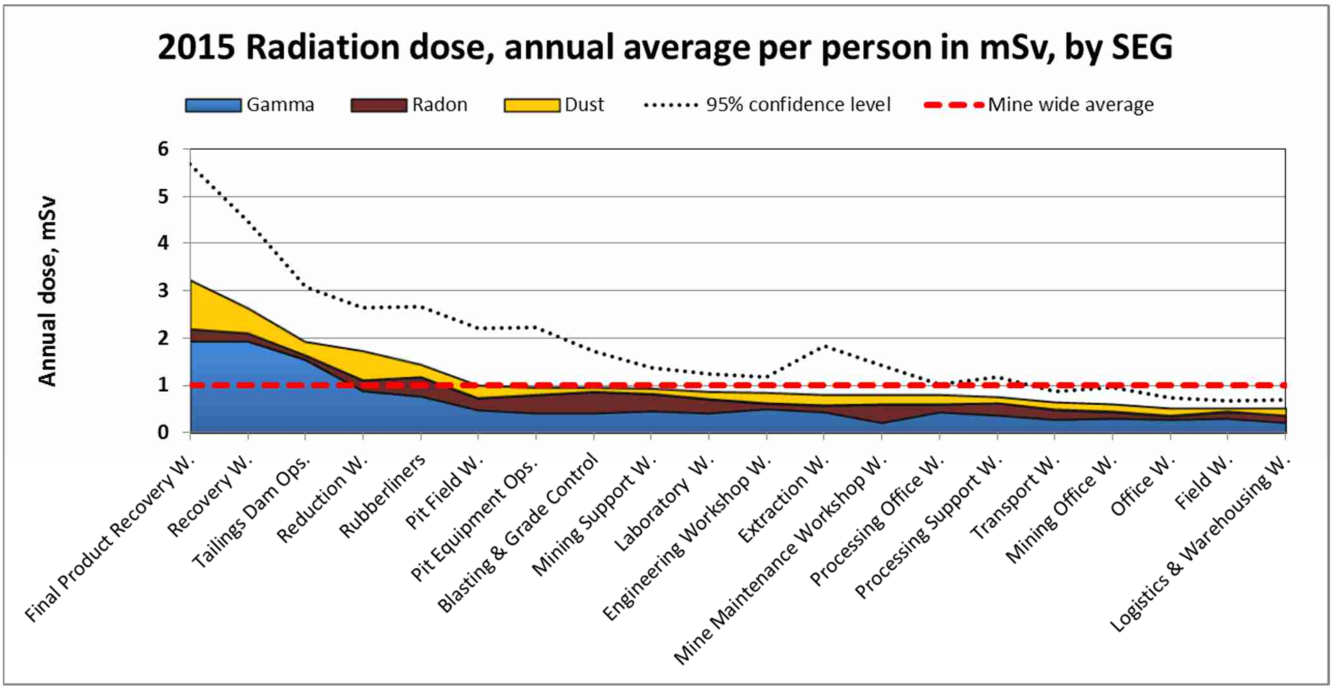
The average occupational exposure dose profile of key exposure groups at the Rössing Mine is shown in Figure 106, and includes the contribution of natural background radiation incurred during 2 000 working hours per year.

Figure 106 includes three distinct exposure pathways, namely direct external gamma radiation, as well as the internal dose contributions from the inhalation of dust and radon. The fourth exposure pathway, i.e.

ingestion, is not included, as it is controlled by exclusion.

Although the occupational exposure doses depicted in Figure 106 are much lower than the annual national exposure dose limit of 20 mSv/a, it can readily happen that much higher exposure doses are incurred in similar operations. For example, dose limits are readily exceeded when effective controls are not in place, or are not enforced, or monitoring is not sufficiently pro-active to indicate where exceedances are likely to occur.

Figure 106: Average occupational radiation dose by similar exposure group, Rössing 2015 [122]



Examples where high dose rates can readily occur in a uranium mining operation include the following scenarios:

- **Inhalation of uranium concentrate dust:** when uranium oxide or yellowcake dust is not controlled by way of effective engineering controls, and/or when relevant and appropriate respiratory protection is not available, or is not used, frequent exceedances are likely;
- **Ingestion of contaminated food:** when this contributing factor is not controlled by way of administrative and engineering controls, and strictly enforced through the application of hygiene measures, repeated exceedances are likely;
- **Direct exposure to gamma radiation:** for example, from sealed radioactive sources, when not controlled, locked out and regularly leak-tested, render exceedances likely;
- **Direct exposure to gamma radiation:** when workers are active in areas that are prone to high gamma radiation for extended periods, such as in tanks containing radioactive scales, handling drums containing uranium concentrate, and packing containers with such product, frequent exceedances are likely; and
- **Inhalation of radon progeny**, as may occur in confined spaces, and those which are not ventilated, such as containers, bunkers, and underground areas where radium-bearing material is stored, exceedance may readily occur.

9.8 Exposure Controls – The Basics

Radiation protection is – to a large extent – about establishing rules that ensure that exposures can be kept *as low as reasonably achievable*, i.e. *ALARA*, while remaining justified, and below the dose limits as are specified by the relevant national regulatory authority.

One of the fundamental controls to limit exposure doses in all exposure situations is the so-called *time-distance-shielding rule*, as is further elaborated below.

9.8.1 Limiting the Exposure Time

Exposure to radiation, such as for example the direct external exposure to X-rays or gamma radiation, can be limited by keeping the time spent at/near the radiation source(s) to a minimum.

The exposure dose resulting from the exposure to radiation is proportional to the time spent at or near the radiation source, which is expressed by the following mathematical relationship:

$$\boldsymbol{Exposure\ dose = time \cdot dose\ rate},$$

One therefore reduces the exposure dose by minimising the time spent in an area that is characterised by a given (possibly high) dose rate. The effect of limiting exposure times is illustrated in Box 24.

9.8.2 Maximising the Distance to a Source

If the radiation source is a 'point source', i.e. is small compared to the area that is being irradiated, then radiation from the source is emitted spherically outwards, as shown in Figure 107. The radiation intensity is therefore distributed over the surface of a sphere that is moving outwards. Mathematically, this relationship is described as:

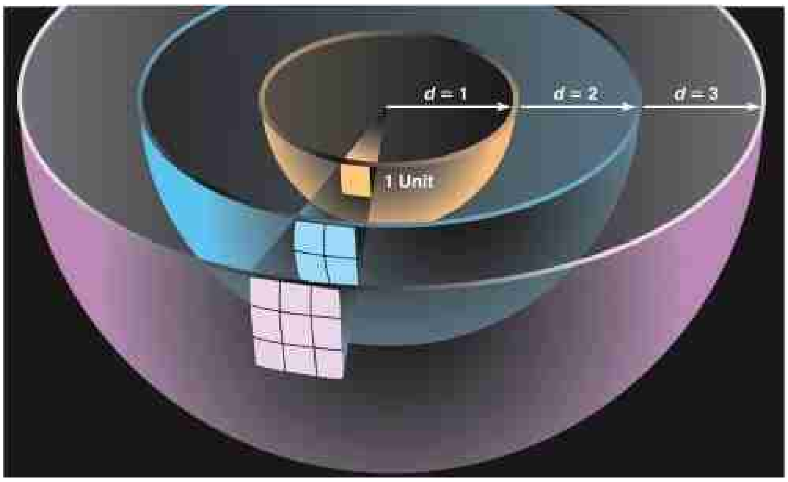
$$\boldsymbol{I_1 d_1^2 = I_2 d_2^2},$$

where $\boldsymbol{I}$ is the radiation intensity, or dose rate, at a distance $\boldsymbol{d}$ from the source, as illustrated in Box 25.

This rule is the *inverse square law, and* implies that if the distance to a source of ionising radiation is doubled, the corresponding exposure is reduced by a factor of 4.

It is important to note that the above rule is less reliable in cases where the distance between source and exposure position is small when compared to the size of the source.

Figure 107: Radiation from a point source [123]



If a radiation source is spread out, and resembles a line rather than a point source, the inverse square law does not hold, and the mathematical relationship between the distance and dose rate is linear, i.e.

$$\boldsymbol{I_1 d_1 = I_2 d_2}.$$

This relationship holds for any source that is close to a receptor. A rule of thumb for its applicability states that *"the distance from a 'line source' must not be more than one half the length of the line"*.

Box 24: Exposure control by limiting the exposure time

A simple method to comply with a specific exposure dose limit is to impose maximum dose levels, or dose reference values, and is illustrated in the following example:

If a specific work area has an average dose rate of 20 µSv/h, how long could radiation workers remain in such a work environment without exceeding an exposure dose limit of 20 mSv/a. in this case, it is assumed that a typical year has 2 000 working hours, which are spent in units of 8 working hours per day.

The exposure dose is calculated as the product of time and dose rate, i.e.

$$\textbf{Exposure dose} = \textbf{time} \cdot \textbf{dose rate.}$$

This relationship is re-written to obtain an expression for the exposure time, i.e.

$$\textbf{time} = \frac{\textbf{Exposure dose}}{\textbf{dose rate}}.$$

This equation is now used to compute the maximum time that one can spend in a work environment if the maximum exposure dose is 20 mSv/a, i.e.

$$\textbf{time} = \frac{\textbf{20 mSv/a}}{\textbf{20 µSv/h}} = \frac{\textbf{20 000 µSv/a}}{\textbf{20 µSv/h}} = \textbf{1 000 h/a.}$$

Often, it is more useful to have a daily exposure limit, rather than one for an entire year. This can be calculated from the above, realising that one can work for one half of the total working time per year, i.e. ½ · 2 000 h/a = 1 000 h/a in a radiation field of 20 µSv/h without exceeding the annual dose limit of 20 mSv/a.

Per day, this implies that one can work ½ · 8 h/d = 4 h/d in such an exposure situation without exceeding the annual dose limit. This implies that a maximum daily dose is computed as follows:

$$\textbf{Exposure dose} = \textbf{time} \cdot \textbf{dose rate} = \textbf{4 h/d} \cdot \textbf{20 µSv/h} = \textbf{80 µSv/d.}$$

Box 25: Exposure control by maximising the distance to a radiation source – X-ray NDT

A simple method to comply with a specific exposure dose limit is to impose distance limitations.

If an X-ray machine used for non-destructive testing (NDT) has a dose rate of 3 mSv/a at one (1) metres from the machine, at what minimum distance would an operator have to be to ensure that the dose rate never exceeds 10 μSv/h?

Using the inverse square law

$$\boldsymbol{I_1 d_1^2 = I_2 d_2^2},$$

where I_1 = 3 mSv/h = 3 000 μSv/h, d_1 = 1 m, and I_2 = 10 μSv/h, one computes d_2, using

$$\boldsymbol{d_2 = \sqrt{\frac{I_1 \cdot d_1^2}{I_2}} = \sqrt{\frac{3\,000 \cdot 1}{10}} = 17.3\ \mathrm{m}.}$$

If, instead of a dose rate of 10 μSv/h (which implies a dose of 20 mSv/a when the exposure to such a dose rate occurs over a work year of 2 000 h/a), one would wish to limit the maximum dose to 10 mSv/a, which implies a maximum dose rate of 10 mSv/a in 2 000 hours/a = 10 000 μSv/a / 2 000 h/a = 5 μSv/h, one would find the minimum distance to the X-ray source as

$$\boldsymbol{d_2 = \sqrt{\frac{I_1 \cdot d_1^2}{I_2}} = \sqrt{\frac{3\,000 \cdot 1}{5}} = 24.5\ \mathrm{m}.}$$

Box 26: Exposure control by maximising the distance to a uranium concentrate source

A quick method to compute maximum dose rates is to assume that the radiation source is a point source.

At one metre from a fully-packed container of uranium concentrate drums one measures a dose rate of 30 μSv/h. If the maximum allowable dose rate for permanent workplace occupation is 1 μSv/h, determine the minimum distance that persons working close to such containers must keep.

Using the inverse square law

$$\boldsymbol{I_1 d_1^2 = I_2 d_2^2},$$

where I_1 = 30 μSv/h, d_1 = 1 m, and I_2 = 1 μSv/h, one computes d_2, using

$$\boldsymbol{d_2 = \sqrt{\frac{I_1 \cdot d_1^2}{I_2}} = \sqrt{\frac{30 \cdot 1}{1}} = 5.5\ \mathrm{m}.}$$

Box 27: Exposure control by maximising the distance to a linear radiation source

A train with 30 containers of uranium oxide needs to be parked overnight at a station. The dose rate was measured at one metre from the train, and was found to be 60 µSv/h. Calculate the minimum distance required to ensure the total dose for a 20-hour period during which the train is to be parked at the station does not exceed the 'trivial' dose of 10 µSv.

One will first have to compute the dose rate associated with an exposure dose of 10 µSv when such a dose is incurred over a period of 20 hours. Using the relationship between exposure time and dose rate, i.e.

$$\textbf{Exposure dose} = \textbf{time} \cdot \textbf{dose rate},$$

one computes the dose rate, i.e.

$$\textbf{dose rate} = \frac{10}{20} = 0.5\ \mu\text{Sv/h}.$$

As the train is packed with 30 containers, and therefore forms a 'line source' rather than a point source, one uses the linear relationship between dose rate and distance, i.e.

$$I_1 d_1 = I_2 d_2, \text{ which implies that}$$

$$d_2 = \frac{I_1 d_1}{I_2} = \frac{60 \cdot 1}{0.5} = 120\ \text{m}.$$

9.9 Using Appropriate Radiation Shielding

Materials absorb radiation. The denser such materials are, the better they absorb the energy of, for example, X-rays and gamma radiation. This does, however, not apply to neutrons, which must be kept in mind.

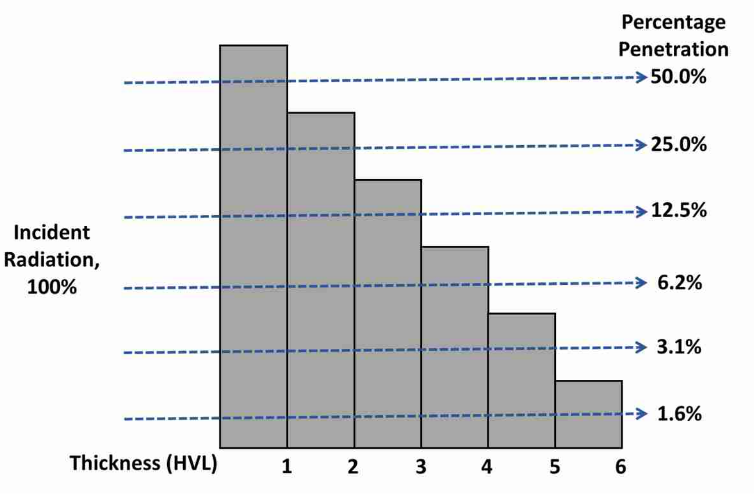
The absorptive properties of various materials are used when determining whether and how effective they are in providing protective shielding from ionising radiation. Shielding materials have a high density, and therefore include concrete, lead, and steel, and in some special applications, depleted uranium.

Each such material has material-specific shielding properties, which are expressed in terms of the material's *half-value layer* (HVL), or *tenth-value layer*.

The half-value layer is that thickness (layer) of material which reduces the intensity of gamma radiation or X-rays by one half. The application of successive half-value layers is used to determine the thickness of material needed to reduce radiation intensities to the required level.

To illustrate: one half-value layer reduces the radiation intensity by 50%, two half-value layers reduce the intensity to 25%, three half-value layers to 12.5%, and so on, as depicted in Figure 108.

Figure 108: Half-value layer [8]



Half-value layers depend on the energy of the incident radiation. This implies that the half-value layer of a specific material that blocks 50% of radiation from a Co-60 source is different than that for an Ir-192 source.

Table 17 illustrates these for a variety of shielding materials that are used in practice. Table 18 provides half-value layers for concrete and lead when using X-ray sources, e.g. those employed for non-destructive testing purposes.

Table 17: Half-value layers for common shielding materials with Ir-192 and Co-60, in mm [124]

Source	**Half-value layer [mm]**				
	Concrete	**Steel**	**Lead**	**Tungsten**	**Uranium**
Iridium-192	44.5	12.7	4.8	3.3	2.8
Cobalt-60	60.5	21.6	12.5	7.9	6.9

Table 18: Half-value layers for concrete and lead using X-ray sources, in mm [124]

Peak Voltage (kV_p)	**Half-value layers [mm]**	
	Concrete	**Lead**
50	4.3	0.06
100	15.1	0.27
150	22.3	0.30
200	25.0	0.52
250	28.0	0.88
300	31.2	1.47
400	33.0	2.5
1 000	44.4	7.9

Box 28: Bunker thickness for a C-60 source using the half-value layer design approach

A bunker for the storage of radioactive sealed Co-60 sources is to be built from concrete.

The design specifications stipulate that the radiation level of a leaking Co-60 source, which is assumed to have a dose rate of 0.1 mSv/h when measured within the bunker, is to be reduced to a maximum dose rate of 1 µSv/h when measured at any point on the outside of the bunker.

To determine the half-value layer, one realises that the percentage reduction that is required is 1%, i.e. radiation levels outside the bunker must not exceed 1% of the radiation levels within the bunker. The number of HVLs is computed as follows:

Number of HVLs = – log(% reduction) / log(2) = – log(1%) / log(2) = – log(0.01) / log(2) = 6.6 ≈ 7.

The above answer implies that, to achieve the desired reduction of the radiation intensity of a Co-60 source, some seven (7) HVLs of concrete are required. This implies a minimum wall thickness of 7 x 60.5 mm = 423.5 mm, i.e. approx. 43 cm, using the HLVs specified in Table 17.

Box 29: Lead shielding for X-ray sources using the half-layer approach

A 250 kV_p and a 400 kV_p X-ray source are used for non-destructive testing purposes. They are to be shielded using lead blankets, to reduce the dose rate from 3 mSv/h to 10 µSv/h, when measured at one metre from these sources.

The percentage reduction is 10 / 3 000 = 0.33%. Using the formula for the number of half-value layers used in Box 28, the following is computed:

Number of HVLs = – log(% reduction) / log(2) = – log(0.33%) / log(2) = 8.2 ≈ 9.

This result implies that almost nine HLVs of lead are required to achieve the desired shielding. For the 250 kV_p X-ray machine, some 9 x 0.88 mm ≈ 8 mm lead shielding is required, using the HLVs for lead as per Table 18.

For the 400 kV_p X-ray source, some 9 x 2.5 mm = 25.5 mm ≈ 2.6 cm of lead shielding are required, using the HLVs for lead for X-ray source operated at 400 kV_p, as listed in Table 18.

9.10 Exercises

9.10.1 Occupational Exposure Doses

1. Select the correct answer(s) for the following setting: in an occupational setting, such as a uranium mine, gamma radiation
    a) is mostly of external origin and contributes significantly to the occupational exposure dose;
    b) does not have to be monitored because it is a long-range form of radiation;
    c) due to the natural background radiation field is the most dominant contributor of occupational exposure doses;
    d) is always the smallest contributor to occupational exposure doses.

2. Select the correct answer(s) for the following setting: in an occupational setting at a uranium mine, alpha radiation
    a) can be safely ignored as there are no sources of alpha radiation;
    b) from long-lived radioactive dust may be a significant risk factor when such dust is inhaled;
    c) does not have to be monitored because it is a short-range form of radiation and is non-penetrative;
    d) is only contributed by radon and its decay products.

3. Select the correct answer(s) for the following setting: in an occupational setting at a uranium mine, radon progeny
    a) is always the most significant risk factor for occupational exposures;
    b) can be safely ignored as radon is a noble gas and does not readily interact with lung tissue;
    c) may be a significant risk factor, for example in poorly ventilated areas;
    d) is readily mitigated by creating a dusty work environment, as radon progeny attaches itself onto the inhalable fraction of airborne dust.

4. Tailings material from gold mining operations has the consistency of fine sand – and may be thought of as being ideal for building purposes. For tailings materials having a uranium content of 300 ppm, and as the operation's RSO, select the answer(s) that correctly identifies what your decision regarding the use of tailings materials for building purposes is:
    a) allow the use of tailings for the construction of a new on-site visitor centre;
    b) allow the use of tailings for the maintenance of roads in the mining area;
    c) allow tailings material to be used to maintain the parking area outside the official mining area;
    d) allow the local community to use tailings to build roads, and thereby reduce road construction costs.

9.10.2 Radiation Risk Estimates

1. Fukushima has a population of some 2 million people. If the total average committed dose per person due to the nuclear incident was 20 mSv, estimate the number of excess adverse health cases (mostly cancers) arising from the accident, if all persons in the above group are adults.

2. Some 2.3 million people live in Namibia, and the country's average natural background radiation amounts to some 2 mSv/a. Calculate the number of annual excess cancers due to the exposure to such background radiation, if all persons in the cohort are adults.

3. The Golden Tomorrow gold mine has a workforce of 2 000 people, including contractors. The operation recovers gold from an ore body containing both uranium and thorium, resulting in a weighted average dose of 1 mSv/a per person. The life of mine is expected to be 50 years. If operating conditions are maintained, estimate the number of workers that may get cancer because of their work during the life of the mine.

9.10.3 Point Source

The exposure dose rate some 2 metres from a sealed radioactive source which emits gamma radiation is found to be 10 µSv/h. How far does one have to be from the source for the dose rate to be reduced by a factor 10, i.e. a dose rate of 1 µSv/h?

9.10.4 Shielding

Calculate the thickness of a concrete wall that is to reduce the intensity of a cobalt-60 source to 6.2% of its original intensity. Assume that the HVL for concrete that is irradiated by Co-60 corresponds to 60 mm.

10 Calculating Exposure Doses

This Chapter provides the tools to quantify exposure doses from exposure to ionising radiation.

10.1 Exposure to Direct External Radiation

To determine the exposure dose resulting from exposure to direct external radiation, such as gamma radiation or radiation from an X-ray source, one measures the dose rate (or determines it from technical specifications provided) and averages this rate over an appropriate period, thereafter multiplying the dose rate by the relevant time over which the exposure occurred.

The annual exposure dose is obtained by extrapolation to a full work year, which usually extends over some 2 000 working hours, or 8 760 hours, i.e. the total hours in a year.

Mathematically, the exposure dose is the product of the dose rate and exposure period, i.e. the dose rate is multiplied by the exposure period as shown below:

$$\boldsymbol{Dose}_{\mathbf{direct\ external\ radiation}}(\mathrm{mSv/a}) = \mathbf{dose\ rate}\ (\mathrm{mSv/h}) \cdot \mathbf{exposure\ time}\ (\mathrm{h/a}).$$

where,

$\boldsymbol{Dose}_{\mathbf{direct\ external\ radiation}}$ is the dose resulting from exposure to direct external radiation, in mSv/a;

$\mathbf{dose\ rate}$ is the dose rate, in mSv/h; and

$\mathbf{exposure\ time}$ is the exposure time, in h/a.

Box 30: Computing the annual average gamma exposure dose

An employee exposure dose monitoring program has established that the average gamma dose rate in the operation's extraction area is 3 µSv/h. Compute the average annual exposure dose of persons working in this work area.

Using the formula expressing the mathematical relationship between the exposure dose as a function of the dose rate and exposure period, i.e.

$$Dose_{\gamma}(\mathrm{mSv/a}) = \mathrm{dose\ rate}\ (\mathrm{mSv/h}) \cdot \mathrm{exposure\ time}\ (\mathrm{h/a}),$$

one determines the annual average gamma exposure dose as follows:

$$Dose_{\gamma}(\mathrm{mSv/a}) = 3\ (\mathrm{\mu Sv/h}) \cdot 2\ 000\ (h/\mathrm{a}) = 6\ 000\ \mathrm{\mu Sv/a} = 6\ \mathrm{mSv/a}.$$

Box 31: Computing the annual average dose from the exposure to an NDT X-ray machine

A company uses an X-ray machine for the non-destructive testing (NDT) of welding seams. The minimum safety distance between the location of the source and the position to where staff retreat to when doing the NDT work is 25 metres, and the average dose rate attributable to X-rays at this distance from the source is 5 µSv/h. If the X-ray machine is operated for 500 hours per year, determine the average annual exposure dose due to such exposures.

Using the above formula for the exposure dose, the annual X-ray exposure dose is computed as:

$$Dose_{X-ray}(\mathrm{mSv/a}) = 5\ (\mathrm{\mu Sv/h}) \cdot 500\ (h/\mathrm{a}) = 2\ 500\ \mathrm{\mu Sv/a} = 2.5\ \mathrm{mSv/a}.$$

10.2 Exposure to Long-Lived Radioactive Dust

The exposure dose resulting from the inhalation of long-lived radioactive dust depends on the following quantities:

1. the particulate concentration in the air which is inhaled;
2. the (radio-)activity of the inhaled dust;
3. the breathing rate at which the dust-laden air is inhaled; and
4. the period over which such an exposure took place.

In considering the inhalation from airborne dust it is important to note that only the dust fraction that contains the inhalable fraction of the inhaled dust is considered. Dust containing particles which are larger than the inhalable fraction is unable to penetrate sufficiently deep into the airways and lungs to cause a significant radiation dose. For this purpose, one usually considers the exposure to the PM_{10} portion of the inhaled dust, as this portion contains most of the inhalable fraction of the dust in air.

Mathematically, the effective exposure dose due to the inhalation of radioactive dust in air is computed as follows:

$$\boldsymbol{Dose_{LLRD}}(\mathrm{mSv/a}) = \boldsymbol{Conc_{LLRD}}(\mathrm{Bq/m^3}) \cdot \boldsymbol{t}(\mathrm{h/a}) \cdot \boldsymbol{BR}\,(\mathrm{m^3/h}) \cdot \boldsymbol{DCF_{LLRD}}(\mathrm{mSv/Bq})$$

where,

$\boldsymbol{Dose_{LLRD}}$ is the inhalation dose, in mSv/a;

$\boldsymbol{Conc_{LLRD}}$ is activity concentration of the dust in air, in Bq/m^3;

$\boldsymbol{t}$ is the exposure time, in h/a, which is typically assumed to be 2 000 h/a for workers or 8 760 h/a for members of the public;

$\boldsymbol{BR}$ is the breathing rate at which airborne dust is inhaled, which is taken to be 1.2 m^3/h for workers, and 0.9 m^3/h for adult members of the public; and

$\boldsymbol{DCF_{LLRD}}$ is the dose conversion coefficient which is specific to the inhaled dust, in mSv/Bq.

To determine the DCF_{LLRD} one needs to know the activity of all radionuclides in the dust. Often, this is not known to any degree of certainty, although it can be determined using a radionuclide composition analysis. In some cases, a simplification is possible, for example when it can be assumed that all radionuclides from a given decay chain are in secular equilibrium. Although this is often an oversimplification, it nevertheless provides a useful order of magnitude estimate of the dose conversion coefficient.

The calculation of the dose conversion coefficient (DCF) for uranium-bearing ore dust is shown in Table 19 below, as per the IAEA safety guide for uranium mining [125].

The DCF for uranium ore is based on the following assumptions:

- the inhaled uranium ore dust is in full secular equilibrium;
- the members of the U-238 and U-235 decay chains occur in the ratio of their specific activities in natural uranium, i.e. 580 / 12 350 ≈ 0.046, as per Table 4;
- the particle sizes of the inhaled dust have the default AMAD of 5 μm; and
- the chemical form of each radionuclide contained in the inhaled dust corresponds to the slowest lung absorption class as per the IAEA Safety Standards [1].

The calculation of the DCF for uranium ore, using the above assumptions, involves the identification of all radionuclides from both the uranium and actinium series, and considering the dose conversion coefficients for the radionuclides, and computing the dose per g inhaled, as illustrated in Table 19.

Table 19: Dose conversion coefficient of uranium ore dust [125]

Decay chain	Radio-nuclide	Slowest lung absorption (solubility) class	Emitter type	Inhalation dose coefficient [µSv/Bq]	Specific alpha activity [Bq]	Specific beta activity [Bq]	Exposure dose [µSv]
Uranium decay chain	U-238	S	α	5.7	1		5.7
	Th-234	S	β	$5.8 \cdot 10^{-3}$		1	$5.8 \cdot 10^{-3}$
	Pa-234m	–	β	–		1	–
	U-234	S	α	6.8	1		6.8
	Th-230	S	α	7.2	1		7.2
	Ra-226	M	α	2.2	1		2.2
	Rn-222	–	α	–	1		–
	Po-218	–	α	–	1		–
	Pb-214	F	β	$4.8 \cdot 10^{-3}$		1	$4.8 \cdot 10^{-3}$
	Bi-214	M	β	$2.1 \cdot 10^{-2}$		1	$2.1 \cdot 10^{-2}$
	Po-214	–	α	–	1		–
	Pb-210	F	β	1.1		1	1.1
	Bi-210	M	β	$6.0 \cdot 10^{-2}$		1	$6.0 \cdot 10^{-2}$
	Po-210	M	α	2.2	1		2.2
Actinium decay chain	U-235	S	α	6.1	0.046		0.28
	Th-231	S	β	$4.0 \cdot 10^{-4}$		0.046	$1.8 \cdot 10^{-5}$
	Pa-231	S	α	17	0.046		0.78
	Ac-227	S	β	47		0.046	2.2
	Th-227	S	α	7.6	0.046		0.35
	Ra-223	M	α	5.7	0.046		0.26
	Rn-219	–	α	–	0.046		–
	Po-215	–	α	–	0.046		–
	Pb-211	F	β	$5.6 \cdot 10^{-3}$		0.046	$2.6 \cdot 10^{-4}$
	Bi-211	–	α	–	0.046		–
	Tl-207	–	β	–		0.046	–
				Gross activity (Bq)	$\mathbf{8.3}$	$\mathbf{6.2}$	
						Total inhalation dose	$\mathbf{29.1}$ **µSv**

Table 19 shows that – if the ore is in full secular equilibrium – it has an alpha activity of 8.3 Bq, and a beta activity of 6.2 Bq for every Bq of U-238 activity. Radionuclide-specific dose coefficients are sourced from the IAEA Safety Standards [1].

This implies that the total activity of uranium ore in secular equilibrium is 8.3 + 6.2 = 14.5 Bq for every Bq of U-238. Based on this, **the total inhalation dose resulting from breathing in uranium ore of an activity of 1 Bq from uranium ore is 29.1 µSv.**

Table 19 reveals that not all radionuclides contribute equally to the total inhalation dose. The radionuclides which contribute significantly to the dose include the following:

- **Uranium chain:**
    - alpha emitters U-238, U-234, Th-230, Ra-226 and Po-210 and
    - beta emitter Pb-210

- **Actinium chain:**
    - alpha emitters U-235, Pa-231, Th-227 and Ra-223 and
    - beta emitter Ac-227.

In the **thorium chain**, which is not included in the calculations shown in Table 19, the significant radionuclides are the

- alpha emitters Th-232, Th-228 and Ra-224.

Usually, for uranium-bearing ores, one only measures the alpha activity, i.e. the measurement quantifies the number of alpha decays of the sample. This implies that a weighted coefficient that translates the alpha counts into an exposure dose is needed, and a corresponding coefficient that translates the beta counts into a dose.

This leads to the *committed dose per unit of alpha activity intake*, which is:

$$DCF_{LLRD,\alpha} = \frac{\mathbf{29.1\ \mu Sv}}{\mathbf{8.3\ Bq_\alpha}} = \mathbf{3.5\ \mu Sv/Bq_\alpha}$$

Similarly, the *committed dose per unit of beta activity intake* is determined by:

$$DCF_{LLRD,\beta} = \frac{\mathbf{29.1\ \mu Sv}}{\mathbf{6.2\ Bq_\beta}} = \mathbf{4.7\ \mu Sv/Bq_\beta}$$

In practice, the beta activity is difficult to quantify accurately, as most counting instruments do not reliably distinguish between beta and gamma counts. Therefore, the weighted dose conversion coefficient for beta activity is not often used.

The dose conversion coefficient mostly used when computing the inhalation dose from a radioactive mix of alpha and beta emitters is the *weighted dose per unit of alpha intake*. In this way, the total internal dose from the inhalation of both alpha and beta emitting radionuclides is obtained from the measurement of the alpha activity only, under the assumption that the radionuclides in the decay chains are in secular equilibrium.

If one deals with a thorium-bearing ore, rather than a uranium-bearing ore, and noting that the specific activity of Th-232 is 4 060 Bq/g, the committed effective dose per unit alpha activity intake of thorium ore is 8 μSv/Bq_α.

It is to be noted that, if the ore contains both uranium and thorium, the thorium decay chain must be added to the calculations as shown in Table 19. Here, the activity ratio (or alternatively the ratio of the weights) of thorium to uranium must be determined, based on empirical evidence, to yield meaningful results.

If the ore is not in secular equilibrium, for example when it must be assumed that a large percentage of radon has escaped from the dust, a radionuclide analysis must be performed, to reveal the activity ratio of the remaining radionuclides that contribute to the radioactivity of the dust.

It is important to note that the radionuclide ratio in PM_{10} dust is often different from that of the ore from which such dust particles originate. Usually, it is safe to assume that secular equilibrium exists in ores, but this is often not the case in dust samples.

Using the same approach as for uranium ore, the dose conversion factor for uranium concentrate dust is computed. It is noticed that uranium concentrate only contains the three uranium isotopes, all of which are alpha emitters. This implies that the calculation is straightforward, as illustrated in Table 20. As before, the radionuclide-specific dose coefficients are from the IAEA Safety Standards [1].

Table 20: Dose conversion coefficient for uranium concentrate of solubility class S [125]

Decay chain	Radio-nuclide	Slowest lung absorption (solubility) class	Emitter type	Inhalation dose coefficient [μSv/Bq]	Specific alpha activity [Bq]	Exposure dose [μSv]
Uranium	U-238	S	α	5.7	1	5.7
	U-234	S	α	6.8	1	6.8
Actinium	U-235	S	α	6.1	0.046	0.28
				Gross activity (Bq)	**2.046**	
					Total dose (μSv)	**12.78**

The weighted dose conversion coefficient for uranium concentrate of solubility (lung absorption) class S per unit of alpha intake is given by

$$DCF_{LLRD,\alpha} = \frac{\mathbf{12.78\ \mu Sv}}{\mathbf{2.05\ Bq_{\alpha}}} = \mathbf{6.2\ \mu Sv/Bq_{\alpha}}$$

Using the same approach as was used to compute the DCF for uranium concentrate dust of solubility class S, the committed effective dose per unit intake of uranium concentrate dust of solubility class M is computed in Table 21.

The weighted dose conversion coefficient for uranium concentrate of solubility class M per unit of alpha intake is given by

$$DCF_{LLRD,\alpha} = \frac{\mathbf{3.78\ \mu Sv}}{\mathbf{2.05\ Bq_{\alpha}}} = \mathbf{1.82\ \mu Sv/Bq_{\alpha}}.$$

Table 21: Dose conversion coefficient of uranium concentrate of solubility class M [125]

Decay chain	Radio-nuclide	Slowest lung absorption (solubility) class	Emitter type	Inhalation dose coefficients [µSv/Bq]	Specific alpha activity [Bq]	Exposure dose [µSv]
Uranium	U-238	M	α	1.6	1	1.6
	U-234	M	α	2.1	1	2.1
Actinium	U-235	M	α	1.8	0.046	0.08
				Gross activity (Bq)	**2.046**	
					Total dose (µSv)	**3.78**

Box 32: Exposure dose from the inhalation of uranium ore dust – Case I

The ore grade of a given uranium mining operation is approx. 300 ppm, which implies that there are 300 parts of uranium for every one million parts of ore. It is known that thorium does not contribute significantly to the activity of the ore as found at the mine under consideration.

The average PM_{10} dust concentration at the mine was measured to be 1 mg/m^3. Based on this information, compute the annual average occupational exposure dose associated with the inhalation of such uranium-bearing ore dust.

As shown in Table 19, natural uranium ore in secular equilibrium has 8.3 alpha emitters. This implies that the alpha activity concentration of 1 mg/m^3 of uranium ore dust with a uranium concentration of 300 ppm is as follows:

$$\mathrm{Conc}_{\mathrm{LLRD},\alpha} = 1\ (\mathrm{mg/m^3}) \cdot \frac{300}{1\,000\,000} \cdot 12\,350\ (\mathrm{Bq/g}) \cdot 8.3 \approx 30.8\ \mathrm{mBq/m^3}$$

At a breathing rate of 1.2 m^3/h, and an occupational exposure time of 2 000 h/a, the committed effective dose resulting from the inhalation of above-mentioned ore dust is found:

$$\mathrm{Dose}_{\mathrm{LLRD}}(\mathrm{mSv/a}) = \mathrm{Conc}_{\mathrm{LLRD},\alpha}(\mathrm{Bq_\alpha/m^3}) \cdot \mathrm{t(h/a)} \cdot \mathrm{BR(m^3/h)} \cdot \mathrm{DCF}_{\mathrm{LLRD},\alpha}(\mathrm{mSv/Bq_\alpha}),$$

Using the dose conversion coefficient for uranium-bearing ore, i.e. $DCF_{LLRD,}$ = 3.5 µSv/Bq, one finds

$$\mathrm{Dose}_{\mathrm{LLRD}}(\mathrm{mSv/a}) = 0.0308(\mathrm{Bq_\alpha/m^3}) \cdot 2\,000\ (\mathrm{h/a}) \cdot 1.2(\mathrm{m^3/h}) \cdot 0.0035\ \mathrm{mSv/Bq_\alpha} = 0.26\ \mathrm{mSv/a}.$$

Box 33: Exposure dose from the inhalation of uranium ore dust – Case II

The radionuclide analysis of PM_{10} dust that was collected at the fine ore crusher at a uranium mine has returned the following activity concentrations as summarised below:

Isotope	Bq/kg
U-238	5 650
Ra-226	3 940
Pb-210	5 460

Isotope	Bq/kg
U-235	260
Ac-227	260

Isotope	Bq/kg
Ra-228	250
Th-228	250

Compute the occupational inhalation dose if the average PM_{10} concentration of the dust amounts to 10 mg/m^3.

As the specific activity of both alpha and beta emitters is provided, the exposure dose is computed without having to resort to a weighted dose conversion coefficient. Using only the radionuclides that contribute significantly, and if the ore is in secular equilibrium (to determine the activity concentration of the radionuclides that are not included in the results of the analysis as summarised in the table above), one has:

Radionuclide	Lung absorption type	Type of emitter	Inhalation dose coefficient [μSv/Bq]	Specific Activity [Bq/kg]	Inhalation dose coefficient [mSv/g]
U-238	S	α	5.7	5 650	3.2
U-234	S	α	6.8	5 650	3.8
Th-230	S	α	7.2	5 650	4.1
Ra-226	M	α	2.2	3 940	0.87
Pb-210	F	β	1.1	5 460	0.6
Po-210	M	α	2.2	5 460	1.2
U-235	S	α	6.1	260	0.16
Pa-231	S	α	17	260	0.44
Ac-227	S	β	47	260	1.2
Th-227	S	α	7.6	260	0.2
Ra-223	M	α	5.7	260	0.15
Th-232	S	α	12	250	0.3
Th-228	S	α	32	250	0.8
Ra-224	M	α	2.4	250	0.06
				Total	**0.17 mSv/g**

In the above table, the radionuclide activities that were measured are highlighted in grey, while the activities of the other radioisotopes which had to be assumed are shown in the cells with a white background. With a breathing rate of 1.2 m^3/h, and 2 000 h/a working time, and keeping in mind that the activity concentration of each radionuclide has already been considered, the committed effective dose is given by

$$\mathrm{Dose_{LLRD}(mSv/a) = Conc_{LLRD}(g/m^3) \cdot t(h/a) \cdot BR\ (m^3/h) \cdot DCF_{LLRD}(mSv/g)},$$

which is used to compute the exposure dose as follows:

$$\mathrm{Dose_{LLRD}(mSv/a) = 10^{-2}(g/m^3) \cdot 2\ 000(h/a) \cdot 1.2(m^3/h) \cdot 0.17(mSv/g) = 4\ mSv/a.}$$

Note: the dose contributions from those radionuclides that are highlighted in white cells must be considered, as ignoring them would significantly underestimate the inhalation dose.

Box 34: Exposure dose from the inhalation of uranium concentrate dust

The average PM_{10} dust concentration in the final product recovery area of a uranium mine was measured to be 1 mg/m^3, and the concentrate has a solubility class S. Compute the annual average occupational exposure dose associated with the inhalation of such dust.

As shown in Table 21, uranium concentrate has some 2.05 alpha emitters. The alpha activity concentration of such dust is

$$\mathrm{Conc}_{\mathrm{LLRD},\alpha} = 1\ (\mathrm{mg/m^3}) \cdot 12\ 350\ (\mathrm{Bq/g}) \cdot 2.05 = 25.32\ \mathrm{Bq/m^3}$$

The committed effective dose, assuming a breathing rate of 1.2 m^3/h, and an exposure time of 2 000 h/a, and using the dose conversion coefficient for uranium concentrate, i.e. $\mathrm{DCF}_{\mathrm{LLRD,}}$ = 6.2 µSv/Bq, one finds

$$\mathrm{Dose}_{\mathrm{LLRD}}(\mathrm{mSv/a}) = 25.32(\mathrm{Bq}_\alpha/\mathrm{m}^3) \cdot 2\ 000\ (\mathrm{h/a}) \cdot 1.2(\mathrm{m^3/h}) \cdot 0.0062\ \mathrm{mSv/Bq}_\alpha \approx 377\ \mathrm{mSv/a}.$$

It is instructive to compare the results of the dose calculation for uranium ore dust with a uranium concentration of 300 ppm, as per Box 32, with that of uranium concentrate of solubility class S, as shown in Box 34. There is a significant difference in the exposure doses resulting from the inhalation of uranium ore dust (0.26 mSv/a) versus that of uranium concentrate dust (377 mSv/a), even though the atmospheric dust concentration, i.e. 1 mg/m^3, is identical in the examples considered.

Box 35: The effect of radon retention on the weighted dose conversion coefficient

The dose conversion coefficient for uranium ore dust was calculated in Table 19, using the assumption that all the radionuclides of the uranium and actinium decay chains are in full secular equilibrium. This assumption implies that there are 8.3 alpha emitters in uranium ore, leading to a weighted dose conversion coefficient per unit alpha intake of

$$\mathrm{DCF}_{\mathrm{LLRD},\alpha} = 29.1\ \mu\mathrm{Sv}\ /\ 8.3\ \mathrm{Bq}_\alpha = 3.5\ \mu\mathrm{Sv/Bq}_\alpha.$$

However, because the alpha emitter Rn-222 is a gas, which readily escapes from dust samples, this radionuclide is seldom in full equilibrium with the other decay chain members. Similarly, the short-lived progeny of Rn-222, i.e. the alpha emitters Po-214 and Po-218, seldom remain in secular equilibrium in ore dust. The longer-lived radionuclide Po-210, on the other hand, usually is in equilibrium with the remainder of the decay chain. A similar argument holds for the relevant members of the actinium chain, i.e. for the alpha emitters Rn-219, Po-215 and Bi-211.

Therefore, when assessing the dust inhalation dose by way of collecting airborne dust on a filter, and analysing the associated alpha activity, the counts obtained include proportionately fewer than 8.3 alpha emitters from the uranium and actinium decay chains. To take the above into account one introduces the so-called **radon retention factor**. Here it is noted that the calculation in Table 19 was made by assuming a radon retention factor of 1, i.e. 100% of the radon remains in the sample. In contrast, when all radon has escaped from the ore sample, the radon retention factor is 0. If this is the case, the number of alpha emitters in the decay chains is 5.2 rather than 8.3, as per Table 19. The corresponding dose conversion coefficient per unit alpha intake changes to

$$\mathrm{DCF}_{\mathrm{LLRD},\alpha} = 29.1\ \mu\mathrm{Sv}\ /\ 5.2\ \mathrm{Bq}_\alpha = 5.6\ \mu\mathrm{Sv/Bq}_\alpha.$$

Often, when assessing a filter containing uranium ore dust, one assumes a radon retention factor of 0.5, i.e. one-half of the radon is retained in the ore sample. In this case, the corresponding dose conversion factor is $4.3\ \mu\mathrm{Sv/Bq}_\alpha$, which is an increase of the dose conversion factor of more than 20% when compared to the DCF corresponding to a radon retention factor of 1.

10.3 Exposure to Radon and Radon Progeny

The inhalation dose from the exposure to radon is mainly due to the presence of the radon decay products (RDP). The first four decay products of radon, as illustrated in Figure 109, are Po-218, Pb-214, Bi-214 and Po-214, and these are short-lived radioisotopes. In contrast, the decay products of Po-214 have a much higher half-life than those of the immediate radon progeny, and therefore do not contribute much to the inhalation dose. The two isotopes of polonium, i.e. Po-218 and Po-214, are alpha emitters and are therefore the main contributors causing the exposure dose associated with the inhalation of radon progeny.

The dose conversion factors (DCF) for radon exposures, DCF_{Rn}, are based on epidemiological analyses, in contrast to the dosimetric evaluations that are often used to determine the DCFs for the inhalation and ingestion of radionuclides. This implies that large populations exposed to radon were studied, to assess and identify the health effects associated with the inhalation of radon decay products. Such studies have provided the foundation of the biological risk due to such exposures.

ICRP Publication 65 provides the DCF_{Rn} for workers, and for members of the public, which are summarised in Table 22 [51]. The difference between the conversion factors for workers and adult members of the public is due to the assumption that workers have a breathing rate of 1.2 m^3/h, while adult members of the public are assumed to have a breathing rate of 0.9 m^3/h.

Figure 109: Radon and its decay products [8]

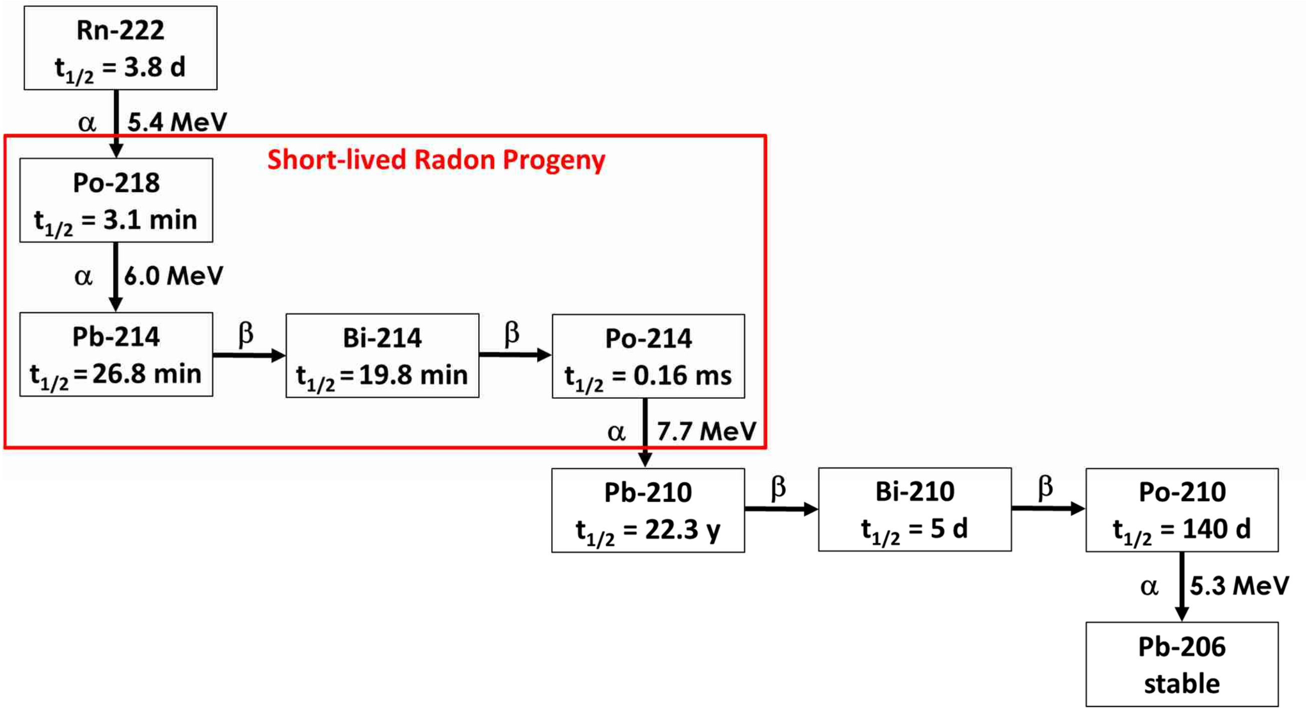


Table 22: Dose conversion factors DCF_{Rn} for radon exposures as per ICRP 65 [51]

	Workers	Adult members of the public
SI units	1.43 mSv per mJ·h/m^3	1.10 mSv per mJ·h/m^3
US units	5.06 mSv per WLM	3.88 mSv per WLM

The inhalation dose resulting from radon, i.e. $Dose_{Rn}$, is the product of the radionuclide uptake, and the dose conversion factor, i.e.

$$\mathrm{Dose_{Rn}(mSv) = Uptake\ (Bq) \cdot DCF_{Rn}(mSv/Bq).}$$

The uptake of radionuclides is determined from the atmospheric radon concentration, $Conc_{Rn}$, the equilibrium factor f, the conversion factor between EEC and PAEC CF_{Rn}, and the exposure time t, i.e.

$$\mathrm{Uptake\ (Bq) = \ Conc_{Rn}(Bq/m^3) \cdot f \cdot CF_{Rn}\left(\frac{mJ}{m^3}/\frac{Bq}{m^3}\right) \cdot t(h/a),}$$

which implies that the formula for the inhalation dose resulting from radon is:

$$\mathbf{Dose_{Rn}(mSv) = Conc_{Rn}(Bq/m^3) \cdot f \cdot CF_{Rn}\left(\frac{mJ}{m^3}/\frac{Bq}{m^3}\right) \cdot t(h/a) \cdot DCF_{Rn}(\frac{mSv}{mJ{\cdot}h/m^3}).}$$

Box 36: Occupational exposure dose from the inhalation of radon

The annual average atmospheric radon concentration at a uranium mine was found to be 50 Bq/m³. Compute the occupational exposure dose from the inhalation of radon, assuming that workers spend some 2 000 h/a in ambient air containing such radon concentrations and using an equilibrium factor $f = 0.4$ and DCF_{Rn} = 1.4 mSv per mJ·h/m³, as provided in Table 22.

The inhalation dose $Dose_{Rn}$ resulting from radon is given by $Dose_{Rn} = Conc_{Rn} \cdot f \cdot CF_{Rn} \cdot t \cdot DCF_{Rn}$, which implies that

$$Dose_{Rn} = 50\ \mathrm{Bq/m^3}\ \cdot 0.4 \cdot 5.56 \cdot 10^{-6}\,\mathrm{\frac{mJ}{m^3}/\frac{Bq}{m^3}} \cdot 2\,000\ \mathrm{h/a} \cdot 1.4\ \mathrm{\frac{mSv}{mJ.h/m^3}} \approx 0.31\ \mathrm{mSv/a}.$$

Box 37: Public exposure dose from the inhalation of radon

The annual ambient average atmospheric radon concentration at a smallholding in the Swakop River is found to be 15 Bq/m³. Compute the public exposure dose resulting from the inhalation of radon for a full year, i.e. 8 760 h/a, assuming an equilibrium factor $f = 0.4$, and DCF_{Rn} = 1.1 mSv per mJ·h/m³, as provided in Table 22.

The inhalation dose $Dose_{Rn}$ resulting from radon is given by $Dose_{Rn} = Conc_{Rn} \cdot f \cdot CF_{Rn} \cdot t \cdot DCF_{Rn}$, which implies that

$$Dose_{Rn} = 15\ \mathrm{Bq/m^3} \cdot 0.4 \cdot 5.56 \cdot 10^{-6}\,\mathrm{\frac{mJ}{m^3}/\frac{Bq}{m^3}} \cdot 8\,760\ \mathrm{h/a} \cdot 1.1\ \mathrm{\frac{mSv}{mJ{\cdot}h/m^3}} \approx 0.32\ \mathrm{mSv/a}.$$

10.3.1 Potential Alpha Energy and Potential Alpha Energy Concentration

The *potential alpha energy* (PAE) of a radionuclide is the energy that is emitted during its alpha decay. The PAE is expressed in units of energy, for example in Joules [J]. Table 23 summarises the PAE for the radon decay products. If it can be assumed that radon is in secular equilibrium with its progeny, the PAE per Bq of radon (i.e. the PAE per unit of radon activity), is the sum of all energies emitted in the decays of the radon decay products (RDP).

Table 23: Potential alpha energy per unit activity [51]

Radionuclide	Half-life	PAE per Bq_{Rn} (10^{-10} J/Bq_{Rn})
Po-218 (α)	3.1 min	5.79
Pb-214 (β)	26.8 min	28.6
Bi-214 (β)	19.8 min	21.2
Po-214 (α)	0.16 ms	$3 \cdot 10^{-6}$
		Total (equilibrium) $55.6 \cdot 10^{-10}$ J/Bq_{Rn}

Often, the ambient atmospheric concentration of radon is expressed as an activity concentration, for example as Bq/m^3. In contrast, the concentration of radon decay products is expressed as the *potential alpha energy concentration*, i.e. PAEC (J/m^3), of a mixture of RDP in air. PAEC is therefore the energy per volume, or energy concentration, while $Conc_{Rn}$ is the activity per volume, or activity concentration. It is also important to note that quantities related to the RDP are expressed in terms of their energy, e.g. in J, while those related to radon are expressed in terms of the radon activity, e.g. the activity density Bq/m^3. This is because RDP concentrations are determined by way of measuring the energies emitted in their decays.

10.3.2 Potential Alpha Energy Exposure

During an exposure to ionising radiation due to the inhalation of RDP, a certain amount of energy absorbed by the exposed tissue. This is the *potential alpha energy exposure* (PAEE), and is the product of the potential alpha energy concentration, PAEC_{Rn}, and the time *t* over which such an exposure took place, i.e.

$$\boldsymbol{PAEE_{Rn} = PAEC_{Rn} \cdot t}\,.$$

10.3.3 Equivalent Equilibrium Concentration

The *equivalent equilibrium concentration* (EEC) of radon is the radon concentration that results in the same PAEC as a mixture of radon and RDP in secular equilibrium.

In other words, if radon and RDP are in equilibrium, then PAEC = EEC.

The EEC is expressed in Bq/m^3. The equilibrium factor f between radon and RDP is the ratio of the actual PAEC to the PAEC provided that the RDP are in secular equilibrium with their parent. This can be expressed as follows:

$$\boldsymbol{f \equiv PAEC \,/\, EEC} \text{ or } \boldsymbol{PAEC = f \cdot EEC}.$$

Based on the PAE values provided in Table 23, the EEC can be expressed in terms of the corresponding PAEC, i.e.

$$\boldsymbol{1\ \mathrm{Bq/m^3}\ (EEC_{Rn}) = 5.56 \cdot 10^{-6}\ \mathrm{mJ/m^3}\ (PAEC_{Rn})}.$$

The relationship between EEC_{Rn} and $PAEC_{Rn}$ is the conversion factor, CF_{Rn}, between these two quantities. If the concentration of radon decay products in air is measured directly, i.e. when the equivalent equilibrium concentration $\mathrm{EEC_{Rn}}$ is determined rather than the radon concentration $\mathrm{Conc_{Rn}}$, the equilibrium factor f is not needed, and the formula for the exposure dose from the inhalation of radon can be expressed as follows:

$$\mathbf{Dose_{Rn}(mSv/a)} = \mathbf{EEC_{Rn}}(\mathrm{Bq/m^3}) \cdot \mathbf{CF_{Rn}}\left(\frac{\mathrm{mJ}}{\mathrm{m^3}} / \frac{\mathrm{Bq}}{\mathrm{m^3}}\right) \cdot \mathbf{t}(\mathrm{h/a}) \cdot \mathbf{DCF_{Rn}}\left(\frac{\mathrm{mSv}}{\mathrm{mJ.h/m^3}}\right).$$

A further simplification of the above formula is possible when using the potential alpha energy concentration, i.e. $PAEC_{Rn}$. If this quantity is available, a conversion between EEC_{Rn} and $PAEC_{Rn}$ is not needed, and therefore results in the following expression:

$$\mathbf{Dose_{Rn}}\left(\frac{\text{mSv}}{\text{a}}\right) = \mathbf{PAEC_{Rn}}\left(\frac{\text{J}}{\text{m}^3}\right) \cdot \mathbf{t}\left(\frac{\text{h}}{\text{a}}\right) \cdot \mathbf{DCF_{Rn}}\left(\frac{\text{mSv}}{\text{mJ}.\frac{\text{h}}{\text{m}^3}}\right).$$

Using the potential alpha energy exposure PAEE_{Rn}, the above equation is further simplified:

$$\mathbf{Dose_{Rn}}(\text{mSv/a}) = \mathbf{PAEE_{Rn}}\left(\frac{\text{J} \cdot \text{h}}{\text{m}^3 \cdot \text{a}}\right) \cdot \mathbf{DCF_{Rn}}\left(\frac{\text{mSv}}{\text{mJ}.\,\text{h/m}^3}\right).$$

Table 24 summarises the main concepts related to the use of the potential alpha energy.

Table 24: Summary of the main concepts related to the potential alpha energy

Name	Symbol	How to obtain it	Unit
Potential alpha energy	$\boldsymbol{PAE_{Rn}}$	Sum of all RDP alpha energies	J, or MeV
Potential alpha energy concentration	$\boldsymbol{PAEC_{Rn}}$	PAE_{Rn} *per* volume of air	J/m^3
Potential alpha energy exposure	$\boldsymbol{PAEE_{Rn}}$	$PAEC_{Rn} \cdot t$	J·h/m^3
Exposure dose, taking the efficiency of particle deposition in the lung into account, as well as the biological effect on the body, as defined by the DCF_{Rn}	$\boldsymbol{Dose_{Rn}}$	$PAEE_{Rn} \cdot DCF_{Rn}$	mSv

The relevant SI units, and their non-metric US equivalents, are summarised in Table 25.

Table 25: Units for radon measurements

Quantity	Unit (SI)	Unit (US)
Activity	Bq	Ci
Activity concentration	Bq/m^3	pCi/L, WL (working level)
Exposure	J·h/m^3	WLM (working level month)
Dose	Sv, mSv, µSv, nSv	rem
Dose conversion coefficient	Sv/(J·h/m^3)	rem/WLM

Box 38: Public exposure dose from the inhalation of radon with different in/outdoor occupancies

UNSCEAR reports average population-weighted indoor radon concentrations of 40 Bq/m^3, and 10 Bq/m^3 outdoors, and suggests that the typical indoor equilibrium factor f = 0.4, while the corresponding factor for outdoors is f = 0.6.

Compute the public exposure dose resulting from the inhalation of radon based on the above information, if the receptor spends 80% (20%) of the time indoors (outdoors).

The inhalation dose for radon, i.e. $Dose_{Rn}$, is computed using the following formula:

$$Dose_{Rn} = Conc_{Rn} \cdot f \cdot CF_{Rn} \cdot t \cdot DCF_{Rn}.$$

As the equilibrium factors and radon concentrations are different for in- and outdoors, the above formula is extended to read as follows:

$$Dose_{Rn} = (Conc_{Rn\_in} \cdot f_{in} + Conc_{Rn_{out}} \cdot f_{out}) \cdot CF_{Rn} \cdot t \cdot DCF_{Rn}.$$

Using the DCF_{Rn} = 1.1 mSv per mJ·h/m^3 as given in Table 22, the above formula implies that

$$Dose_{Rn} = (40 \cdot 0.4 \cdot 80\% + 10 \cdot 0.6 \cdot 20\%)\ \mathrm{Bq/m^3} \cdot 5.56 \cdot 10^{-6} (\frac{\mathrm{mJ}}{\mathrm{m^3}} / \frac{\mathrm{Bq}}{\mathrm{m^3}}) \cdot 8\,760\ \mathrm{h/a} \cdot 1.1\ \frac{\mathrm{mSv}}{\mathrm{mJ \cdot h/m^3}},$$

which yields a public exposure dose of

$$Dose_{Rn} = 0.75\ \mathrm{mSv/a}.$$

Box 39: Occupational exposure dose from the inhalation of radon using the EEC

The annual average outdoor equilibrium equivalent concentration (EEC) for radon – at a mineral sand mine – is found to be 50 Bq/m^3.

Compute the occupational exposure dose from the inhalation of radon, if workers spend 2 000 h/a at the work site, and therefore inhale air with an average radon concentration as specified above.

The inhalation dose resulting from the inhalation of radon, as a function of the EEC_{Rn}, is given by

$$Dose_{Rn} = EEC_{Rn} \cdot CF_{Rn} \cdot t \cdot DCF_{Rn}.$$

Using the DCF_{Rn} = 1.4 mSv per mJ·h/m^3 as given in Table 22, the above formula yields

$$Dose_{Rn} = 50\ \mathrm{Bq/m^3} \cdot 5.56 \cdot 10^{-6}\ \frac{\mathrm{mJ}}{\mathrm{m^3}} / \frac{\mathrm{Bq}}{\mathrm{m^3}} \cdot 2\,000\ \mathrm{h/a} \cdot 1.4\ \frac{mSv}{mJ \cdot h/m^3} = 0.78\ \mathrm{mSv/a}.$$

Box 40: Public exposure dose from the inhalation of radon using the PAEC

At an old age home, the indoor potential alpha energy concentration due to radon, i.e. $PAEC_{Rn}$, is quantified to be 60 µJ/m^3.

Compute the public exposure dose resulting from the inhalation of radon, if residents of the old age home do not leave the indoors area where the $PAEC_{Rn}$ was determined.

The inhalation dose resulting from the inhalation of radon, as a function of the $PAEC_{Rn}$ is given by

$$Dose_{Rn} = PAEC_{Rn} \cdot t \cdot DCF_{Rn}.$$

Using the DCF_{Rn} = 1.1 mSv per mJ·h/m^3 as given in Table 22, the above formula yields

$$Dose_{Rn} = 60\ \mathrm{\mu J/m3} \cdot 8\,760\ \mathrm{h/a} \cdot 1.1\ \frac{mSv}{mJ \cdot h/m^3} = 0.58\ \mathrm{mSv/a}.$$

10.3.4 Typical Environmental Radon Concentrations

Atmospheric radon concentrations in Namibia’s Erongo Region have been measured at Walvis Bay (5 Bq/m^3), Swakopmund (6.5 Bq/m^3), and Arandis (15 Bq/m^3), at some six metres above ground level, using a network of real-time radon monitoring stations which are in operation since 2011 [8]. The atmospheric radon concentrations as determined in Swakopmund and Arandis are shown in Figure 110 to Figure 113.

The Strategic Environmental Assessment undertaken in the Erongo Region in 2010 determined that atmospheric radon concentrations in the Erongo Region ranged between 1.6 Bq/m^3 and 62.5 Bq/m^3, which implies a population-weighted regional radon inhalation dose of 0.46 mSv/a [33].

A recently completed radon survey at the Rössing Mine quantified average atmospheric radon concentrations, which are presented as averages over three years, refer to Table 26 [127].

The ICRP presents the results of select indoor radon concentration measurements of up to 85 000 Bq/m^3 [51].

In the 1940s and 1950s, radon concentration as high as 10 MBq/m^3 were measured in underground uranium mines in Canada [126].

Figure 110: Atmospheric radon concentrations at Swakopmund in November 2017 [8]

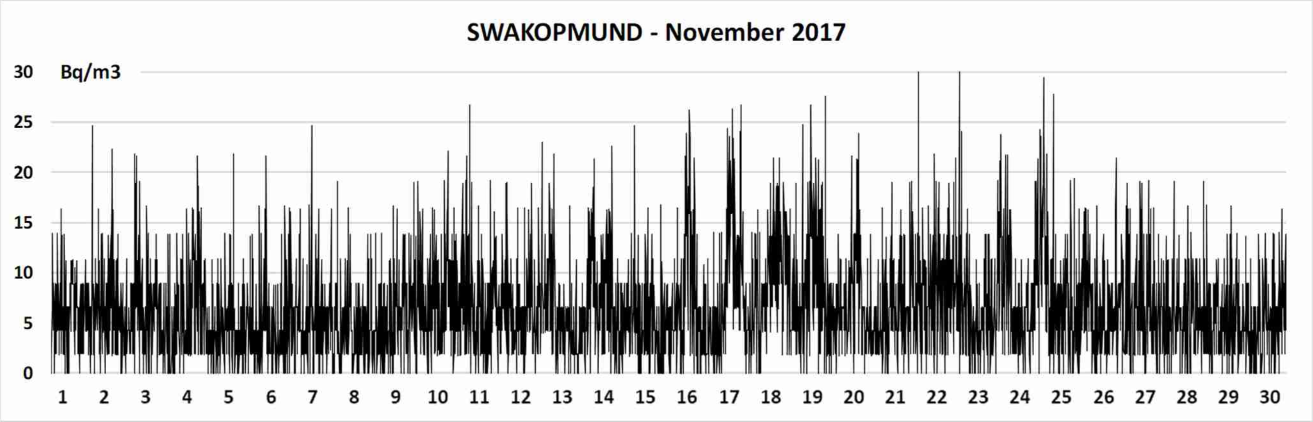


Figure 111: Frequency distribution of radon concentrations at Swakopmund in November 2017 [8]

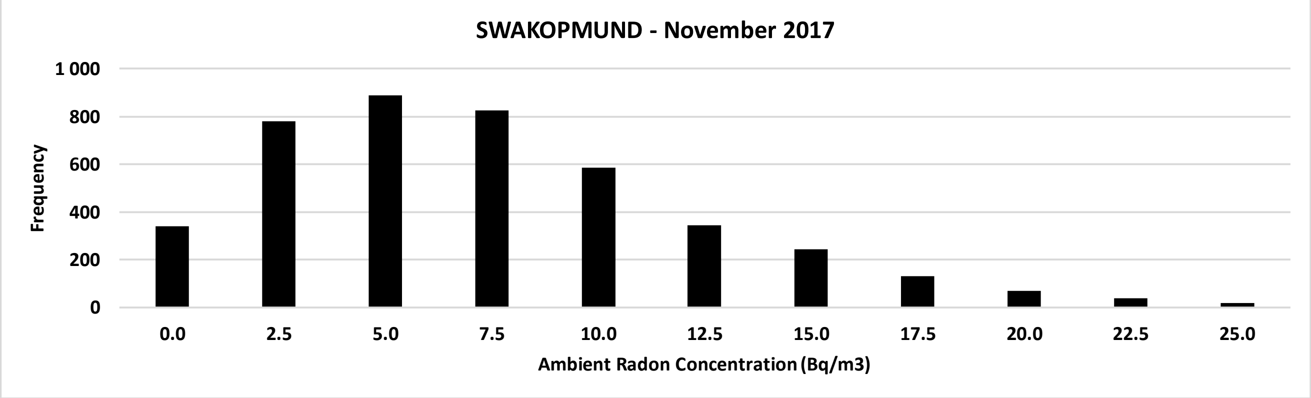


Figure 112: Atmospheric radon concentrations at Arandis in November 2017 [8]

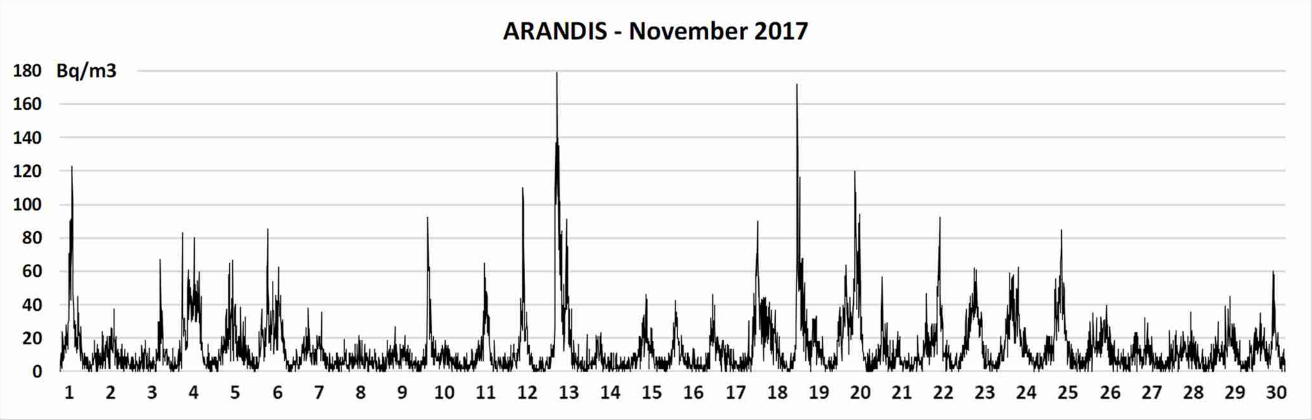


Figure 113: Frequency distribution of radon concentrations at Arandis in November 2017 [8]

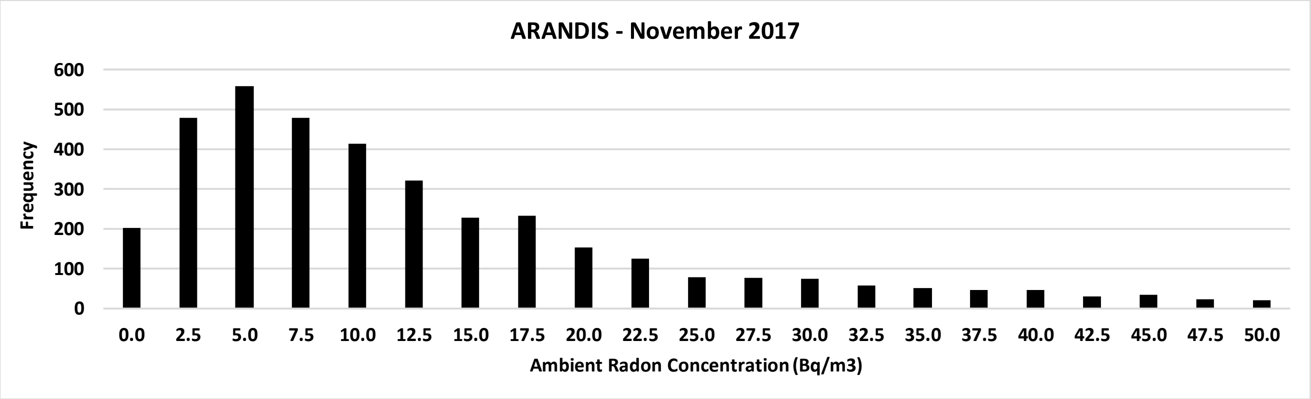


Table 26: Results of atmospheric radon concentrations at Rössing [127]

Area	Average concentration [Bq/m³]	Range [Bq/m³]
Khan River	57	46-68
Dome geological formation	63	48-73
Arandis	54	44-71
Rössing tailings facility	162	66-256
Rössing open pit	156	117-213
Rössing processing area	96	73-123
Indoor areas, ventilated	50	20-160
Indoor areas, unventilated	n/a	Up to 1 400

10.3.5 Typical Exposure Doses from Radon in Air

The methods described above are used to determine exposure doses resulting from some typical radon concentrations. Table 27 further illustrates some typical exposure doses resulting from the inhalation of RDP.

Table 27: Typical radon concentrations and associated annual exposure doses

	$Dose_{Rn}$ [mSv/a]				
	Public, 8 760 h/a	**Occupational, 2 000 h/a**			
$Conc_{Rn}$ [Bq/m^3]	$f = 0.4$ **DCF = 1.1 * 1**	$f = 0.4$ **DCF = 1.4 * 1**	$f = 0.2$ **DCF = 3 'mine' * 1**	$f = 0.4$ **DCF = 5.9 'indoor' * 1**	**Context**
1	0.02	0.01	0.01	0.03	ocean shores
10	0.21	0.06	0.1	0.3	mean continental ambient atmospheric concentration
21	0.4	0.1	0.1	0.6	Arandis mean outdoor
40	0.9	0.3	0.3	1.0	world average indoor
50	1.1	0.3	0.3	1.3	Arandis mean indoor
100	2.1	0.6	0.7	2.6	typical European indoor
118	2.5	0.7	0.8	3.1	average outdoor concentration at the Rössing Mine
1 000	21	6.2	6.7	26	indoor concentration in houses built with uranium-rich soils
100 000	2 100	620	670	2 600	Stanley Watras' basement
1 000 000	21 000	6 200	6 700	26 000	unventilated underground uranium mine (example only)

*** 1: the unit of the dose conversion factor DCF is mSv/ (mJ · h/m^3).**

Columns 4 and 5 in Table 27 illustrate the impact of the new ICRP Recommendations on Radon, and the associated dose conversion factors, as is further discussed in section 10.3.6.

The second last row in Table 27 refers to *Stanley Watras*, whose claim to fame, according to Wikipedia [128], is as follows: *'That radon levels in particular dwellings can occasionally be orders of magnitude higher than typical was dramatised by the so-called Watras incident (named after the American construction engineer Stanley Watras), in which an employee at a U.S. nuclear plant triggered radiation monitors while leaving work over several days—despite the fact that the plant had yet to be fuelled, and despite the employee being decontaminated and sent home 'clean' each evening. This implied a source of contamination outside the plant, which turned out to be radon levels of 100 000 Bq/m^3 in the worker's basement. Radon soon became a standard homeowner concern, although typical domestic exposures are two to three orders of magnitude lower (100 Bq/m^3), making individual testing essential to determine the radon risk in any particular dwelling.'*

Box 41: Stanley Watras' exposure dose from ambient radon concentrations at his home

The radon concentration in Stanley Watras' basement was found to be 100 kBq/m³. While the radon concentrations in other parts of Watras' house are not known, one can test the implications of scenarios. To this end it is assumed that – under scenario 1, the radon concentration in the remainder of Watras' home was also at approx. 100 kBq/m³.

If Mr Watras spent an entire year in his home, the associated exposure dose would be

$$Dose_{Rn} = 100\,000 \cdot 0.4 \cdot 5.56 \cdot 10^{-6} \cdot 8\,760 \ \cdot 1.1 \approx 2.1 \text{ Sv/a. (Sv, not mSv !)}$$

If Mr Watras spent 10 hours/day for the year in his home, the associated exposure dose would be

$$Dose_{Rn} = 100\,000 \cdot 0.4 \cdot 5.56 \cdot 10^{-6} \cdot 8\,760 \ \cdot (10\,/\,24) \ \cdot 1.1 \approx 0.89 \text{ Sv/a (Sv, not mSv !).}$$

If the radon concentration in the home was 1/10th the concentration in the basement, and Mr Watras spends 10 hours/day for the year in his home, the associated exposure dose would be

$$Dose_{Rn} = 100\,000 \cdot (1\,/\,10) \cdot 0.4 \cdot 5.56 \cdot 10^{-6} \cdot 8\,760 \ \cdot (10\,/\,24) \ \cdot 1.1 \approx 89 \text{ mSv/a.}$$

Box 42: Public exposure dose with different in- and outdoor equilibrium factors

Determine the annual average public exposure dose resulting from the inhalation of an atmospheric radon concentration of 100 Bq/m³, assuming an indoor equilibrium factor of $f = 0.4$, and an outdoor equilibrium factor of $f = 0.6$.

When using different equilibrium factors f for indoors and outdoors, one needs to specify the time spent in- and outdoors. If 80% of time is spent indoors, and 20% of time is spent outdoors, and using the in- and outdoor equilibrium factors provided, the weighted equilibrium factor is computed as follows:

$$f = (0.6 \cdot 0.2 + 0.4 \cdot 0.8) = 0.44.$$

The exposure dose – using the formula provided in this section – is therefore calculated as follows:

$$Dose_{Rn} = 100 \ \cdot 0.44 \cdot 5.56 \cdot 10^{-6} \cdot 8\,760 \ \cdot 1.1 \approx 2.4 \text{ mSv/a.}$$

When assuming an equilibrium factor of $f = 0.4$ throughout the year, the annual public inhalation dose because of the inhalation of the radon concentration of 100 Bq/m³ is:

$$Dose_{Rn} = 100 \ \cdot 0.4 \cdot 5.56 \cdot 10^{-6} \cdot 8\,760 \ \cdot 1.1 \approx 2.1 \text{ mSv/a.}$$

If, instead of an equilibrium factor $f = 0.4$ throughout the year, the factor is $f = 0.6$ throughout, the annual public inhalation dose from the inhalation of a radon concentration of 100 Bq/m³ is:

$$Dose_{Rn} = 100 \ \cdot 0.6 \cdot 5.56 \cdot 10^{-6} \cdot 8\,760 \ \cdot 1.1 \approx 3.2 \text{ mSv/a.}$$

10.3.6 ICRP 115 – Emerging Dose Coefficients for Radon

The radon dose coefficients in ICRP 65 [51] are derived from epidemiological studies.

More recent studies however have led to the conclusion that the risk from the inhalation of radon is about a factor 2 larger than was suggested earlier. This is a significant change and has led the ICRP to revisit the dose calculation methods used to compute the exposure dose resulting from the inhalation of radon and radon progeny.

Specifically, the ICRP's intention was to change the previous method which was based on epidemiological studies, to coincide with the approach used to determine the exposure dose resulting from the inhalation of all radionuclides other than radon, namely to use a dosimetric approach.

The ICRP Publication 115 summarises the outcomes of these investigations [129], and includes an update on the detriment from the inhalation of radon. It is important to note that ICRP 115 adjusts the detriment associated with radon from the values which were previously put forward in ICRP 65, which is summarised in Table 28.

The ICRP also published a draft document for consultation, i.e. ICRP 2012 [130], providing a summary of the current thinking around the methods and approaches that may be used in future to determine exposure doses from the inhalation of radon. ICRP 2012 is not a final recommendation but provides an indication of what may eventually be recommended once all inputs have been considered in full.

Table 28: Update on the detriment of radon as per ICRP Publications 65 [51], and 115 [129]

Risk Coefficient	**per WLM**	**per mJ·h/m^3**	**per Bq·h/m^3**
ICRP 65 (1993)	$2.8 \cdot 10^{-4}$	$8.0 \cdot 10^{-5}$	$4.5 \cdot 10^{-10}$
ICRP 115 (2012)	$5.0 \cdot 10^{-4}$	$14 \cdot 10^{-5}$	$8.0 \cdot 10^{-10}$

ICRP 115 does not provide dose conversion coefficients. Central to the discussion of the risk associated with radon is the fact that smoking is a primary cause of lung cancer, and the realisation that the risk from radon to smokers, irrespective of whether they are active or passive smokers, is significantly larger (approx. 25 times higher) than that of persons who have never smoked. This realisation has led to an attempt to formulate risk factors for 'average' people, who are assumed to be in part smokers, in part never-smokers, in proportion to the percentage of smokers in the population. The new dose conversion coefficients, once they are officially published, will therefore not represent the risk to an individual (who is either a smoker, or a past smoker, or a never-smoker), but to the population at large, thereby providing an expression for the 'average' population rather than specific risk groups.

ICRP 2012, which is a draft proposal, provides values for the dose conversion coefficients for radon that may come into force once they are broadly accepted and published. Table 29 summarises the tentative conversion factors for radon as per ICRP 2012 [130].

Table 29: Effective dose per unit exposure to radon decay products as per ICRP 2012 [130]

Location	**Unattached fraction**	**Equilibrium factor *f***	**mSv per WLM**	**mSv per mJ·h/m^3**	**Sv per Bq·h/m^3**
Indoors	0.1	0.4	21	5.9	$1.3 \cdot 10^{-8}$
Mine	0.01	0.2	11	3.0	-

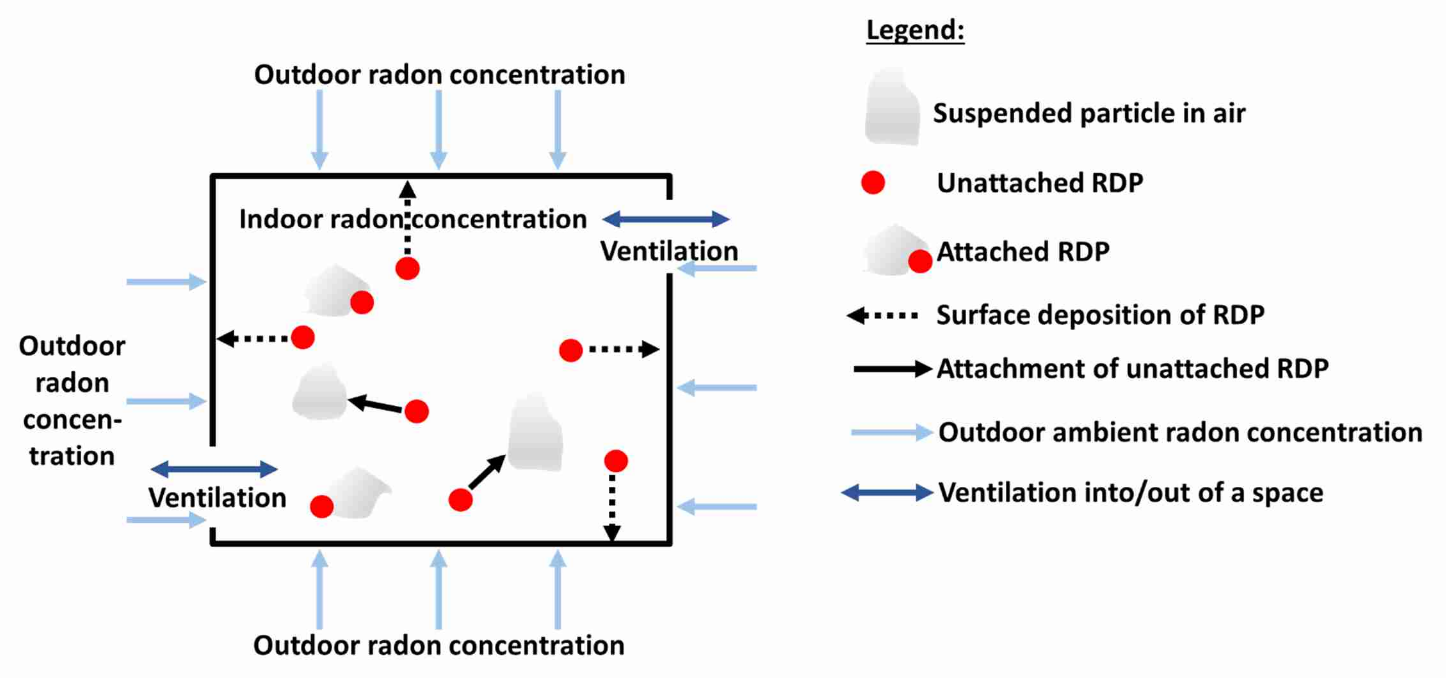
Table 29 shows that the proposed new dose conversion coefficients are no longer specific to public or occupational settings but differentiate only between 'indoors' and 'mine' locations.

These environments are characterised by their 'unattached fraction', i.e. those RDPs which have not attached themselves to suspended particles in the air.

For unventilated indoor workplaces, the attached fraction and the equilibrium factor are correlated: a lower attached fraction leads to a higher equilibrium factor, as more RDPs remain in the air, as illustrated in Figure 114.

For underground uranium mines, which are using forced ventilation, there is no correlation between the equilibrium factor and the attached fraction, and the equilibrium factor is assumed to be low (0.2). Ventilation changes the composition of air, and removes suspended particles in air, including those to which RDPs have attached themselves. This implies that the attached fraction in such environments is low.

Figure 114: Schematic of the behaviours of RDP in enclosed spaces [8]



It must be noted that neither of the above scenarios truly reflects the reality in open cast mines in dry environments, such as those in Namibia, where mining areas are unventilated, while being outdoors (which implies that the 'indoor' characterisation proposed by the ICRP does not apply either). However, the natural ventilation taking place in such outdoor areas is good, except at times, such as in the early hours of the morning, when there is neither wind nor any thermal turbulence. This implies that future dose conversion coefficients of relevance to the Namibian uranium mining industry may have to be determined by establishing representative values for the most realistic equilibrium factors and attached fractions that are typically found in such environments.

Box 43: Occupational exposure dose from the inhalation of radon as per ICRP 2012

Determine the occupational exposure dose resulting from the inhalation of air with a radon concentration of 100 Bq/m^3, using the dose conversion and equilibrium factors as provided in ICRP 2012.

The exposure dose resulting from the inhalation of radon is expressed as follows:

$$Dose_{Rn} = Conc_{Rn} \cdot f \cdot CF_{Rn} \cdot t \cdot DCF_{Rn}.$$

For an indoor workplace setting, and using the factors put forward in ICRP 2012, refer to Table 29, the exposure dose is calculated as follows:

$$Dose_{Rn} = 100\ \mathrm{Bq/m^3} \cdot 0.4 \cdot 5.56 \cdot 10^{-6}\,\frac{\mathrm{mJ}}{\mathrm{m^3}}/\frac{\mathrm{Bq}}{\mathrm{m^3}} \cdot 2\,000\ \mathrm{h/a} \cdot 5.9\,\frac{mSv}{mJ.h/m^3} \approx 2.6\ \mathrm{mSv/a}.$$

In contrast, and using the ICRP 65 DCF_{Rn}= 1.43 mSv per mJ·h/m^3 for workers, Table 22, one finds:

$$Dose_{Rn} = 100\ \mathrm{Bq/m^3} \cdot 0.4 \cdot 5.56 \cdot 10^{-6}\,\frac{\mathrm{mJ}}{\mathrm{m^3}}/\frac{\mathrm{Bq}}{\mathrm{m^3}} \cdot 2\,000\ \mathrm{h/a} \cdot 1.43\,\frac{mSv}{mJ \cdot h/m^3} \approx 0.6\ \mathrm{mSv/a}.$$

For a force-ventilated mine, and using the factors as per Table 29, the exposure dose is:

$$Dose_{Rn} = 100\ \mathrm{Bq/m^3} \cdot 0.2 \cdot 5.56 \cdot 10^{-6}\,\frac{\mathrm{mJ}}{\mathrm{m^3}}/\frac{\mathrm{Bq}}{\mathrm{m^3}} \cdot 2\,000\ \mathrm{h/a} \cdot 3\,\frac{mSv}{mJ \cdot h/m^3} \approx 0.7\ \mathrm{mSv/a}.$$

10.3.7 Exposure to Thoron

Up to this point, the discussion about radon focused exclusively on the radon isotope Rn-222. However, under certain conditions, thoron, i.e. radon isotope Rn-220, can also be a risk factor.

Thoron has a much shorter half-life than Rn-222 has, as is evident when comparing the decay chains shown in Figure 24 and Figure 25, i.e. 55 seconds for the former versus 3.8 days for the latter radon isotope. This implies that the probability of Rn-220 to successfully diffuse through the surrounding substrate and be exhaled into the air is much smaller than is the case for the longer-lived Rn-222. As a result, the thoron concentrations in air are invariably smaller, often significantly so, than those of the radon isotope Rn-222.

According to UNSCEAR, the world average thoron concentration, both indoors and outdoors, amounts to about 10 Bq/m^3 [101]. The annual average exposure dose from thoron is estimated to be 0.09 mSv. This implies that the dose contribution from thoron is more than an order of magnitude smaller than that of Rn-222, and is only of significance under special circumstances, for example in areas where high thorium concentrations are found in the soil.

10.3.8 Action Levels for Radon

The ICRP recommendations serve to guide the policies and regulations of countries, where the latter defines location-specific requirements. In this context, an *action level for radon* is a radon concentration in air that warrants remediation action. Often, different action levels are in use for existing homes, and for newly-built homes. These, in turn, are different from those used in outdoor environments, e.g. in the mining sector.

ICRP 65 first recommended action levels for radon in workplaces and homes [51]. In ICRP 103, these action levels were confirmed [45]. However, ICRP 115 which was published in 2012, has since revised the action levels downwards from those recommended previously [129]. The evolution of workplace action levels and those for domestic residences, as put forward by the ICRP in the past years, is summarised in Table 30.

European action levels for existing homes range between 100 and 400 Bq/m³, while those for new homes range between 100 and 800 Bq/m³.

The strictest action level for existing as well as new dwellings is applied in Germany and is set at 100 Bq/m³.

Table 30: Action levels for radon as per the ICRP [45], [51], [129]

	Action level for homes [Bq/m³]	**Action level for workplaces and mines [Bq/m³]**
ICRP 65 [51]	200 to 600	500 to 1 500
ICRP 103 [45]	200 to 600	500 to 1 500
ICRP 115 [129]	300	1 000

10.3.9 Working Level (WL) and Working Level Month (WLM)

The units *working level* (WL) and *working level month* (WLM) reflect the occupational realities because of the presence of radon in underground mines in the early 20th century. The WL and WLM were intended to guide occupational exposures in such work environments.

The WL is a unit for the concentration of radon decay products, while the WLM expresses cumulative exposures. One WL refers to the concentration of short-lived decay products of radon in equilibrium in air, with an activity concentration of 3 700 Bq/m³. Once fully decayed, the RDP in such a concentration in air will have released a total energy of $1.3 \cdot 10^5$ MeV.

The WL is an energy density, defined as

$$\mathbf{1\ WL \equiv 2.06 \cdot 10^{-5}\ J/m^3,}$$

as illustrated in Box 44.

The WLM is an energy density in a given period, i.e. an exposure dose, defined as

$$\mathbf{1\ WLM \equiv 3.6 \cdot 10^{-3}\ J{\cdot}h/m^3.}$$

An exposure to one WL for one working month, which is equivalent to an exposure period of 170 hours, is equal to an exposure dose of one WLM.

The cumulative exposure dose equivalent to 1 WLM is approximately equivalent to inhaling an atmospheric mix of ambient air and radon with a radon concentration of 75 Bq/m³ for one year, as shown in Box 45.

In a workplace, an exposure dose of one WLM results from working in an average radon concentration of 324 Bq/m³, as shown in Box 48.

Table 31 summarises the relevant conversions between the most common units used when dealing with radon and RDP.

Table 31: Conversions of common units used when dealing with radon and RDP

Entity	**Conversion**	
Activity	1 Bq = 27 pCi	1 pCi = 0.037 Bq
Activity concentration	1 Bq/m³ = 0.027 pCi/L	1 pCi/L = 37 Bq/m³
Potential alpha energy concentration	1 WL = 0.0208 mJ/m³	1 mJ/m³ = 48 WL
Exposure dose I	1 WLM = 3.54 mJ·h/m³	1 mJ·h/m³ = 0.282 WLM
Exposure dose II	1 Sv = 100 rem	1 rem = 10 mSv

Box 44: Definition of the working level (WL)

Demonstrate that the energy released in the decay of radon progeny contained in one cubic metre of air with a radon concentration of 3 700 Bq is equivalent to 2.08 · 10^{-5} J/m^3.

The potential alpha energy per unit activity released by the RDP is 5.56 · 10^{-9} $\mathrm{J/Bq_{Rn}}$, as shown in Table 23. The energy released by RDP in an atmosphere with radon activity of 3 700 Bq is therefore:

$$\mathrm{Energy_{Rn}} = \mathrm{Conc_{Rn}} \cdot \mathrm{CF_{Rn}} = 3\,700\ \mathrm{Bq/m^3} \cdot\ 5.56 \cdot 10^{-6}\,\frac{\mathrm{mJ}}{\mathrm{m^3}}/\frac{\mathrm{Bq}}{\mathrm{m^3}} \approx 2.06 \cdot 10^{-2}\,\frac{\mathrm{mJ}}{\mathrm{m^3}} = 2.06 \cdot 10^{-5}\ \mathrm{J/m^3}\ \equiv 1\ \mathrm{WL}.$$

Box 45: Definition of the working level month (WLM)

Demonstrate that the cumulative exposure dose of one WLM is approximately equivalent to inhaling a radon concentration of 75 Bq/m^3 for one year.

The exposure dose due to RDP decay over one year in air with a Rn concentration of 75 Bq/m^3 is:

$$\mathrm{Exposure\ Dose_{Rn}} = \mathrm{Conc_{Rn}} \cdot \mathrm{CF_{Rn}} \cdot \mathrm{t} = 75\ \mathrm{Bq/m^3} \cdot\ 5.56 \cdot 10^{-6}\,\frac{\mathrm{mJ}}{\mathrm{m^3}}/\frac{\mathrm{Bq}}{\mathrm{m^3}} \cdot 8\,760\ \mathrm{h} \approx 3.6\ \mathrm{mJ \cdot h\ /\ m^3} \equiv 1\ \mathrm{WLM}.$$

Box 46: Occupational exposure dose associated with an exposure to one WLM over one year

Determine the occupational exposure dose associated with an exposure to one WLM over a year.

Occupational exposure doses are typically incurred within 2 000 working hours per year. This implies that the exposure dose resulting from an exposure to 1 WLM over one year is, and assuming an equilibrium factor $f = 0.4$ and $\mathrm{DCF_{Rn}}$ as per ICRP 65, refer to Table 22, is as follows:

$$\mathrm{Dose_{Rn}} = Conc_{Rn} \cdot f \cdot CF_{Rn} \cdot t \cdot DCF_{Rn}$$

$$= 3\,700\ \mathrm{Bq/m^3} \cdot\ 0.4\ \cdot 5.56 \cdot 10^{-6}\,\frac{\mathrm{mJ}}{\mathrm{m^3}}/\frac{\mathrm{Bq}}{\mathrm{m^3}} \cdot 2\,000\ \mathrm{h/a}\ \cdot\ 1.43\ \mathrm{mSv\ /\ (mJ \cdot h/m^3)} \approx 23.5\ \mathrm{mSv/a}.$$

Box 47: Public exposure dose associated with an exposure to one WLM over one year

Determine the public exposure dose associated with an exposure to one WLM over a year.

Public exposure doses incurred over one year imply that the exposure occurred over 8 760 hours per year. The exposure dose resulting from an exposure to 1 WLM over one year, and assuming an equilibrium factor $f = 0.4$ and $\mathrm{DCF_{Rn}}$ as per ICRP 65, refer to Table 22, is as follows:

$$\mathrm{Dose_{Rn}} = 3\,700\ \mathrm{Bq/m^3} \cdot\ 0.4\ \cdot 5.56 \cdot 10^{-6}\,\frac{\mathrm{mJ}}{\mathrm{m^3}}/\frac{\mathrm{Bq}}{\mathrm{m^3}} \cdot 8\,760\ \mathrm{h/a}\ \cdot\ 1.1\ \mathrm{mSv\ /\ (mJ \cdot h/m^3)}\ \approx 79.3\ \mathrm{mSv/a}.$$

Box 48: Workplace radon concentration corresponding to an exposure dose of one WLM

What is the average radon concentration corresponding to an exposure of 1 WLM incurred by a radiation worker over one year?

The exposure dose corresponding to one WLM is $3.6\ \mathrm{mJ \cdot h/m^3}$, as demonstrated in Box 45. The corresponding radon concentration in a workplace leading to the same dose is therefore

$$\mathrm{Conc_{Rn}} = 3.6\ \mathrm{mJ \cdot h/m^3}\ /\ (\ \mathrm{CF_{Rn}} \cdot \mathrm{t}\ )\ = \frac{3.6\ \mathrm{mJ{\cdot}h/m^3}}{5.56{\cdot}10^{-6}\frac{\mathrm{mJ}}{\mathrm{m^3}}/\frac{\mathrm{Bq}}{\mathrm{m^3}}\ {\cdot}2\,000\ \mathrm{h}} \approx 324\ \mathrm{Bq/m^3}.$$

10.4 Annual Limit on Intake (ALI)

The *annual limit on intake* (ALI) is the amount of radioactive material that a worker ingests / inhales to deliver an annual effective dose of 20 mSv.

ALI values are derived from dose conversion coefficients and were developed by the ICRP. They are based on reviews of published estimates of radiation doses which are delivered to specific organs and tissues resulting from the intake of a given quantity of radionuclides.

Because a total annual exposure dose is the result of several exposure pathways, the ALI for a specific exposure pathway is not the maximum allowable intake. Therefore, ALIs are guideline values only, and must not be used as action levels or threshold values in an occupational setting.

10.4.1 ALI for Uranium Ore

The ALI for the alpha activity of uranium ore is the ratio of the annual dose limit to the committed dose per unit of intake of uranium ore with an alpha activity of 3.5 μSv/Bq$_{\alpha}$, based on the dose conversion factor per unit of alpha activity intake, as provided in section 10.2.

The ALI corresponding to an annual dose of 20 mSv from uranium ore is therefore calculated as:

$$ALI = \frac{20 \text{ mSv}}{0.0035 \text{ mSv/Bq}} = 5\,700 \text{ Bq}_{\alpha}.$$

10.4.2 ALI for Uranium Concentrate

The ALI for the alpha activity of uranium concentrate is the ratio of the annual dose limit to the committed dose per unit of intake of uranium concentrate. As uranium concentrate has various solubility classes, the applicable solubility that best fits the product must be used.

The ALI for uranium oxide of solubility class S, which corresponds to an annual exposure dose of 20 mSv, is calculated as:

$$ALI = \frac{20 \text{ mSv}}{0.0062 \text{ mSv/Bq}} = 3\,200 \text{ Bq}.$$

Correspondingly, the ALI for yellowcake of solubility class M and an annual exposure dose of 20 mSv is calculated as follows:

$$ALI = \frac{20 \text{ mSv}}{0.0018 \text{ mSv/Bq}} = 11\,000 \text{ Bq}.$$

Box 49: Annual limit on intake for the potential alpha energy due to radon

Using the PAEC$_{Rn}$ of radon, compute the ALI for radon in terms of the potential alpha energy, assuming an occupational setting with an annual exposure dose limit of 20 mSv over 2 000 h/a.

From the relationship for the exposure dose from radon, i.e. $Dose_{Rn} = PAEC_{Rn} \cdot t \cdot DCF_{Rn}$, the potential alpha energy concentration PAEC$_{Rn}$, is expressed as $PAEC_{Rn} = \frac{Dose_{Rn}}{t \cdot DCF_{Rn}}$.

Using the annual dose limit, maximum exposure time, and the DCF for radon, one then finds

$$PAEC_{Rn} = \frac{Dose_{Rn}}{t \cdot DCF_{Rn}} = \frac{20 \text{ mSv/a}}{2\,000 \text{ h/a} \cdot 1.4 \text{ mSv /mJ} \cdot \text{h/m}^3} \approx 0.007 \text{ mJ/m}^3.$$

From this, the potential alpha energy, PAE, is computed as follows:

$$PAE = PAEC_{Rn} \cdot BR_{Rn} \cdot t = 0.007 \frac{\text{mJ}}{m^3} \cdot 1.2 \frac{m^3}{h} \cdot 2\,000\, h \approx 16 \text{ mJ}.$$

10.5 Solubility of Uranium

Health effects arising in response to the exposure to natural uranium are mostly the result of the chemical (i.e. toxicological) properties of uranium, and less so because of its radioactivity.

Uranium occurs in three solubility types, which are also referred to as lung absorption types, refer to Table 32.

Table 32: Uranium solubility types [125]

Fast (F)	Medium (M)	Slow (S)
Most hexavalent uranium compounds, e.g. UF_6, UO_2F_2, $UO_2(NO_3)_2$	Less soluble uranium compounds, e.g. UO_3, UF_4, UCl_4 yellowcake	Highly insoluble uranium compounds, e.g. UO_2, U_3O_8

The absorption of uranium into the body is low, regardless of whether it is inhaled or ingested. The World Health Organisation (WHO) provides estimates of the tolerable intake due to the inhalation and ingestion of uranium, based on the chemical toxicity rather than the radiological toxicity [78]. For soluble uranium compounds (F and M type), the tolerable intake is 0.5 µg/kg of body weight per day, and 5.0 µg/kg of body weight per day for insoluble compounds (S type).

The inhalation of uranium leads to its internal deposition in the respiratory tract and the lungs, depending on the particle sizes. Larger particles are deposited in the upper parts of the respiratory tract. The smaller the particle size, the deeper such deposition is. Less soluble uranium can – in parts – reside in the lungs for years. Most of the uranium deposited in the respiratory tract is rapidly cleared via the mucociliary transport to the throat. Once there, the uranium is cleared via sputum, or by swallowing, which delivers it to the digestive tract, from where it is primarily excreted through the faeces.

The more soluble the uranium is, the more readily it dissolves, and the easier it is absorbed into the circulatory system. Adults absorb between 0.5 and 5% of uranium that is ingested into the blood stream. The solubility of the uranium compound determines to what degree the absorption occurs.

Therefore, when uranium enters the body

- most of the inhaled uranium is cleared through mucociliary transport, swallowed, and excreted in the faeces;
- a small portion of the inhaled uranium is absorbed into the blood;
- an even smaller fraction of ingested uranium is absorbed into the blood; and
- ingested uranium is primarily excreted in the faeces.

The IAEA Safety Standards provide the inhalation dose coefficients for uranium for occupationally exposed persons [1]. Table 33 summarises the inhalation dose coefficients for uranium with a mean aerodynamic diameter (AMAD) of 5 µm, as a function of the uranium radionuclide in question and the specific solubility class. Table 33 illustrates that the dose from the inhalation of uranium is more than a factor 3 larger for uranium type S, than it is for uranium type M, while it is some factor 10 larger for type S than it is for type F.

Table 33: Uranium inhalation dose coefficients for workers for a particle size of 5 µm AMAD [1]

Radionuclide	Unit	Fast	Medium	Slow
U-238	Sv/Bq	$5.8 \cdot 10^{-7}$	$1.6 \cdot 10^{-6}$	$5.7 \cdot 10^{-6}$
U-235	Sv/Bq	$6.0 \cdot 10^{-7}$	$1.8 \cdot 10^{-6}$	$6.1 \cdot 10^{-6}$
U-234	Sv/Bq	$6.4 \cdot 10^{-7}$	$2.1 \cdot 10^{-6}$	$6.8 \cdot 10^{-6}$

Box 50: Exposure dose resulting from the inhalation of 1 g of uranium type M and type S

Compute the exposure dose resulting from the inhalation of 1 g of uranium type M and type S.

As shown in section 10.2, the exposure dose as a function of intake is as follows:

$$\mathbf{Dose} = \mathbf{intake} \cdot \boldsymbol{DCF}.$$

Using the dose conversion factors provided in Table 33 (for type M), the exposure dose is

$$\text{Dose} = (1\text{ g} \cdot 12\,350\ Bq/g) \cdot (1.6 \cdot 10^{-6} +\ 2.1 \cdot 10^{-6})\text{ Sv/Bq} \approx 45.7\text{ mSv}.$$

It is noted that U-235 was not included in the above calculation as its contribution is small.

Similarly, the inhalation dose resulting from the inhalation of 1 g of uranium of type S is

$$\text{Dose} = (1\text{ g} \cdot 12\,350\ Bq/g) \cdot (5.7 \cdot 10^{-6} +\ 6.8 \cdot 10^{-6})\text{ Sv/Bq} \approx 154.4\text{ mSv}.$$

The difference between uranium of type S and that of type M is significant, as the dose from uranium of type S is more than a factor 3 larger than that due to type M uranium.

For ingestion, bodily processes that are different to the ones taking place on inhalation are relevant. The committed effective dose per unit intake resulting from ingestion is a function of the so-called *gut transfer factor*, f_1, which quantifies the proportion of intake transferred to the bodily fluids in the gut and depends on the chemical form in which the radionuclides are made available.

The ICRP's human respiratory tract model [131] proposes two different gut transfer factors for uranium: a transfer factor of 0.02 for uranium of type F and M, and a transfer factor of 0.002 for uranium of type S [132].

The biological half-life of uranium in the body, which is introduced in section 10.7 below, is also called the retention time of ingested uranium, and depends on the gut transfer factor. Approximate values for the biological half-life of uranium are provided in Table 34.

Table 34: Uranium retention times in the body by solubility type [131]

	Solubility Type Fast	Solubility Type Medium	Solubility Type Slow
Retention half-time	< 10 days	10-100 days	>100 days
Time for absorption	10 min (100%)	10 min (10%), 140 d (90%)	10 min (0.01%), 7 000 d (99.9%)

The IAEA Safety Standards provides the dose coefficients for the ingestion of uranium for occupationally exposed persons [1], as summarised in Table 35. It shows that the dose coefficient for the ingestion of uranium of type M exceeds that of type S by a factor of almost 6.

Table 35: Uranium ingestion dose coefficients for workers by solubility type [1]

Radionuclide	Unit	Type M $f_1 = 0.02$	Type S $f_1 = 0.002$
U-238	Sv/Bq	4.4×10^{-8}	7.6×10^{-9}
U-235	Sv/Bq	4.6×10^{-8}	8.3×10^{-9}
U-234	Sv/Bq	4.9×10^{-8}	8.3×10^{-9}

Box 51: Exposure dose resulting from the ingestion of 1 g of uranium of type M and type S

Compute the exposure dose resulting from the ingestion of 1 g of uranium of type S and type M.

As shown in section 10.2, the exposure dose as a function of intake is as follows:

$$\mathbf{Dose} = \mathbf{intake} \cdot \boldsymbol{DCF}.$$

Using the dose conversion factors provided in Table 35 (for type M), the exposure dose is

$$\mathrm{Dose} = (1\ \mathrm{g} \cdot 12\ 350\ \mathrm{Bq/g}) \cdot (4.4 \cdot 10^{-8} +\ 4.9 \cdot 10^{-8})\ \mathrm{Sv/Bq} \approx 1.15\ \mathrm{mSv}.$$

Using the dose conversion factors provided in Table 35 (for type S), the exposure dose is

$$\mathrm{Dose} = (1\ \mathrm{g} \cdot 12\ 350\ \mathrm{Bq/g}) \cdot (7.6 \cdot 10^{-9} +\ 8.3 \cdot 10^{-9})\ \mathrm{Sv/Bq} \approx 0.20\ \mathrm{mSv}.$$

It is noted that the contribution from U-235 was not considered, as this is a factor 20 smaller than that from U-238 and U-234.

The difference between uranium of type M and that of type S is significant, as the ingestion dose from uranium of type M is almost a factor 6 larger than that due to type S uranium.

10.6 Uranium-in-Urine Bioassays

It is not possible to use the results from *uranium-in-urine bioassays* to calculate an ingestion dose. This is because of several factors that complicate the ingestion pathway, thereby rendering a direct assessment impossible.

If the result of the uranium-in-urine bioassay shows the presence of uranium, it is usually not known

- whether the ingestion was acute (i.e. once-off), or chronic, i.e. continuous over a longer period;
- what the solubility class of the ingested uranium was;
- over what period the ingestion took place; and
- whether secondary effects, such as inhalation, may also have contributed to the total intake.

Because of the uncertainties as identified above, uranium-in-urine bioassays are only used as a first-off indicator, to assess and reaffirm the absence of an ingestion risk [134]. As a result, such bioassays are ineffective and cannot be used to quantify the radiation risk that led to the intake of uranium and can also not be used to compute an exposure dose associated with such an intake.

Regarding the interpretation of the results of uranium-in-urine bioassays, the following basic principles apply:

- they provide a first rough measure of the amount of uranium that was ingested and/or inhaled;
- a comparison of the dose coefficients for inhalation and ingestion, refer to Table 33 and Table 35 respectively, for the same solubility type differ by factors ranging between a few hundred to factor 1 000;
- the result of a urine bioassay result could indicate an acute (i.e. short-term) or chronic (i.e. long-term) exposure;
- as the excretion behaviour of uranium is not linear, a bioassay alone will not allow a judgement about the time, pathway, and duration of the exposure; and
- the result of the ingestion of uranium of type M, i.e. yellowcake, as given in a urine bioassay, cannot be directly compared to the result from the ingestion of type S uranium (uranium oxide), as the dose conversion factor for type M is some 5 times larger than that of type S.

10.7 Effective Half-Life

The radiological half-life of a radionuclide indicates how long it takes before one half of a given substance has disappeared because of a radioactive decay. In contrast, the *biological half-life* is an indication of how long a given substance remains in the body and is therefore a measure of the retention time of a given substance in the body. The biological half-life is a function of the solubility as well as the retaining characteristics of a given substance.

To illustrate: the biological half-life of uranium of solubility type F is 6 days. This implies that one-halve of it has been excreted through the urine or the faeces after having been in the body for 6 days.

If the radiological and biological half-lives of a substance are of similar magnitude, the total effective half-life of the substance is smaller than either of the two quantities. This is because each process, i.e. the absorption through chemical and biological mechanisms, and the radioactive decay, is influenced by the other process taking place.

Mathematically, the *effective half-life* is given by

$$\boldsymbol{T_{eff}} = \frac{\boldsymbol{T_r \cdot T_b}}{\boldsymbol{T_r + T_b}},$$

where

$\boldsymbol{T_r}$ is the radiological half-life, and

$\boldsymbol{T_b}$ is the biological half-life.

Table 36 summarises the radiological and biological half-lives of select radionuclides and provides their effective half-life.

It is noted that if one of the two half-lives are very significantly larger than the other one, the effective half-life is equal to the smaller of the two.

Table 36: Radiological, biological, and effective half-lives of select radionuclides [133]

Radio-nuclide	Radiological half-life T_r [days]	Biological half-life T_b [days]	Effective half-life [days]
H-3	4 500	12	12
Mn-54	300	25	23
Fe-59	45	600	42
Co-58	72	9.5	8
Co-60	1 900	10	10
Sr-90	10 000	18 000	6 828
I-131	8	138	8
Cs-134	840	70	65
Cs-137	$1.1 \cdot 10^4$	70	70
U-238	$1.6 \cdot 10^{12}$	6 to 5 000	6 to 5 000
Pu-239	$8.7 \cdot 10^6$	7 200	7 194

Box 52: Effective half-life of uranium of solubility type S

Determine the effective half-life of uranium of solubility type S, noting that the biological half-life of uranium is 5 000 days, while the radiological half-life is 4.5 billion years, i.e. some $1.6 \cdot 10^{12}$ days.

The effective half-life is computed as follows:

$$\boldsymbol{T}_{\text{eff}} = \frac{\boldsymbol{T_r \cdot T_b}}{\boldsymbol{T_r + T_b}} = \frac{4.5 \cdot 10^9 \cdot 365 \cdot 5\,000}{4.5 \cdot 10^9 \cdot 365 + 5\,000} \approx \frac{(4.5 \cdot 10^9 \cdot 365) \cdot 5000}{4.5 \cdot 10^9 \cdot 365} = 5\,000 \text{ days}.$$

This demonstrates that the addition of a small number (here 5 000 days) to a very large number (i.e. $1.6 \cdot 10^{12}$ days) does not change the big number significantly, and implies that the small number in the denominator, which is to be added to the very large number, can be safely ignored.

10.8 Total Effective Whole-Body Dose

In both occupational and public exposure scenarios, several pathways can contribute to the radiation exposure dose of an individual. For comparison with dose limits, the total effective whole-body dose needs to be calculated by summing over the dose contributions from all relevant exposure pathways, as illustrated in Box 53.

Box 53: Calculating the total annual occupational exposure dose from a monitoring program

Compute the total annual occupational exposure dose over 2 000 h/a based on the results of an employee monitoring program, which included the determination of the

1. average gamma dose rate of 3 μSv/h;
2. inhalation dose from radon decay products (RDPs) of 0.3 mSv per year; and
3. inhalation dose from long-lived radioactive dust (LLRD) of 0.05 mSv per quarter.

The total annual exposure dose is calculated as follows:

a. Using the average gamma dose rate provided above, the annual gamma dose is

$$\boldsymbol{Dose_{\gamma}} = 3\ \mu\mathrm{Sv/h}\ \cdot 2\ 000\ \mathrm{h/a} =\ 6\ \mathrm{mSv/a}.$$

b. Using the inhalation dose from RDPs provided above, the annual dose is

$$\boldsymbol{Dose_{Rn}} =\ 0.3\ \mathrm{mSv/a}.$$

c. Using the quarterly LLRD dose provided above, the annual dose is

$$\boldsymbol{Dose_{LLRD}} = 0.05\ \mathrm{mSv/q} \cdot 4\ \mathrm{q/a} = 0.2\ \mathrm{mSv/a}.$$

The total annual dose is the sum of the three individual annual doses, i.e.

$$\boldsymbol{Dose_{total}} = \boldsymbol{Dose_{\gamma}} + \boldsymbol{Dose_{Rn}} + \boldsymbol{Dose_{LLRD}} = (6 + 0.3 + 0.2\ )\ \mathrm{mSv/a} = 6.5\ \mathrm{mSv/a}.$$

10.9 Derived Air Concentration (DAC)

Similar to the ALI, the *derived air concentration* (DAC) is the concentration of radioactive material in air that results in an annual intake equal to the ALI if a person were to inhale such air for the duration of a year. Here it is important to note that the DAC for occupational settings assumes that inhalation takes place for 2 000 hours per year, while the corresponding public DAC assumes an inhalation period of 8 760 hours per year.

Box 54: Derived air concentration for uranium-bearing ore dust

Compute the DAC that corresponds to an annual occupational exposure dose of 20 mSv from the inhalation of uranium-bearing ore dust.

The mathematical relationship for the exposure dose as a function of the concentration is

$$\mathbf{Dose_{LLRD}} = \mathbf{Conc_{LLRD}} \cdot \mathbf{t} \cdot \mathbf{BR}\ \cdot \mathbf{DCF_{LLRD}}.$$

Hence, the derived air concentration is given by

$$\boldsymbol{DAC} = \mathbf{Conc_{LLRD}} = \frac{\boldsymbol{Dose_{LLRD}}}{\boldsymbol{t \cdot BR \cdot DCF_{LLRD,\alpha}}} = \frac{20\ mSv/a}{2\ 000\,\frac{h}{a} \cdot 1.2\frac{m^3}{h} \cdot 0.0035\frac{mSv}{Bq}} \approx 2.4\ \mathrm{Bq_{\alpha}/m^3}.$$

Box 55: Derived air concentration for uranium concentrate dust of solubility class S

Compute the DAC that corresponds to an annual occupational exposure dose of 20 mSv from the inhalation of uranium concentrate dust of solubility class S.

The exposure dose as a function of the concentration is given by

$$\mathbf{Dose_{LLRD} = Conc_{LLRD} \cdot t \cdot BR \ \cdot DCF_{LLRD}}.$$

Hence, the derived air concentration is given by

$$\boldsymbol{DAC} = \mathbf{Conc_{LLRD}} = \frac{\mathbf{Dose_{LLRD}}}{\mathbf{t \cdot BR \cdot DCF_{LLRD,\alpha}}} = \frac{20\ \mathrm{mSv/a}}{2\,000\ \mathrm{h/a} \cdot 1.2\ \ \mathrm{m^3/h} \cdot 0.0062\ \mathrm{mSv/Bq}} \approx 1.3\ \mathrm{Bq_\alpha/m^3}.$$

Box 56: Derived air concentration for yellowcake dust of solubility class M

Compute the DAC that corresponds to an annual occupational exposure dose of 20 mSv from the inhalation of yellowcake dust of solubility class M.

As similarly used in Box 55, the derived air concentration is given by

$$\boldsymbol{DAC} = \mathbf{Conc_{LLRD}} = \frac{\mathbf{Dose_{LLRD}}}{\mathbf{t \cdot BR \cdot DCF_{LLRD,\alpha}}} = \frac{20\ \mathrm{mSv/a}}{2\,000\ \mathrm{h/a} \cdot 1.2\ \ \mathrm{m^3/h} \cdot 0.0018\ \mathrm{mSv/Bq}} \approx 4.6\ \mathrm{Bq_\alpha/m^3}.$$

Box 57: Derived air concentration for radon

Compute the DAC that corresponds to an annual occupational exposure dose of 20 mSv from radon.

Using the relationship between the $PAEC_{Rn}$, the annual dose, maximum exposure time, and the DCF for radon, as used in Box 49, one finds

$$\boldsymbol{PAEC_{Rn}} = \frac{Dose_{Rn}}{t \cdot DCF_{Rn}} = \frac{20\ \mathrm{mSv/a}}{2\,000\ \mathrm{h/a} \cdot 1.4\ \mathrm{mSv\ /mJ{\cdot}h/m^3}} \approx 0.007\ \mathrm{mJ/m^3}.$$

10.10 Exercises

10.10.1 Calculating Exposure Doses

1. From the individual exposure doses below, work out the average annual exposure dose from the exposure to external radiation:
   a) P Louw, 4.5 hours, 4 µSv
   b) S Visagie, 6 hours, 3 µSv
   c) H Pompies, 3.5 hours, 3 µSv
   d) F Jacobs, 6 hours, 2 µSv

2. If the maximum allowed daily limit for external exposure in a given practice is 80 µSv, how long are workers allowed to work in a location where the dose rate is
   a) 10 µSv/h
   b) 20 µSv/h
   c) 1/2 µSv/h
   d) 0.1 µSv/h

3. The dose rate on the tailings area is found to be 3 µSv/h. What external occupational exposure will this lead to when the exposure takes place throughout the year?

4. Work out the weighted average annual dose from external radiation for the operation, using the following measured exposure doses from three similar exposure groups:

Group	Annual dose (mSv)	Number of workers
office workers	0.8	400
pit workers	1.5	100
plant workers	3.1	40

5. A radiation worker is someone potentially exceeding a pre-determined annual dose. The ICRP recommendation for the radiation worker classification is 6 mSv per annum. If typical dose rates measured in a mining processing area are 3 µSv/h for gamma radiation, and the average doses recorded for dust inhalation and radon inhalation are 1 mSv and 1.5 mSv per year respectively, determine whether workers in this area should be radiation workers according to the ICRP. Assume a working year of 2 000 hours.

10.10.2 Dose Limits

What are the appropriate dose limits for

a) Visitors to a uranium mine;

b) Tour operators acting as guides during tours at a uranium mine;

c) Medical staff active in radiography;

d) Medical staff working in an onsite mine medical clinic;

e) Contractor cleaning mine offices;

f) Quality control worker managing the transport of uranium from the mine to the harbour;

g) Pregnant office workers in an office.

10.10.3 Effective Half-life

Calculate the effective half-life for I-131 and for U-238 in the body. The radiological half-life of I-131 is 8 days and for U-238 is 4.5 billion years. The biological half-life for I-131 is 138 days, and for U-238 it is 6 to 5 000 days.

10.10.4 Inhalation Dose

Work out the inhalation dose per annum from breathing air at 1 Bq/m^3 from uranium of type S. Assume that the breathing rate is 1.2 m^3/h, over 2 000 h/a.

10.10.5 Internal Contamination

Assume a worker has ingested 10 g of uranium type M on a particular day at 10 am in the morning. If 10% of this material is absorbed by the body within 10 minutes, and the worker drinks 1 litre of water to flush out the uranium, what uranium in urine density would we find 1 hour after ingestion? Assume that all the water is excreted within one hour.

11 Measuring Radiation and Instrumentation for Radiation Monitoring

This Chapter introduces the main approaches and instruments to reliably quantify dose rates and doses resulting from an exposure to ionising radiation.

11.1 Introduction

The measurement of radiation takes different forms. It depends on the context in which a measurement is to be undertaken, and how best the result can be expressed. For example, if one wishes to quantify how radioactive a given substance is, one uses a different measurement approach than in the case where the risk of exposure to people is to be quantified, or where radioactive emissions into the environment must be measured.

Radioactivity is quantified by measuring the rate of decay of a given substance. It entails measuring the number of radioactive decays per time interval. A common unit used in radioactivity measurements is the Becquerel, abbreviated Bq, and which is defined as follows:

$$\mathbf{1\ Bq \equiv 1}\ \textbf{disintegration per second.}$$

In other applications, the energy of the radiation emitted as part of a radioactive decay is determined. Here, a common unit to quantify such energies is the electron-Volt, abbreviated eV, or million electron-Volt, i.e. MeV. The eV unit can be expressed in terms of the common energy unit Joule, abbreviated J, which is

$$\mathbf{1\ eV = 1.6 \cdot 10^{-19}\ Joule.}$$

When quantifying the risk of exposure to ionising radiation, dose rates and associated exposure doses are a common metric. Dose rates are quantified in nSv/h, μSv/h, or mSv/h. The corresponding exposure doses are expressed in units of nSv, μSv, mSv or even Sv, as introduced in chapter 9.

11.2 Radiation Monitoring Instruments

Radiation detection and monitoring instruments are used to

- quantify the radioactivity of a given substance, for example by determining the number of disintegrations per second;
- identify and locate the presence of radioactive material;
- identify the presence of specific radionuclides, for example when surveying for uranium or other radionuclides;
- determine the dose rate resulting from the presence of a radiation source; and
- quantify the exposure dose in a given exposure situation, for example to confirm compliance with set dose limits, or as part of a radiation risk assessment, or as part of a dose monitoring program.

Depending on their intended use, the choice of the instrument to be used is important. A variety of radiation monitoring instruments exists. This chapter introduces the following main instrument types which are used to monitor radiation and quantify radiation impacts:

- ionisation detectors, such as Geiger-Müller and proportional counters;
- scintillation counters;
- solid state detectors; and
- radiation dosimeters.

The following subsections briefly describe these instrument types.

11.2.1 Geiger-Müller Tubes and Counters

Geiger-Müller counters are used to detect the presence of radioactivity. They are based on the principle of counting the number of radioactive disintegrations which occur in each period.

A Geiger-Müller tube consists of a chamber which is filled with a gas mixture at a pressure of about 0.1 atmosphere. The chamber is connected to two electrodes, with a potential difference of several hundred Volts applied between them. The outer walls of the tube are either made of metal, or have their inside surface coated with a conducting material or a spiral wire to form the cathode. The anode consists of a wire which is located in the centre of the chamber.

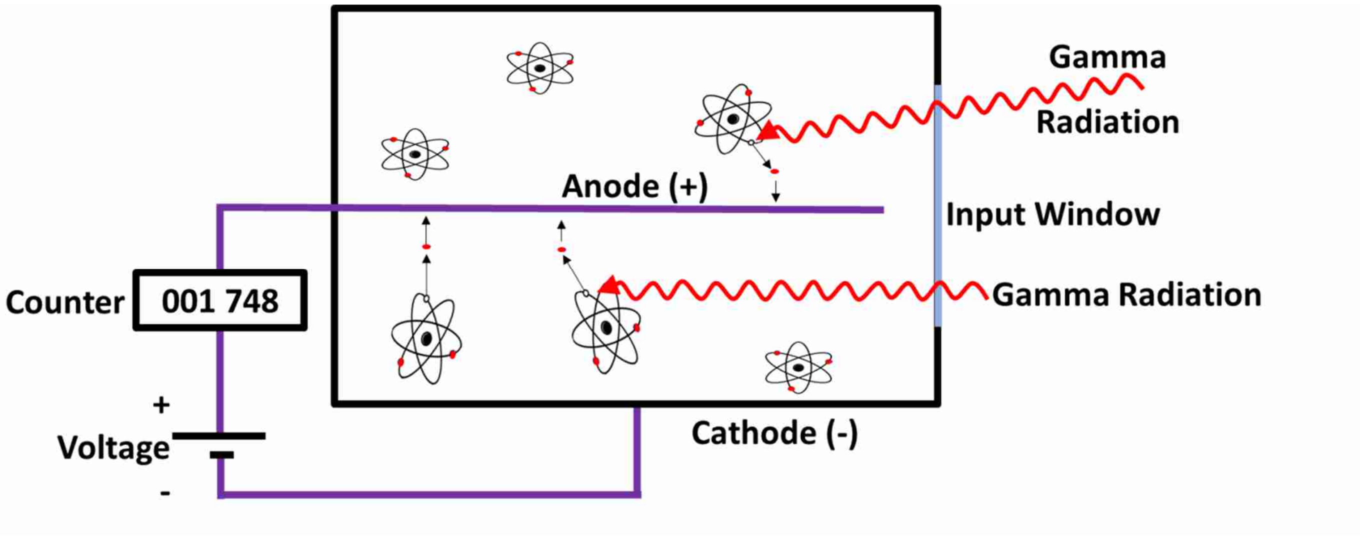
When incident radiation penetrates the chamber filled with gas, some of the gas molecules are ionised. Because of the negative and a positively charged poles, i.e. the electrodes in form of the anode and cathode, and the high voltage which is applied between them, an electric field exists in the chamber. This field causes negatively charged particles, such as electrons, to be attracted by the positive anode, while positively charged particles such as protons are attracted to the negatively charged cathode.

As illustrated in Figure 115, once charged particles arrive at the anode (or cathode), an electrical current flow takes place in the circuit which connects the anode, counter, voltage supply and cathode. The counter converts this current into an optical and/or acoustic signal, and thereby provides a measure for the number of ionising events that took place in the Geiger-Müller tube following its exposure to ionising radiation.

Geiger-Müller counters are gaseous ionisation detectors which use the so-called Townsend avalanche phenomenon to produce an electronic pulse from as little as a single ionising event. Such counters are readily used for the detection of gamma radiation and X-rays, while they can be modified to also detect alpha and beta particles, as well as neutrons.

Instruments which use Geiger-Müller tubes are mostly robust, and inexpensive, but have their limitations too. For example, Geiger-Müller counters are unable to effectively and accurately quantify high radiation rates, they have a finite life in high radiation areas, and they cannot distinguish between incident radiation types.

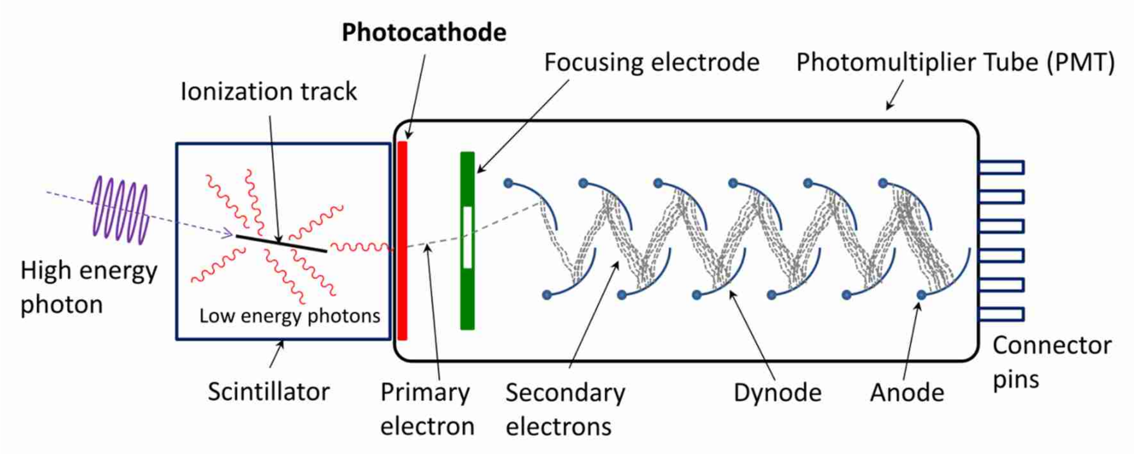
Figure 115: Geiger-Müller tube with electric circuit and counter as used for radiation detection [8]



11.2.2 Scintillation Counters

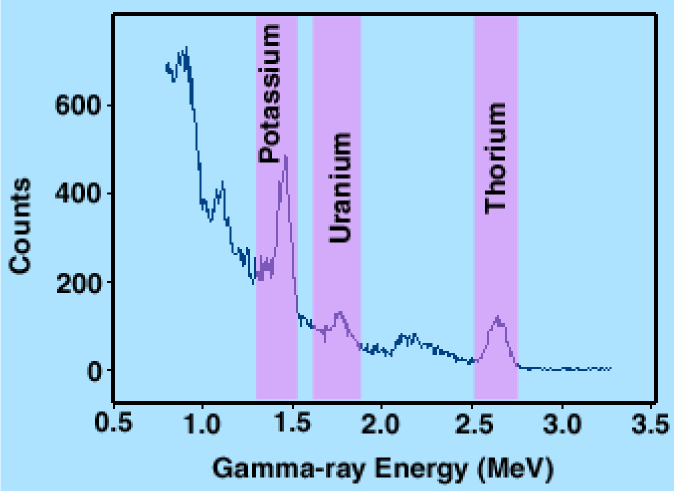
Scintillation counters detect both X-rays and gamma radiation and determine their energy. Such instruments consist of a crystal that emits light in form of low—energy photons, when it is excited, for example when it is irradiated with ionising radiation. Such light flashes give rise to a photoelectron which is emitted by a photocathode following its exposure, thereby converting the incident light into one or several electrons. These primary electrons in turn create an avalanche of secondary electrons in a photomultiplier tube, as illustrated in Figure 116.

Figure 116: Scintillation counter and electric circuit for radiation detection [135]



The energy of the incident radiation is proportional to the number of electrons produced in the photomultiplier tube. An amplifier creates a resultant output signal, which is in the form of a measurable pulse for each group of photons that arrive at the photocathode, and each pulse is passed on to the device's processing electronics. Such pulses carry information about the energy of the original incident radiation while the number of pulses per unit time gives information about the intensity of the incident radiation. When converted into a graph showing the number of counts recorded versus the energy of the incident radiation, a characteristic energy spectrum including radiation-specific energy peaks can be displayed, which indicate the presence of specific radiation emitters, as shown in Figure 117.

Figure 117: Energy spectrum produced by a scintillation counter [136]



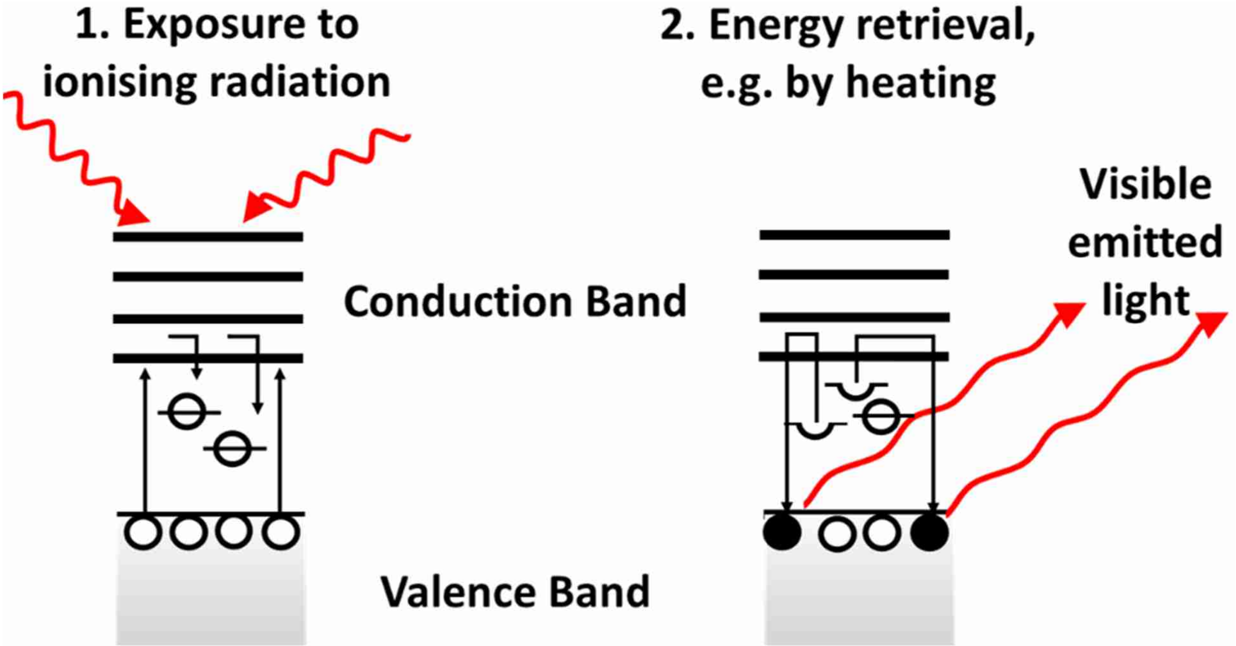
11.2.3 Solid State Detectors

Detectors made from semiconducting or thermo-luminescent crystals, as for example shown in Figure 118, are used to collect cumulative information about the exposure to ionising radiation. In this way, such devices are used to measure an exposure dose incurred in a specific period.

The principle on which solid state detectors are based is that they 'record' exposure incidents within the detector material. When this material is exposed to incident radiation, free electrons, and holes (i.e. the absence of an electron in a specific location in the material), and these are trapped in the material, refer to number 1. in Figure 118.

On reading out the detector, which is for example achieved by heating, the detector substrate is stimulated, and releases the trapped energy in form of visible light, which is turned into an electric signal, as illustrated in number 2. in Figure 118. The amount of light emitted is proportional to the incident radiation that was absorbed by the material, and in this way provides a measure of the exposure dose that the detector material was exposed to.

Figure 118: Schematic illustration of the operation of thermo-luminescent dosimeters [8]



Solid state devices, such as thermo-luminescent dosimeters are often used to verify compliance with dose limits. For such purposes, they are issued to specific groups for a set period in which such group members are exposed to radiation. During the exposure period, thermo-luminescent dosimeters absorb an amount of radiation that is proportional to the exposure dose incurred by the wearer). In this way, they create a record of the exposure dose absorbed by the wearer of the device during the period in which the device was worn.

11.2.4 Dosimeters

Dosimeters are used to measure the exposure of individuals. Usually, the name dosimeter refers to instruments that measure the penetrating radiation dose, i.e. the dose from gamma radiation, X-rays, and neutrons. The exposure dose is either measured to confirm compliance with dose limits, or as part of a radiation risk or dose assessment. Depending on the specific application and requirements, solid state detectors or Geiger-Müller type instruments are often used as dosimeters. If continuous monitoring is required, thermoluminescent dosimeters are used. For short- and shorter-term use, electronic dosimeters are common. These usually have the functionality to be able to quantify the exposure dose and dose rate and are either based on miniaturised Geiger-Müller or scintillation counters.

11.3 Monitoring Instruments in Practice

Radiation detection and monitoring instruments are often technically complex, and in most cases, they are expensive. It is therefore important that care is taken that the correct choices are made when selecting radiation monitoring instruments. This includes, amongst others, taking their functional and calibration requirements, user-friendliness, hardiness, cost, end-user requirements and wearing comfort into account.

The following subsections summarise a few applications of radiation detection and monitoring instruments and highlights some typical uses of such instruments. It is to be noted that this section only includes a small sub-set of the large variety of instruments that are readily available today.

11.3.1 Area Monitoring Instruments

Area monitoring is undertaken to assess the radiation risk in a work area or public area. Such assessments are of importance as part of pre-operational impact or risk assessments, occupational risk assessments, or the reassessment of risk conditions in areas that have been modified or undergone process and/or procedural changes.

11.3.1.1 Radon Monitoring

For the monitoring of radon concentrations, the cheapest option is a so-called *radon cup*, as shown in Table 37, which is a small plastic container which has an alpha-sensitive film mounted inside.

Radon can readily diffuse into the cup, through a tiny hole at the bottom of the cup. On decay, the alpha radiation emitted etches a track into the film. Radon cups are set up in areas for extended periods, usually between one to three months at a time, after which they are collected, disassembled, and have their films removed. In a laboratory, these films are developed, and the tracks on the films are counted using a microscope. In this way, the track density is converted into an average atmospheric radon concentration over the period in which the cup was monitored.

A variety of radon monitoring devices for use in the home exist, these are usually handheld instruments that monitor either the radon concentration in air, or the concentration of radon progeny, and in this way, allow for a near- instantaneous reading of the radon concentration.

More expensive area monitoring devices can be used to simultaneously monitor both radon and radon progeny, which allows for the determination of the equilibrium factor between radon and its progeny.

Table 37 illustrates some of the instruments that are used to quantify radon concentrations in ambient air.

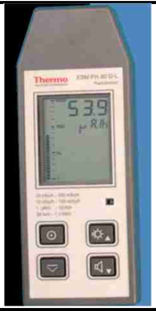
Table 37: Radon concentration monitoring devices and instruments

Pathway	Instrument	Image of instrument
Atmospheric - Internal because of radon progeny	Radon cup, e.g. by PARC RGM™	
Atmospheric - Internal because of radon progeny	Home radon monitoring device, such as the AlphaE, by Saphymo™	
Atmospheric - Internal because of radon progeny	DoseMan (right) & DoseManPro (left), by SARAD™	
Atmospheric - Internal because of radon progeny	Alpha Guard, by Saphymo™	
Atmospheric - Internal because of radon progeny	AlphaPM, by Saphymo™	

11.3.1.2 Gamma Monitoring

For area monitoring of gamma radiation, a multitude of instruments are available, as illustrated in Table 38. These monitoring instruments are, for example, used to undertake dose rate measurements needed for area risk assessments, to locate hidden sources of radioactive material, and for area dose monitoring. For detailed area gamma measurements, instruments such as FH-40 are available, and offer the additional advantage that alpha / beta probes can be connected, in case contamination measurements (in small areas only) are to be made.

Table 38: Gamma monitoring instruments

Pathway	Instrument	Image of instrument
Direct – External	Thermo-luminescent dosimeter (TLD), (often in a bar-coded protective pouch)	
Direct – External	Electronic personal dosimeter (EPD), by Thermo™	
Direct – External	Gamma survey meter, by Automess™	
Direct – External	RadEye PRD, by Thermo™	
Direct – External	Tracerco™ PED + software	
Direct – External	FH-40 GL-10, by Thermo™	

11.3.1.3 Dust Monitoring

Monitoring (radioactive) dust concentrations in air requires sophisticated instruments, a selection of which is shown in Table 39. Often, because it is easier and less expensive, one monitors particulate concentrations in air, and only thereafter quantifies the radioactivity.

To monitor the radioactivity contained in airborne dust, one can also use pumps equipped with removable filters. Such instruments limit the risk of having to deal with a clogged-up instrument filter, which readily occurs when operating the instrument in dusty environments. An example is the iCAM alpha/beta monitor. On the other hand, a simpler option is a PM_{10} sampler, if the radionuclide concentration is not that important to measure, or if it is to be analysed following the collection of dust. However, in some cases, measuring the PM_{10} content of dust is not sufficient, and the concentration of total particulates is needed. In such cases, high-volume samplers are used instead.

Some instruments used to monitor the radioactivity in dust, or the ambient dust concentration in are depicted in Table 39.

Table 39: Dust monitoring instruments used for area monitoring

Pathway	Instrument	Image of instrument
Atmospheric - Internal radioactive dust	iCAM radioactivity in air monitor, by Canberra™	
Atmospheric - Internal radioactive dust	MyRIAM, active air sampler with integrated alpha spectrometer, by SARAD™	
Atmospheric - Internal dust in air	PM_{10} E-sampler, which necessitate the analysis of filters to determine the radioactive content of dust, by Enviro Technology™	
Atmospheric - Internal dust in air	Gilair™ pump	
Atmospheric - Internal dust in air	High-volume continuous particulate monitor, by Thermo™	

11.3.2 Personal Radiation Monitoring Instruments

Instruments to be used for personal monitoring must be sufficiently small to allow the wearer to comfortably carry them, and they must be robust to withstand day-to-day handling in the harsh work environment. It is helps if such instruments do not need to be calibrated too frequently.

11.3.2.1 X-ray and Gamma Monitoring

For compliance monitoring, continuous gamma monitors are needed, such as film or badge dosimeters. There are a considerable number of suppliers of such dosimeters, including for use in medical practices (X-ray), and for gamma monitoring. Table 38 depicts a selection of common X-ray and gamma monitoring instruments, and dosimeters.

For day-to-day and ad hoc monitoring applications, electronic dosimeters are often useful. A relatively cost-effective option is the Electronic Personal Dosimeter (EPD) by Thermo™, refer to Table 38. It must be calibrated in two-year intervals, has a good battery life, and is robust. It has an infrared link, through which its dose and dose rate alarms are enabled, and for data downloads. To avoid tampering with the instrument while it is worn, access to the instrument can be locked via the infrared link.

The Personal Electronic Dosimeter (PED) by Tracero™, refer to Table 38, offers a colour display, allowing the user to read off the accumulated dose, the present dose rate, and the peak dose rate for a task. The display and alarm functionality make this a user-friendly instrument. Settings and data downloads are achieved through an instrument cradle. Calibration is annual, at an approved facility. For Africa, this implies that calibrations must be done in the United Kingdom or United Arab Emirates.

11.3.2.2 Dust and Radon Monitors

Personal monitoring of dust and radon is less common, although various manufacturers offer instruments for this purpose. For example, to monitor the inhalation of radioactive dust, the MYRIAM instrument by SARAD™ can be used. It pumps air through a filter, which is positioned below an alpha detector. Following the sampling of dust-laden air, filter analysis allows for the determination of the inhalation dose due to airborne radioactive dust, with the user specifying the dose conversion coefficient that is to be used. The instrument does not separate dust particles by size as it does not distinguish between the inhalable and environmental dust. Calibration is annual, at a facility as specified by the manufacturer.

Another option for assessing the radioactive dust in air is the use of dust pumps, for example the instrument by GilAir™. It can be supplied with a PM_{10} and $PM_{2.5}$ cyclone, to separate the inhalable and respirable fraction of airborne dust. If one wishes to use such an instrument to quantify the activity of dust, the residue deposited on a filter is weighed and analysed for its radioactivity, from which the inhalation dose is calculated. Calibration of this instrument is usually done in-house.

To monitor the radon inhalation dose, instruments that assess radon progeny directly allow for a more accurate assessment of the personal inhalation dose. An example is the DoseManPro by SARAD™, as shown in Table 37, where air is pumped through a filter placed below a detector. The response time of the instrument is 30 minutes, which allows for a rapid assessment and quantification of the inhalation dose due to the radon concentration in air. Calibration must be done annually, at a facility as specified by the manufacturer. Other instruments as shown in Table 37 measure the radon concentration in air, as is useful for rapid risk assessments.

11.3.2.3 Personal Integrated Monitoring

In work environments where several exposure pathways must be assessed at the same time, the simultaneous monitoring of such relevant pathways offers an effective way to achieve this. A combined personal radiation monitoring solution is offered by ALGADE, i.e. the so-called *Personal Integrated Dosimeter* (PID), as shown in Figure 119.

This instrument combines a thermo-luminescent dosimeter for gamma exposures, a radon track-etch film, and a pump with an integrated filter element which is used to collect dust on a filter. The operation of the pump must be regularly checked, and weekly monitoring runs are essential if the instrument is worn in dusty environments. It comes with a charging and docking station and is intended for personal use over an extended time periods, spanning between a few weeks to several months.

Calibration, and the analysis of the detachable cartridge which contains the TLD, track-edge film and filter element, is undertaken at the manufacturer's facility in France.

Figure 119: Personal Integrated Dosimeter by ALGADE [137]

11.4 Urine Bioassays

Direct monitoring of the ingestion of radionuclides is complicated, as several chemical compounds are likely to be ingested at any a given time. Regarding the ingestion of uranium, for example as part of the uranium mining and concentration processes, several factors complicate the direct assessment of an ingestion dose:

- Uranium occurs in two solubility classes in plants where uranium concentrate is prepared: yellowcake is of solubility type M, while the solubility class of uranium oxide is type S, and these solubilities lead to different excretion behaviours upon the release in urine.
- Both the ingestion and inhalation of uranium-bearing products leads to their excretion in urine, but the excretion behaviours differ significantly between the exposure pathways.
- For the determination of an ingestion dose, it must be known whether the ingestion was acute (i.e. once off), or chronic (i.e. occurring all the time). In addition, the period and timing when the ingestion occurred must be known to be able to interpret bioassay results correctly.
- To undertake a reasonably accurate dose assessment, all the urine excreted by a person within at least a 24-hour period must be collected, as short-term concentration variations of the uranium excreted in the urine occur because of a variety of metabolic as well as behavioural factors.

Because of these complications, it is often not possible to determine an exposure dose based on urine bioassays alone, and these can therefore only serve as a measure to verify that common hygiene practices, as are mandatory in the uranium production processes, are followed.

Various operations make use of *occupational exposure limits* (OELs) for uranium in urine, based on the chemical toxicity of uranium, rather than the radiological risk. Here, a uranium in urine concentration of for example 20 µg/L can serve as a *warning level*, while a concentration of 40 µg/L is viewed as a level that necessitates immediate action, i.e. it serves as an *action level*.

In Namibia, legal reference values are not available for monitoring uranium in urine.

11.5 Calibration of Radiation Monitoring Instruments

Most radiation monitoring instruments are issued with a calibration schedule. For instruments that are used for legal compliance checks, such as dose measurements and for contamination control, calibration is essential, and associated calibration certificates must be kept on record.

Instruments that are used for ad hoc radiation risk assessments and/or for qualitative purposes only, regular in-house calibration (e.g. using a long-lived check source) is often sufficient.

When monitoring radiation, it is important to make a record of the instrument number and its latest calibration date. For this purpose, one should keep an instrument register, including the calibration records, and devise a rotation schedule for the calibration of instruments to ensure that these do not all expire within the same period.

11.6 Some Pointers for Measuring Exposure Doses

This brief section includes a few helpful tips and comments that apply when measuring exposure doses:

1. Every instrument has characteristic detection limits, and sensitivities.
2. Instruments are designed for specific purposes and applications only. Using them for other monitoring purposes is likely to deliver non-sensible results.
3. Most radiation monitoring instruments require regular calibration.
4. Radioactive decays follow a statistical distribution. This must be kept in mind, as variations in the count and dose rate readings will occur, and these will fluctuate about an average long-term value.
5. Some instruments apply in-built electronic damping to overcome short-term fluctuations. This slows down the instrument's response capabilities and implies that small variations in the count/dose rate may be missed.
6. The measuring error can be reduced by increasing the monitoring period.
7. Average values determined over a longer measurement period are more reliable than instantaneous readings.
8. The result of gamma measurements includes both a terrestrial and cosmic radiation component. This is important to remember and must be considered in the analysis of the data. The cosmic component usually shows considerable variations over time, above those arising from the statistical nature of radioactive decays.
9. Internal exposure pathways are always measured separately. This implies that each of the internal exposure doses resulting from the inhalation of radon, radioactive dust, and ingestion must be measured on their own.
10. The presence of internal radiation sources is determined using a full body scan. However, this is rarely used or required in the uranium mining sector.

12 Radioactive Contamination

This Chapter describes radioactive contamination, and how it is controlled and managed.

12.1 Non-fixed and Fixed Radioactive Contamination

In the context of this book, *contamination* refers to *radioactive contamination*, which is sometimes also referred to as *radiological contamination*.

The IAEA defines radioactive contamination as the deposition of, or the presence of radioactive substances on surfaces, in solids, liquids or gases, or the human body, where their presence is unintended and/or undesirable [96].

Radioactive contamination occurs in form of *surface contamination*, and *internal contamination*, and means that radioactive materials are deposited on or occur in substances, including those that can be inhaled and/or ingested.

Surface contamination occurs when radioactive source material is externally distributed on the surface of an object. Here, one differentiates between *fixed contamination*, and *non-fixed contamination*: **non-fixed contamination** is contamination that can be readily removed from a surface, while **fixed contamination** is contamination other than non-fixed contamination and refers to contamination that is part of the matrix of the material under consideration.

Non-fixed contamination can become airborne. Once airborne it can be inhaled or ingested. As a result, non-fixed contaminants often represent a larger risk factor than fixed contaminants.

The radiological risk associated with fixed contamination mainly arises from the gamma radiation from such sources. However, for a significant gamma dose from a surface-contaminated object, the activity of the surface contaminant must be very high. In the uranium exploration and mining sector, for example, the risk of exposure from fixed contaminants is limited, as uranium is a weakly radioactive element.

12.2 Clearance Level for Public Release of Radioactively Contaminated Objects

Radioactively contaminated objects may only be released into the public domain if they fulfil certain *clearance conditions*. The IAEA defines radioactive contamination as follows:

> *Radioactive contamination is the presence of a radioactive substance on a surface in quantities in excess of 0.4 Bq/cm^2 of beta and gamma emitters and low toxicity alpha emitters, or 0.04 Bq/cm^2 for all other alpha emitters [96].*

This definition serves as clearance criterion for the release of radioactively contaminated items from a site, for example a uranium mine. Any item that is to be released for further public use must comply with the above contamination threshold. If it does not, it must be decontaminated, until it is below the threshold concentration limit stated above.

For the application of the above definition and noting that uranium is a *low toxicity alpha emitter*. To illustrate: for a uranium mine, the IAEA definition of radioactive contamination implies that the clearance level for releasing objects for further public use is 0.4 Bq/cm^2 for alpha, beta, or gamma emitters, when averaged over a surface area of 300 cm^2 on any part of the surface of the object under consideration.

12.3 Determining whether to Release a Potentially Contaminated Object

Releasing a contaminated object into the public domain necessitates reliable measurements, as well as some judgement.

The following steps are useful when assessing whether to release a contaminated or potentially contaminated object from a mining operation such as a uranium mine into the public:

1. First, do a visual inspection of the object. If it is clean, measure the contamination levels. If it is found to be contaminated, clean it thoroughly (this process is called *decontamination*) before measuring its contamination levels again.
2. If any of the surfaces of the potentially contaminated object are wet, alpha contamination cannot be effectively measured, as alpha radiation does not penetrate water. Wet objects should be dried, prior to being assessed for contamination.
3. If the object has curved surfaces, these cannot effectively be monitored using a flat alpha probe. In such cases, wipe sample tests must be undertaken.
4. Using the monitoring instrument, determine the relevant background radiation levels. While this is not essential for alpha radiation, because the alpha background is – in most cases – close to zero due to the short distance that alpha radiation travels in air, it is important for beta contamination. It is recommended that the instrument's background subtraction mode is used when determining beta contamination levels, to minimise contributions from beta and gamma radiation while assessing contamination levels.
5. Switch the instrument to integration mode, so as not to monitor peak rates.
6. Keep the monitoring probe's surface clean and avoid contaminating the probe while undertaking measurements. This is easiest achieved by holding the surface of the probe sufficiently close to the surface of the contaminated object without ever touching it, but close enough for alpha radiation to reach the probe's surface. In other words, the probe's distance to the contaminated object – for alpha contaminated materials – is to be kept at approx. two (2) centimetres from the surface that is being monitored. This is achieved by holding the probe between the thumb and index finger and using the thumb and finger tips as a measure to fix the distance between the surface of the probe and the contaminated object, as illustrated in Figure 120.

Figure 120: Monitoring surface contamination using a flat plate probe [8]

7. Determine the alpha contamination level if the source material in question is uranium ore, or if it consists of residues of uranium concentrate. Other sources of contamination may require alpha as well as beta, or only beta measurements, depending on the source characteristics.
8. The contamination measurement is to be undertaken across an area of some 300 cm^2, which is about the area of an adult footprint, or that of a large hand with all fingers extended.

9. To distinguish between non-fixed contamination, and fixed contamination, a wipe sample test is used.
10. for a wipe sample test, ensure that a known surface area, for example 100 cm^2, is wiped. This area must be properly accounted for when using the wipe area and specific removal factor when analysing the wipe sample.
11. Ensure that internal spaces in objects / equipment are considered too. In many cases, potentially hidden areas may contain the largest contamination levels. Equipment that has such hidden internal spaces, such as pumps and heat exchangers, must be opened for inspection before their internal and external surface areas are subjected to contamination monitoring.
12. All objects exceeding the public release threshold of 0.4 Bq/cm^2 must be detained and kept on site.
13. Some contaminated objects can be decontaminated, for others this is not feasible.
14. Decontaminated objects must be reassessed to quantify the remaining contamination levels.
15. For large quantities of scrap material that must be assessed for potential contamination, the gamma dose rate may serve as a proxy for the presence of contamination, provided the measurement is undertaken near the source(s). A rule-of-thumb is to detain all such parts and equipment that have dose rates which are twice (or more) as large as the prevailing natural background levels in the area, provided that such levels are not themselves elevated because of the presence of radioactive contaminants.

12.4 Surface-Contaminated Objects

For specific applications, such when radioactively contaminated objects are not intended for public release, less stringent release criteria may apply. This is of relevance where radioactive materials are in transit from one contaminated work area to another one. In such cases, the allowable surface contamination level is ten (10) times higher than the public clearance level as defined in section 12.2.

If radioactively contaminated objects are to be moved within or across a radiation-controlled site, the so-called SCO-I limit, i.e. the *surface contaminated object level I limit*, is applied. A SCO and the associated SCO-I limits are defined as follows:

A SCO-I is a solid object on which

I. *the non-fixed contamination on the accessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed 4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters, or 0.4 Bq/cm^2 for all other alpha emitters;*

II. *the fixed contamination on the accessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed 4×10^4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters, or 4 000 Bq/cm^2 for all other alpha emitters;*

III. *the non-fixed contamination plus the fixed contamination on the inaccessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed 4×10^4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters, or 4 000 Bq/cm^2 for all other alpha emitters. [96]*

The provision for surface-contaminated objects takes cognisance of the fact that various work sites exist where it is either difficult or impossible to effectively remove the radioactive contamination from surface areas, while such objects continue to be used in a contaminated environment. To illustrate: a uranium mine has numerous work areas in which radioactive contamination occurs. When moving a contaminated object between such contaminated work areas it is not necessary and often not viable to reduce the surface contamination levels to fulfil the public clearance level, as the work area to which a contaminated object is to be relocated is also known to be contaminated. In this context, it remains important to emphasise that all non-fixed contaminants are removed as far as possible, to ensure that the contamination of previously clean areas – i.e. *cross-contamination* – is kept to an absolute minimum.

12.5 Uranium as a Radioactive Contaminant

Uranium-bearing ore which is in full secular equilibrium consists of 8 alpha emitters, and 6 beta emitters, e.g. refer to section 4.8.1. The number of alpha emitters therefore exceeds the number of beta emitters for such sources.

Freshly extracted uranium, on the other hand, only has two alpha emitters. Once partial equilibrium is reached, i.e. when the concentrate is 100+ days old, two alpha and two beta emitters are present, as is shown in Figure 186.

In the tailings material of a uranium mine, the significance of the two uranium alpha emitters from the U-238 decay chain is markedly reduced, because of the extraction of uranium. However, the total number of alpha emitters present in uranium mine tailings is still at least equal to the number of beta emitters.

12.6 Measuring Surface Contamination

Often, when dealing with radioactive contaminants that are consisting of alpha and beta emitters, it is simpler to focus on the measurement of the surface activity due to alpha radiation only, provided the surface activity from beta radiation is equal or less than that of the alpha contamination. This is due to various challenges that one is faced with when measuring the surface activity from beta sources, which include:

- Monitoring instruments often do not accurately differentiate between beta and gamma radiation. This implies that there is an additional contribution from gamma radiation when determining the beta activity on a given surface;
- Gamma radiation is penetrating radiation, which implies that gamma radiation from the natural background as well as from radioactive sources within the monitored material may contribute to measurements when determining surface activities; and
- In many environments, beta radiation from natural sources may contribute to surface activity results. When this happens, contamination levels may appear to exceed public clearance levels, even though the beta contributions are from naturally occurring sources in the environment.

Figure 121: Monitoring surface contamination in a container stacking area [34]

It is important to note, however, that there are some critical exceptions to the above observation: for example, if the contaminant is not related or originating from uranium mining activities, beta contamination can readily exceed alpha contamination.

For example, multi-use containers that are, amongst others, used to ship uranium concentrate are a case in point. Prior to their release into the public domain, and after they were used to transport uranium concentrate, every container must be cleared. However, radioactive contamination of a container could also have happened before it was used to transport uranium concentrate. For this reason, uranium conveyors thoroughly monitor the inside and outside of shipping containers before they are being packed with uranium concentrate. When undertaking such clearances, the assessor usually does not know for what purposes the container was used prior to it being screened for contamination. In such cases, one cannot assume that alpha contaminants are more important than beta contaminants, and one will therefore have to assess the contamination levels for both alpha and beta radiation. If this is not done, the conveyor may face significant financial penalties when it is later found that the container is radioactively contaminated. It is therefore good practice to ensure that shipping containers are monitored prior to them being accepted for use, to ensure that all possible radioactive contaminants are detected before they are re-used. Such monitoring must preferably be undertaken in a low-background environment, to minimise the interference of ambient gamma radiation during monitoring.

Sometimes, it is not possible to directly measure the surface contamination on all surfaces. This may be because such surfaces may not be readily accessible, or they may be curved in a way that does not allow for a sensible measurement to be made using a flat plate probe. In such cases, the total contamination is estimated by way of a gamma scan. If the dose rate close to the object in question is twice (or more) of the prevailing background in the area, the object is considered contaminated, and must therefore not be cleared for release.

Figure 122: Curved surfaces are not always readily monitored using a flat probe [34]

Wipe sample tests are used to decide whether one is dealing with fixed or non-fixed contamination, as are further described in section 12.8. A *wipe sample test* usually enables the quantification of the non-fixed contamination levels, if the *removal factor* of the surface is known. This factor, which quantifies how much of the non-fixed contamination is removed from a surface when a wipe sample test is undertaken, ranges between 0 and 1, where a factor close-to 1 is used for highly polished surfaces, while a factor much smaller than 1 is used for porous and/or absorbent and rough surfaces which retain some or most of the contaminants when a wipe test is done. As a rule, and provided that a wipe test returns measurable surface contamination levels, the surface area in question should be cleaned before its contamination levels are re-assessed.

12.7 Surface Contamination Monitoring

Various instruments are available to quantify radioactive surface contamination. One example is the Thermo™ Electra equipped with dual alpha/beta probe, as shown in Figure 121 and Figure 122. In addition, several RadEye instruments are available, such as the RadEye SX, that can be equipped with probes that are suitable for monitoring surface contamination.

The following general rules apply when using instruments for the detection and quantification of surface contamination:

1. Read the manual supplied with the instrument.
2. Connect the alpha / beta probe before switching on the instrument.
3. Prior to undertaking measurements, ensure that
   a. the cable connecting the probe to the instrument is undamaged;
   b. the probe's Mylar film and the protective grill on the probe's surface are clean, and do not show any signs of contamination. If there are contaminants on either one, carefully clean them before doing any measurements.
4. Do not touch the surface of the surface of the probe.
5. Ensure that the instrument and the probe have been jointly calibrated.
6. Check that the calibration stickers on the probe and on the instrument show that both are within the calibration validity period on the day of use.
7. Some instruments used to monitor surface contamination will, after they have been switched on, be in ratemeter mode. If so, perform the so-called *light check,* which is done by checking whether the count rate increases when the probe is exposed to direct sunlight. Should such an increase be found, the instrument cannot be used for monitoring, and must have its Mylar film replaced. To be able to remedy such situations it is recommended that a spare Mylar film is kept in the instrument's carrycase.
8. Switch the sound button, if available, to the 'off' position. This minimises potential distractions while monitoring and may also limit the concerns that persons close to where the measurement is undertaken have.
9. Set the unit of measurement to Bq/cm^2. For illustration, using the Thermo™ Electra, this is done by
   a. pressing 'setup', then using the 'up' or 'down' buttons to scroll to parameter 8;
   b. pressing 'enter', noting that the parameter 8 should be flashing, and scrolling to the unit 'Bq/cm^2', and pressing 'enter' again;
   c. scrolling to parameter 9, pressing 'enter' again, noting that parameter 9 should be flashing;
   d. scrolling to the relevant alpha calibration factor, which is recorded on the calibration certificate, and pressing the 'alpha/beta' button;
   e. repeating the same for the beta calibration factor; and
   f. then pressing 'enter' again, and 'setup', to exit the setup mode.
10. Enable the background subtraction mode. For illustration, using the Thermo™ Electra, this is done by
    a. setting the parameter 'A' to 'off';
    b. then, when in the area where contamination monitoring is to take place, pressing the 'rate/integrate' button, and allowing the instrument to integrate until the alarm indicates the completion of the counting interval, which is usually set to 1 minute (can be changed via settings);
    c. pressing 'enter' to save the integrated background to memory, in which case a letter 'b' appears in the lower left corner of the instrument's display; and
    d. beginning with the monitoring process, with the background now being automatically subtracted.

12.8 Non-fixed Surface Contamination Monitoring

Non-fixed contamination is radioactive contamination which can be readily removed from the surface of the object on which it occurs.

Whether an object is contaminated with non-fixed contaminants can be readily tested using a *wipe sample test*, as illustrated in Figure 123, and thereafter analysing the wipe sample for alpha / beta emissions. Such an analysis, which is also called *filter analysis*, can be done using an alpha / beta monitor equipped with a flat plate probe, as illustrated in Figure 124. An example of such an instrument is the Thermo™ Electra, as shown in Figure 121 and Figure 122. Alternatively, a purpose-built alpha / beta counter can be used for filter analysis, such as the Thermo™ Hand-e-Count (HEC sampler), which is the instrument depicted in Figure 81.

Figure 123: Taking wipe sample test [8]

The following process is used when taking a wipe sample test to collect non-fixed contamination for filter analysis:

1. On the object to be tested, wipe across an area A of known size, e.g. 100 cm^2;
2. Determine the most sensible removal factor R, by deciding how much of the non-fixed material on the surface would be removed during one wipe. For high-gloss surfaces, such as those of coated steel drums, the removal is complete which implies that the removal factor is 1. For rough or very rough surfaces, a removal factor 0.1 is often used. It is important to remember that the removal factor is never an exact number, but remains an estimate, and therefore a variable that one must determine with when undertaking wipe test sampling.
3. Set the instrument to count rate per minute, i.e. D.
4. Perform an efficiency test with a check source of known activity and determine the measurement efficiency $\boldsymbol{\varepsilon}$.
5. Integrate the background and enable the background subtraction mode.
6. Using the integration mode, count the filter for a period which is sufficiently long to obtain a meaningful number of counts. Counting periods of between 30 to 60 seconds are often used.
7. Determine the non-fixed surface contamination SA, in Bq/cm^2, by using the following mathematical formula:

$$\boldsymbol{SA} = \frac{\textbf{filter activity in cpm}}{\boldsymbol{A \cdot R \cdot \varepsilon \cdot 60}}$$

Figure 124: Analysing a wipe sample filter [8]

12.9 Atmospheric Contamination Monitoring

The particulate concentration in air can be measured, for example, with a pumping device, such as the Gilian™ dust monitoring pump, as depicted in Figure 125.

Such devices pump air through a filter, which then collects the dust contained in air. After a set sampling period, the volume of air that has passed through the filter is known, and the filter activity can be analysed, for example using a HEC sampler. From the activity concentration determined in this way, an inhalation exposure dose can be computed.

Figure 125: Gilian dust monitoring pumps [138]

The following procedure is used to determine the activity of the ambient dust in air, and the associated inhalation exposure dose:

1. Use the air pump as per the instructions provided for the specific instrument;
2. Determine the flow rate at which air is sampled. This is the volume V of air which is pumped during a time interval t, and then computing the flow rate V/t expressed in m^3/h;
3. For the instrument to be used for the activity determination, find the counting efficiency ε using a standardised test source of known activity, and obtain the number of counts from the background per unit time, i.e. N_0;
4. Analyse the filter by determining the number of counts N per unit time, using an analysis period which leads to a representative counting value;
5. Determine the activity concentration in air, C, in Bq/m^3, by computing

$$\boldsymbol{C} = \frac{\boldsymbol{N} - \boldsymbol{N_0}}{\boldsymbol{\varepsilon} \cdot \boldsymbol{V}/\boldsymbol{t}};$$

6. As shown in section 10.2, use the activity concentration to compute the associated inhalation dose.

12.10 Internal Contamination

Internal contamination occurs when radioactive material is either ingested or inhaled, or when contamination enters the body through an open wound. Because the latter contamination process is usually prevented by using adequate personal protective equipment, this form of internal contamination is not considered further in this section.

Internal contamination is best avoided by having effective engineering measures limit contamination, and by way of workplace controls. The latter include washing facilities, which may reduce the risk of ingestion, if all potentially contaminated persons properly and systematically apply strict hygiene measures.

Also, house rules regarding where to eat, drink and smoke, are effective, and can ensure that these do not take place in contaminated or potentially contaminated workplaces.

As a measure relating to PPE, the use of effective respiratory protection equipment, such as dust masks or respirators, can reduce the inhalation of potentially radioactive dust, and thereby lower the risk of internal contamination.

As described in section 10.6, urine bioassays can provide a first indication whether uranium was ingested. However, as covered in section 11.4, determining the exposure dose from bioassays is usually ineffective, and therefore seldom done.

12.11 Minimising Contamination

If possible, contamination must be prevented. If it is practically impossible to prevent contamination from occurring, its occurrence and spread must be minimised.

Minimising contamination implies keeping contamination levels as low as reasonably achievable at all times, rather than initiating clean-up activities when contamination levels have become unmanageable.

Activities aimed at minimising contamination include:

a. ensuring that work areas prone to contamination are regularly and systematically decontaminated, rather than sporadically only;
b. bagging and covering contaminated items prior to their removal or transport;
c. using sleeves and sleeve hoses on tools and cables before using them in contaminated areas;
d. keeping areas wet to minimise the spread of airborne contamination;
e. disallowing the transfer or removal of tools / equipment from contaminated to clean areas, without strict contamination and clearance tests being undertaken. For example, tool sets that are specifically and only for use in contaminated areas prevent the requirement to have them removed from such areas;
f. using suitable PPE, which should be disposable unless they can be effectively cleaned;
g. avoiding the use of hard-bristled brushes when sweeping the surfaces of work areas;
h. not using compressed air to clean contaminated areas and/or remove contaminants from contaminated tools and equipment; and
i. avoiding any contact of the skin or hair with contaminated tools, equipment, or gloves.

12.12 Contamination Controls

As with all control measures, the control of contamination must follow the hierarchy of controls, as described in section 7.4.

The following **engineering controls** are suitable contaminations controls:

a. **Physical design** of the workplace, to minimise contamination and maximally avoid any cross-contamination. For example, deliberate design is used to ensure that 'clean' and 'dirty' work areas are physically separated from one another.

b. **Covering techniques**, including
   - o covering uncontaminated areas prior to them becoming contaminated. For example, using paper sheets to cover tables on which soil samples are to be placed, or using removable rubber liners before stacking heavy and potentially contaminated objects on a floor;
   - o covering contaminated items prior to their transport, to prevent or at least limit any spread of contamination during their conveyance.

c. **Confinement techniques**, including
   - o covering contaminated items in bags, to limit the cross-contamination of clean areas;
   - o using glove boxes when handling contaminated items, as shown in Figure 126;
   - o using enclosures, e.g. a tent, before releasing pollutants and contaminants in an area. To illustrate: when sand-blasting contaminated objects, only do so in a special-purpose enclosure that prevents airborne material to be swept away by the wind.

Figure 126: Use of glove boxes when working with contaminated objects [139]

Suitable **administration controls** include

a. demarcating controlled and contaminated work areas;
b. using access controls, and access rules for controlled and contaminated areas;
c. restricting access to controlled and contaminated areas;
d. prescribing which PPE is to be used in each work area, with special emphasis on controlled and contaminated work areas;
e. restricting the movement of contaminated PPE, tools, and equipment, to ensure that clean areas remain uncontaminated;
f. using warning signs and labels to identify contaminated areas;
g. setting and enforcing suitable workplace hygiene rules, including that smoking, eating, and drinking is always prohibited in controlled and contaminated areas;
h. establishing and ensuring that PPE is regularly checked, for example that the wearing of respirators or dust masks is monitored, and their proper fitment and functionality is assured;
i. regularly monitoring workplaces, equipment, and PPE, to ensure workforce compliance and that minimum standards are met;
j. providing workplace-specific inductions, to ensure that staff understand, accept, and apply all relevant controls; and
k. training of personnel in the implementation of control measures, with emphasis on those measures that prevent or minimise contamination.

While **personal protective equipment (PPE)** is the control measure of last resort, PPE nevertheless remains important, and is best used to

a. ensuring that proper respiratory protection is provided and meets the requirements of a specific risk or class of risks, for example using particulate filters with specified rating for the control of airborne dust;
b. servicing, fit-testing and regularly cleaning respiratory protection devices; and
c. choosing respirators with an adequate respirator protection factor to ensure that the desired protection levels are guaranteed if such PPE is used (the respirator protection factor expresses the factor by which the dust concentration in air is reduced when the device is worn).

Figure 127: Contamination monitoring [8]

12.13 Decontamination

In a mining environment, sources of radioactive contamination include spills that occur because of equipment failure, overfilling tanks, malfunctioning valves, pipe rupture, or related breakdowns. Contamination can also occur during the conveyance of source material. Examples include spills during the transit of ore samples, incidents and accidents while conveying radioactive materials, and the transfer of contaminated scrap and similar materials. Contamination may also occur because of sloppy housekeeping, poor hygiene, sabotage, and terrorism.

When decontaminating a radioactively contaminated area, the focus must be on
a. addressing and containing the source of the problem;
b. preventing the spread of contamination; and only thereafter,
c. cleaning up the contamination.

When decontaminating a work area, the following approaches are useful:
a. always start decontamination efforts in the area(s) of lowest contamination, and work towards the area(s) with the highest concentration of contamination;
b. keep the overall costs and benefits of a clean-up in mind, remembering the ALARA principle and its adage.

When decontaminating equipment used in contaminated workplaces, the following activities are undertaken prior to clearing them for removal to unrestricted areas:
a. use a vacuum cleaner to remove loose (removable) contamination on dry porous surfaces;
b. use moist absorbent wipes to clean up loose contamination;
c. use soap and water for non-porous, water-proof items and smooth surfaces;
d. hose off non-porous surfaces, while ensuring that run-off water is recycled for later use in the plant;
e. use a high-pressure water sprayer to clean large non-porous surfaces;
f. use ultrasound on robust objects with semi-fixed contamination;
g. use solvents when decontaminating areas which are otherwise hard to clean, and rinse them off with water afterwards, while ensuring that the substrate is compatible with the solvent/cleaner used in such activities;
h. use abrasion techniques on non-porous surfaces, such as sanding, chipping, wire brushing, grinding, while minimising the generation of dust and the further spread of filings, chippings and dust arising from such activities; and
i. only use sandblasting as a last resort and ensure that the area in which it is used is fully enclosed, while minimising the emission of dust, and minimising the inhalation of dust by using PPE.

For the decontamination of floors,
a. use floor scrubbing machines;
b. avoid using hard-bristled brooms; and
c. when using the mob-and-bucket approach, ensure that the spread of contamination remains limited, which is difficult if water and cleaning tools are used to clean-up an entire area.

For the decontamination of persons, the following approaches are useful:
a. remove loose contamination from contaminated areas on the skin, e.g. use masking tape to ease the removal of such contaminants;
b. use soap and hot water to wash off contaminants, and minimise the use of cold water which tends to trap contaminants in the pores;
c. use cotton swabs to clean smaller contaminated areas, such as the nose and ears;
d. properly clean the areas under the fingernails and in-between the fingers; and
e. use detergents as required, but ensure that there are judiciously used, as some detergents and solvents may contain chemicals that cause the inflammation of the skin as well as other health-related problems.

12.14 Exercises

12.14.1 Identify the correct answer(s) in each of the following questions:

1. Contamination controls at a uranium mine are
   a) essential because workers seldom adhere to strict hygiene measures;
   b) essential because uranium is a toxic heavy metal;
   c) essential because uranium oxide is valuable and should not be wasted;
   d) essential to minimise the cross-contamination of clean work areas.

2. Tools that were used in an area with low toxicity alpha-decaying radionuclides must be repaired. How does one best clear these tools before they can be released into the public domain?
   a) Measure alpha surface contamination and clear if less than 0.04 Bq/cm^2;
   b) Measure alpha surface contamination and clear if less than 0.4 Bq/cm^2;
   c) Measure alpha and beta surface contamination and clear if less than 0.4 Bq/cm^2 for alpha and beta combined;
   d) Measure beta surface contamination and clear if less than 0.4 Bq/cm^2;
   e) Do not clear the tools if they do not meet the relevant clearance levels.

3. The tailings facility at a uranium mine are also used to permanently dispose of radioactively contaminated waste. All materials buried in this way are covered with a layer of sand at the end of each day. Which of the following applies?
   a) Upon closure, the area must be fenced off to ensure that people do not dig up contaminated scrap for at least the next 10 years;
   b) Upon closure, the area must be covered with sufficient material to ensure that the digging up of scrap is not viable;
   c) Upon closure, the area must to be covered with sufficient material to ensure that the digging up of scrap is not viable, while also ensuring that the public dose from dust and radon to all critical groups remains less than 1 mSv per year;
   d) Upon closure, the contaminated waste will have decayed sufficiently and will therefore not pose any harm to present or future generations;
   e) Radioactive waste originating in the uranium mining industry cannot be disposed of and must therefore remain wherever it was produced.

13 Ionising Radiation Sources in Uranium Exploration and Mining

This Chapter describes the main sources of ionising radiation in uranium exploration and mining.

13.1 Radiation Sources in the Uranium Exploration and Mining Industry

Numerous exploration and mining activities involve *naturally occurring radioactive materials* (NORM), i.e. mineral ore that contains naturally occurring radioactive materials. These include ores containing uranium, thorium, radioactive potassium, or a combination of these elements and their radioactive decay products.

Some NORM is characterised by low or very low specific activities of their head-of-chain members, such as U-238, U-235, and Th-232. Here it is important to note that some of the members of these decay chains have high specific activities: amongst others, these include radium, Ra-226, and radon, Rn-222. Often however, their natural concentration is low, because their rate of formation when in secular equilibrium is very slow. Radon can be an exception, as this radioactive noble gas often readily escapes from the crystal lattice of the uranium-bearing medium, and may accumulate in unventilated spaces, which is hazardous.

A variety of radioactive materials are produced in the nuclear fuel cycle, either in form of a nuclear fuel, or as secondary products which are used in medicine and industry, and as waste materials. An example of a secondary product is the radioactive isotope Cs-137, which is often used in nuclear gauges, for example those used for level and density measurements. Such radionuclides are often characterised by significantly higher specific activities than that typically found in NORM. To illustrate: the activity of a gram of Cs-137 is $3.2 \cdot 10^{12}$ Bq/g, while the activity of one gram of freshly extracted uranium concentrate is $2.5 \cdot 10^{4}$ Bq. A gram of Cs-137 therefore has the same activity as almost 130 tons of such concentrate.

The risks associated with uranium- and thorium-bearing ores depend on the concentration of the radioactive mineral ore, which is referred to as the *ore grade*. In most Namibian uranium mines, the uranium ore grade is low, i.e. containing much less than one weight-percent of uranium. As a result, the radiation-related risk associated with these naturally occurring radioactive minerals is relatively low.

The activity concentration of uranium concentrate is significantly higher than that of the ores from which it is produced. While uranium concentrate is still characterised as a low specific activity material, large volumes of such substances increase the risk of exposure to ionising radiation, especially at or close to where uranium concentrate is produced, and stockpiled.

It is also important to realise that the risk of exposure from industrial sources of radiation, e.g. nuclear gauges, as are frequently used in the mining industry, can be high, especially when being operated outside the design envelope. Sealed radioactive sources usually only contain very small quantities of actual radioactive source material, but they remain a definite radiation risk even when operated to technical specifications.

Exposure to NORM can result in exposure doses due to ionising radiation, including to workers, members of the public, and the environment. Such exposures mainly occur along the exposure pathways, as highlighted below. In addition, the uranium exploration and mining sector also uses a variety of electric and electronic tools and equipment that emit ionising radiation, including X-ray machines, XRF and ICP-MS instruments, as well as those used for non-destructive evaluation and testing.

In Namibia, activities relating to the exploration and mining of uranium are associated with low uranium-bearing ore grades. The uranium concentration of these ores is typically in a range from 100 and 1 000 parts per million (ppm), which is equivalent to a uranium concentration of between 0.01% and 0.1%.

At the exploration stage, the potential occupational and public exposure to ionising radiation is usually very low, and on average, similar to or even below the exposure due to natural background radiation. The main sources of ionising radiation in this sector include

- gamma radiation from exposed mineral ores, drill samples and drill cores;
- inhalation of dust that is generated in the drilling and blasting processes; and
- radon inhalation taking place in confined storage spaces where ore and drill samples are stored.

In the uranium mining and crushing process, the most important sources of exposure to ionising radiation include

- gamma radiation from sealed radioactive sources, uranium concentrates and the ore body, e.g. the mining pit;
- inhalation of uranium concentrate dust;
- inhalation of radon exhaled from uranium-rich ore, waste rock and tailings;
- inhalation of dust that created by drilling, blasting, mining, and crushing, and from vehicle movements associated with mining;
- inhalation of wind-blown radioactive dust from waste rock, rock dumps and tailings material; and
- ingestion of contamination, for example when having poor hygiene standards, when consuming contaminated food, or when drinking contaminated groundwater, which may happen when operations are inadequately managed and controlled.

Figure 128: Waste rock dumps, open pit, and dry tailings storage facility at Rössing [26]

Processing of uranium ore entails the successive concentration of uranium. As a result, the radiation levels along select locations of the processing chain are higher than those from natural background radiation. Potential sources of exposure to ionising radiation from this production phase include

- tanks, pipes and containers with concentrated process fluids, i.e. *pregnant liquids*, emitting gamma radiation;
- radioactive scales (jarosite) forming in tanks, pipes, pumps, and heat exchangers, emitting gamma radiation;
- uranium concentrate dust, which can be inhaled;
- confined spaces rich in radium, thereby creating high ambient radon concentrations;
- tailings material, which emit gamma radiation and can give rise to wind-blown dust;
- unsafe work practices, poor hygiene, as well as incidents and accidents resulting in spills of uranium-bearing liquids, concentrate and mineral waste, emitting gamma radiation and leading to inhalation and ingestion, and when drinking contaminated process water which has seeped into the groundwater in the absence of effective controls.

Figure 129: Processing plant at Rössing [34]

When conveying and transporting uranium oxide and yellowcake, sources of exposure to ionising radiation include

- containers and drums containing such products, emitting gamma radiation; and
- uranium dust arising from incidents or accidents in which such products are spilled.

Because radon is a decay product of radium, there is no tangible potential for radon exhalation from drums or containers in which such products are conveyed.

Figure 130: Final product drum storage at Langer Heinrich Mine [8]

13.2 Gamma Radiation

Uranium and thorium are low toxicity alpha emitters and are weakly radioactive. In most cases, appreciable gamma exposure dose rates occur where uranium or thorium are either present in significant quantities, or in a concentrated form.

Potential gamma exposure situations in the uranium exploration and mining sectors arise in the following context:

1. Ore bodies containing NORM, especially in areas where high-concentrate ores are exposed, such as in the mining pit;
2. Ore stockpiles, waste rock dumps and tailings containing NORM and its processing residues;
3. Uranium / thorium extraction plant and equipment, including
    a. tanks, pipes, and equipment used to store, leach, pump, convey or handle solutions containing radionuclides;
    b. thickener assemblies, including the continuous ion exchange (CIX), solvent extraction (SX), and roasting plants;
    c. pumps, pipes, and tanks with a build-up of radioactive scales of jarosite;
4. Uranium / thorium concentrate drums, and containers in which these are packed;
5. Sealed radioactive sources used as part of the exploration / mining operations;
6. X-ray sources, including from portable and lab-mounted XRF instruments, and other electric instruments which emit ionising radiation.

While both workers and members of the public can potentially be exposed to gamma radiation which arises in the uranium exploration and mining sectors, the risk to members of the public is usually small, unless radioactive materials are conveyed and/or stored in or close to public spaces. In addition, incidents and accidents involving radioactive sources and leading to an uncontrollable spread of radioisotopes may occur in areas that are also frequented by members of the public, which may in turn give rise to exposure doses from gamma radiation. Figure 131 illustrates some typical radioactive source materials associated with the uranium exploration and mining sectors and provides an indication of the increasing activity and concentration of radionuclides.

Figure 131: Typical radioactive source material in order of increasing activity [8]

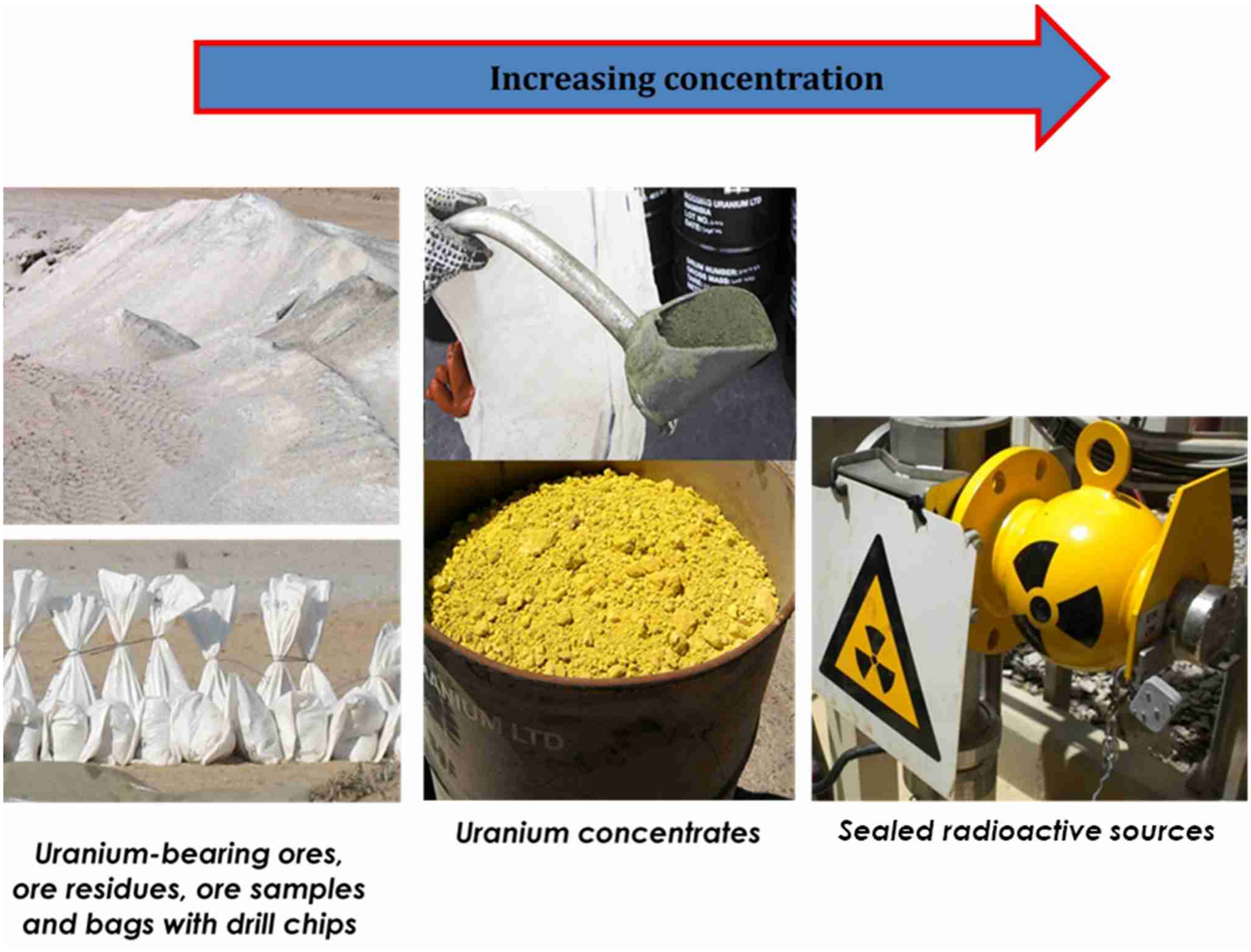


Figure 132: Crushing plant and coarse ore stockpile at Rössing [34]

13.3 Ionising Radiation from Electric Instruments

A variety of electric instruments are used in the mineral exploration and mining sectors that emit ionising radiation when in use. Such sources of ionising radiation include

1. Portable X-ray fluorescence (XRF) instruments, as are used for the analysis of ore samples, as shown in Figure 133;

Figure 133: Portable XRF analyser [140]

2. Laboratory-type X-ray fluorescent spectrometer used for mineral analysis, as illustrated in Figure 134;

Figure 134: XRF analyser used in mineral analysis laboratories [141]

3. X-ray machines, used for medical purposes, and those used for non-destructive testing (NDT), refer to Figure 135;

Figure 135: X-ray instrument for NDT [142]

4. Inductively coupled plasma mass spectrometers (ICP-MS), as are used in the analysis of minerals and mineral concentrates, and illustrated in Figure 136; and

Figure 136: Inductively coupled plasma mass spectrometer [143]

5. Ultraviolet sources of light, as are for example used for molecular absorption spectrometry in a laboratory setting, refer to Figure 137.

Figure 137: UV absorption spectroscope [144]

Exposure to radiation from any of the above sources of ionising radiation can lead to occupational exposure doses. Should such radiation sources be used close to or in public settings, which is unlikely, exposure to radiation may take place. However, provided that best practices are applied, the risk of exposure of members of the public is considered very low, as facilities at which any of the above-mentioned sources of ionising radiation are used are often strictly access controlled and often use shielding to decrease the likelihood of accidental and/or involuntary exposures.

13.4 Long-Lived Radioactive Dust

Dust is ubiquitous in the environment, particularly when it is dry or hyper dry, with little or no vegetation and other ground cover, as is the parts of Namibia's Erongo Region.

The action of the wind generates dust. Human activities enhance the potential for copious dust production, particularly those associated with mineral exploration, mining, and milling.

The environment contains various naturally occurring radioactive materials, notably uranium and thorium and their decay products, as well as potassium-40 (K-40). These elements are therefore also contained in environmental dust. The concentration of radionuclides from the uranium and thorium decay chains is enhanced if mineral deposits are rich in these elements, such as is often the case in areas where uranium, gold, thorium, rare earth elements, lead and copper are mined, as well as in mineral sands mines.

In dry climates, exploration and mining activities generate substantial amounts of dust, which enhance the potential that long-lived radioactive dust (LLRD) is added to the natural environmental dust load. Once LLRD is mobilised, it is readily inhaled, ingested and deposited.

At uranium mines, mineral ore dust is an important source of low-level radioactivity, and its impacts depend on the ore grade. Once uranium is concentrated, its activity is much higher than that of mineral ore dust, which implies that it is an additional important source of potentially inhalable and ingestible dust.

Figure 138: A mobile uranium ore crushing plant [8]

Atmospheric dust mainly originates from

1. mineral exploration activities, especially when dry-drilling techniques are employed, as well as from sample collection and splitting, and to a lesser extent from sample storage;
2. mineral mining and milling activities, including crushing (as shown in Figure 138), load and haul operation (Figure 139), and from blasting as illustrated in Figure 141;
3. vehicle entrainment, i.e. dust generated from the movement of vehicles in areas with radioactive dust;
4. emissions from vehicles, from stacks of power plant, roasters, incinerators, burners and other sources in which material is combusted or burnt, as well as fires;
5. dry storage of mining tailings materials; and from the
6. forces of the wind, and wind erosion, especially those acting in areas where radioactive ores are exposed, such as the pit area, stockpiles, waste rock dumps, and tailings storage facilities.

Figure 139: Load and haul operations at Rössing [34]

At uranium production facilities, both yellowcake and calcined uranium oxide can cause considerable inhalation doses in exposed persons. Care must be taken to physically separate workers from those areas where such dust is generated, which is usually achieved through engineering controls. This ensures that work processes are designed to minimise any direct contact with uranium concentrate. Handling the product is minimised through the application of administrative controls, and PPE is a strict requirement in all process areas and must be worn.

As an important atmospheric pollutant, radioactive dust from the exploration and mining sector can be a source of both occupational and public exposures to ionising radiation.

Figure 140: Uranium drumming facility showing where uranium concentrate dust is deposited [8]

Figure 141: Blasting at Rössing [34]

13.5 Radon and Radon Decay Products

Radon and the radon decay products (RDP) are a part of the uranium and thorium decay chains. The radon exhalation rate from disturbed soils and mineral ores increases as the concentration of uranium/thorium and/or their decay products increases in the substrate, and as the soil's permeability increases.

When uranium is mined in open pits, the risk associated with elevated radon concentrations is mostly low, as natural ventilation causes the rapid mixing of radon into the ambient air. However, higher concentrations of radon and RDP can occur, and are frequent in non-ventilated spaces as well as poorly ventilated areas.

Locations that may exhibit elevated radon (thoron) concentrations include

1. Areas underlain by uranium (thorium);
2. Uranium mining areas, especially in underground mines, and to a much lesser extent, in mining pits where uranium-bearing ore is produced;
3. Dry tailings storage facilities, such as those at uranium mining operations;
4. Work places having inadequate ventilation, and those built on uranium- and radium-rich foundations;
5. Poorly ventilated mining shafts, underground tunnels and volume-constrained work areas containing uranium; and
6. Containers that are used to store uranium-bearing ore, crusher bins and other containments in which uranium-bearing material is stored.

Radon inhalation, and the inhalation of RDP, are associated with an inhalation exposure dose, and these can be a source of both occupational and public exposures to ionising radiation.

Figure 142: Backfilling the contaminated waste site in the tailings storage facility at Rössing [34]

13.6 Ingestion of Radionuclides

Radionuclides that arise because of mineral exploration and mining activities can be ingested, and in this way, contribute to an internal exposure dose.

Such exposures can occur in an occupational setting, as well as in public settings. In many cases, such exposures to radionuclides depends on the concentration of airborne dust in the ambient air, the dust fall-out rate, and the prevailing hygiene practices that are applied.

In an occupational setting, an accidental ingestion can occur when

1. uranium-bearing materials, such as uranium concentrate dust, or uranium-bearing ore dust are inhaled and/or ingested while at work;
2. radioactive materials are ingested because of the intake of contaminated food and/or liquids; and
3. when poor hygiene standards and practices cause the radioactive contamination of food and/or water or other liquids, which are then consumed.

Members of the public can ingest radionuclides when

1. uranium-bearing ore dust is inhaled and/or ingested while in public areas;
2. ingesting food and/or liquids which are contaminated with radioactive dust originating at uranium exploration and/or mining operations;
3. drinking contaminated groundwater that contains seepage from tailings storage facilities or uranium processing facilities;
4. ingesting food that is produced with water which is radioactively contaminated; and
5. ingesting food (mostly fruits and vegetables) including dust deposits containing uranium-bearing ore particles.

Figure 143: Wind-blown ore dust at a coarse ore stockpile [34]

13.7 Radiation Hazards in the Mineral Exploration and Mining Sectors

This section quantifies the risk of exposure to the most important sources of ionising radiation that are common in the mineral exploration and mining sectors when dealing with NORM.

13.7.1 Gamma Radiation

In many cases, the activities of NORM sources dealt with in the mineral exploration and mining sectors are of low. This implies that the risk associated with an exposure to such NORM is often considered low, especially when compared to the risk of exposure from industrial sources. However, it is important to quantify area- and activity-specific risks rather than rely on generalised opinions or beliefs.

Below is a summary of the typical radiation risk areas as found in the NORM exploration and mining sectors, and the characteristic dose rates in such areas:

- Uranium mining areas: between 0.1 and 5 µSv/h;
- Ore and waste rock stockpiles in uranium mining: up to 3 µSv/h near ore stockpiles;
- Tailings storage facilities of uranium mines: between 0.5 and 5 µSv/h;

- Processing areas in a uranium mine: between 0.5 and 5 µSv/h;
- Pipes and tanks containing pregnant liquid in uranium mining: between 0.2 and 25 µSv/h;
- Pipes, pumps, and related equipment containing radioactive scales: between 0.2 and 40 µSv/h when in direct contact with jarosite scales, and some solution tanks. In case of an extended build-up of scales, the contact dose rate may be in the range between 25 µSv/h and 150 µSv/h;
- Product recovery area, drum filling plant, and container packing areas in a uranium production facility: between 1 and 40 µSv/h in areas of high product concentration, such as drum storage areas, as well as inside packed shipping containers;
- At 1 m from a drum containing uranium concentrate: up to 5 µSv/h;
- Contact dose rate on a container in which uranium concentrate drums are stored: up to 50 µSv/h;
- Sealed radioactive sources: 1 µSv/h at 1 m from a locked source, and readily exceeding 200 µSv/h when directly in the beam of an unlocked source.

In minerals sands mining operations, for example titanium sands with thorium-rich ores and tailings, the dose rate at stockpiles can reach 40 µSv/h and depends on the uranium and/or thorium concentration of such mineral resources.

In gold, lead and copper mines, uranium and thorium can be present in the ore, and will therefore also be found in tailings materials. As before, the dose rates for stockpiles and tailings depend on the uranium / thorium concentration of the ore and are often like those in the uranium mining sector, as highlighted above.

Figure 144: Cleaning of uranium concentrate drums prior to loading at Rössing [34]

13.7.2 Ionising Radiation from Electric Instruments

Electrically-powered instruments that emit ionising radiation while in operation do mostly not contain radioactive source materials. Therefore, the instruments touched on in this section exclude those containing radioactive sources.

Provided that electric instruments emitting ionising radiation are used as specified, the radiation-related risks of such instruments are low. It is nevertheless instructive to consider and quantify the area- and task-specific risks associated with such sources.

The following summary identifies some typical risk areas and provides order-of-magnitude estimates of the dose rates of such instruments:

- X-ray scanner: between 0.01 and 2 μSv/h;
- Portable XRF machine: between 0.1 and 10 μSv/h;
- ICP-MS in a laboratory: between 0.005 and 2 μSv/h;
- X-ray unit used for non-destructive testing: between 20 mSv/h and 40 mSv/h at 1 m distance from the instrument.

Figure 145: Sealed sources store [8]

13.7.3 Long-Lived Radioactive Dust

The presence of LLRD in ambient air implies an inhalation risk. This risk is directly proportional to the activities of the ores contained in such dust, implying that a high ore concentration leads to proportionally higher exposures than a low concentration does.

In the uranium exploration and mining sectors, i.e. whenever uranium is present in the mineral ores that are handled, the ore grade and therefore the concentration of uranium in such ores determines the exposure risk from inhalation.

In Namibia, where uranium ore grades are mostly low, exposure doses from the inhalation of ore dust are low. Consequently, the radiation-related risk from the inhalation of dust generated in the exploration, mining, and crushing of low-concentration uranium ore is mostly low and implies that the precautionary application of dust masks is usually sufficient. This applies to all mining environments characterised by low uranium and/or thorium ore grades, including those in related mining operations such as gold, rare earths, lead, copper, and mineral sands operations. In such mining environments, inhalation dose rates can reach 0.5 µSv/h or more, especially when dust control measures are not effectively applied, and/or when personal protective measures such as dust masks are not worn.

When uranium is extracted, concentrated, and dried, the inhalation risk increases as the activity of the product increases. In such production environments, effective engineering controls are necessary, and respiratory protection in the form of half-face or full-face respirators are often necessary. In the absence of proper engineering controls, or if these are ineffective, and without adequate respiratory protection, inhalation dose rates can reach 50 µSv/h or more.

In view of the considerable dose rates in areas where uranium is concentrated, dried, and drummed, facilities must be designed to minimise the leakage of concentrate. In addition, strict process and related administrative controls are necessary, and the use of respiratory protection is obligatory.

In minerals separation plants, particle separation occurs by way of magnetic and electric separation, which implies that copious amounts of airborne dust are generated in such processes. Inhalation dose rates in magnetic separation plants can reach 25 µSv/h if they are not sufficiently controlled. If the substrate is rich in either thorium or uranium or both, engineering and administrative controls, as well as efficient respiratory protection are essential.

Figure 146: Mining pit used for backfilling, Energy Resources Australia [91]

13.7.4 Radon and Radon Decay Products

Radon is exhaled from soils which contain uranium, and from tailings which include uranium progeny, such as radium. While natural or forced ventilation effectively reduces the risk of inhalation of radon and its decay products, at-risk areas include confined spaces such as tunnels and containers that are not or cannot effectively be ventilated.

Typical open-area ambient atmospheric radon concentrations at a uranium mining site range between 20 and 200 Bq/m^3, in contrast to areas which are far-away from such mining operations, where ambient atmospheric radon concentrations are typically of the order of 10 Bq/m^3.

The risk of inhaling radon-rich air, or particulates which have radon progeny attached, can be considerably higher in unventilated and closed areas than in the open. To illustrate: in offices which are built on radon-emitting substrates, or in underground tunnels and tanks containing radium scales, radon concentrations can reach 2 000 Bq/m^3 or more.

In thorium-rich environments, such as in mineral sands operations, the risk associated with the inhalation of thoron is low, because of the short half-life of this radioactive isotope of radon. As a result, controls are often not needed, although this is both process- and area-specific and must be verified for each potential risk area.

13.7.5 Ingestion of Radionuclides

In the exploration and mining sectors, ingestion of radionuclides can be minimised by physically and procedurally separating contaminated work environments from areas which are used for eating, drinking, and smoking. In addition, strict hygiene measures, and the availability of facilities to minimise cross-contamination, can reduce the probability of an accidental ingestion of radionuclides further.

In uranium mines, the most significant ingestion risk exists in work areas in which uranium concentrate is present. To illustrate: areas such as those where yellowcake is dried and drummed, or uranium concentrate is calcined, crushed, and drummed, are the areas in which the risk of ingestion is highest.

It is important to note that ingestion can occur directly, through the direct intake of uranium concentrate, or by way of secondary ingestion. In the latter case, ingestion is the result of the inhalation of dust, in situations where respiratory protection is either not used at all, or its use is ineffective, for example because the equipment is not properly fit-tested before it is used.

Urine bioassays for uranium in urine are a crude method to establish if uranium ingestion has taken place, but it does not allow for the monitoring of ingestion of radionuclides such as radium. As a result, bioassays are not used to make predictions of an exposure dose associated with the ingestion of radionuclides and remain an indicator of the effectiveness of hygiene measures as they are applied at work.

13.8 Members of Critical Groups

When considering the exposure to radiation, a *critical group* is the group of individuals that are expected to receive the largest exposure dose from radiation for any specific pathway in a given location [140].

Therefore, to identify the critical group for a specific exposure situation one asks: who is most at risk of being exposed given a specific exposure pathway? When an individual or group that is most exposed given a specific exposure scenario can be identified, the critical group for the given exposure situation has been found.

The principle of a critical group has been refined by the ICRP and has more recently been referred to as the *representative person* [146].

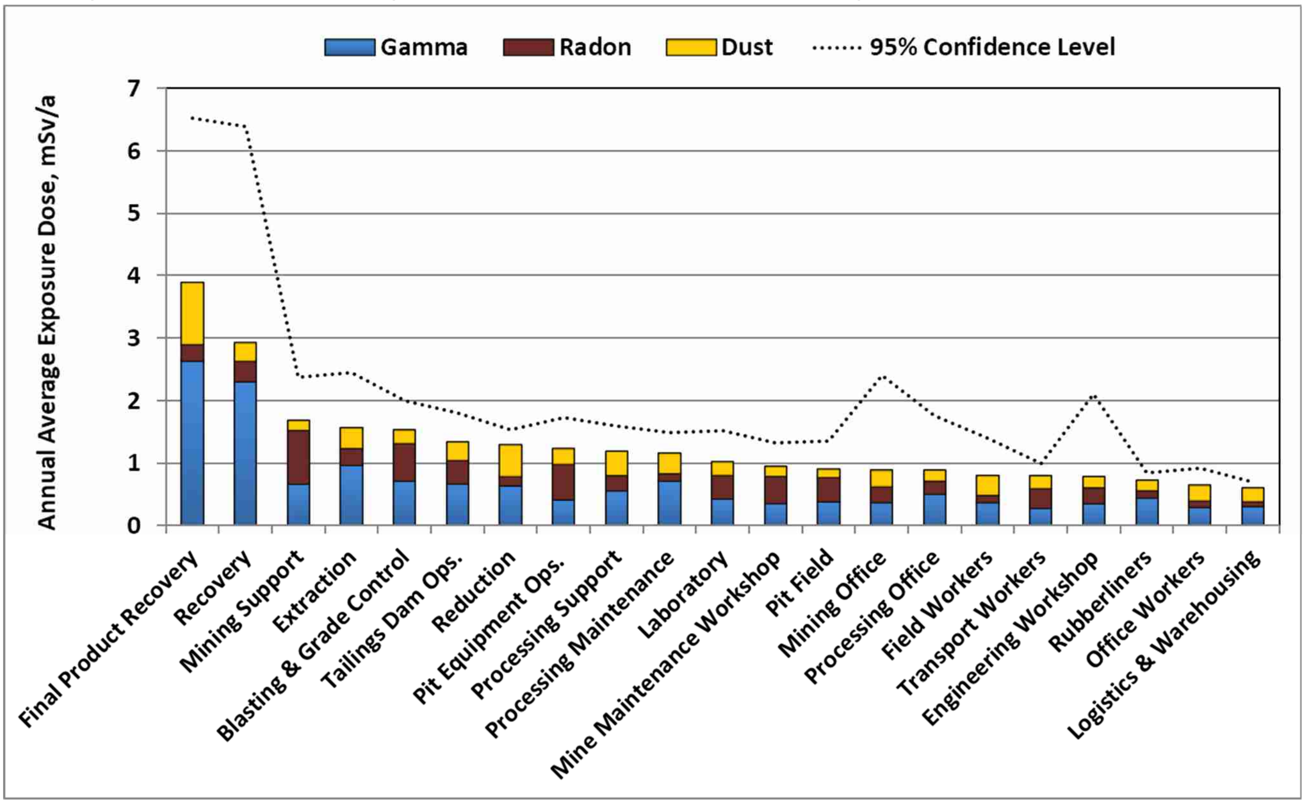
In an occupational setting, critical groups are sometimes defined in terms of *similar exposure groups*, or *job exposure matrix*. In contrast, for members of the public, critical groups are defined in terms of communities that have specific habits and/or reside in a location that can lead to exposure to ionising radiation. The similarities and differences between occupational and public critical groups are illustrated in the examples presented in the next subsections.

13.8.1 Critical Groups in the Occupational Context

Persons working in the final product recovery work area at a uranium mine constitute a critical group relative to the inhalation risk of uranium concentrate dust, as well as to the exposure to penetrating gamma radiation. Such a group of persons who are similarly exposed because of the specific occupational setting is one of several critical groups at a uranium mine.

Often, a group of persons that are similarly exposed because of the specific occupational setting in which they are active is referred to as a *similar exposure group*, which is abbreviated SEG. An SEG is unique in terms of the specific work area and set of occupational activities that are undertaken, and therefore in terms of the occupational exposure to ionising radiation incurred in a typical work year.

Figure 147: Annual average exposure doses of SEGs at Rössing in 2016, in mSv/a [147]



13.8.2 Critical Groups in the Public Context

Members of the public may be exposed to ionising radiation originating at a practice using radioactive source materials or other sources emitting such radiation. Such members of the public can then form a critical group given a specific exposure situation.

The following examples illustrate the concept of critical groups as it applies to members of the public.

- A mineral exploration company has decided to use their property which is immediately adjacent to a golf estate where members of the public reside to store considerable quantities of uranium-bearing mineral ore samples. The residents living in the estate form a critical group of exposed members of the public, specifically in terms of the direct external exposure pathway, and the atmospheric pathway relating to the inhalation of dust, radon, and radon progeny.
- Members of a community living nearby a uranium mining operation, refer to Figure 148, in terms of the atmospheric pathways relating to the inhalation of dust originating at the mine, and the deposition and ingestion of such dust on their crops.
- A group of farmers depends on groundwater resources to meet their water requirements. It is speculated that this resource is steadily contaminated with radionuclides originating from tailings seepage of a near-by mining operation. The group of farmers therefore forms a critical group of members of the public as it relates to the aquatic pathway.
- Members of a group of residents, in terms of the direct external exposure pathway relating to a broken-down truck conveying uranium concentrate, as it entered the suburb.
- Members of a group of residents, in terms of the direct external exposure pathway relating to the use of X-ray equipment for the non-destructive testing of welding seams of a pipeline that is constructed adjacent to their suburb.

To determine the exposure dose of members of a critical group, a dose assessment is undertaken. This may entail the definition of one or several critical groups, to quantify the maximum exposure dose by way of an exposure pathway at specific receptor locations, even if people do not permanently live and/or work in such locations.

Figure 148: Member of a critical group of members of the public near-by a uranium mine [34]

14 The Radiation Baseline Assessment

This Chapter introduces the process and steps that underpin a radiation baseline assessment.

14.1 Introduction

Before a NORM exploration or mining operation can commence, a radiation impact assessment is needed. This must identify, describe, and quantify the potential impacts that the operation will have on people and the environment. In this way, a radiation impact assessment enables rational decision-making, most notably those of regulatory authorities responsible for radiation protection, water, the environment, and others. If the assessment suggests that the impacts associated with the proposed project are socially acceptable, and can be mitigated and managed, such projects have the official blessing to proceed.

In terms of radiation risks, an impact assessment needs to include a baseline assessment of the existing radiation levels in the environment prior to the commencement of activities or operations. Without a baseline assessment, it is often challenging to determine occupational, public, and environmental exposures resulting from the operational phase. As such, it is important that a baseline assessment quantifies the likely and expected contributions and changes that are brought about by new operations. This enables the practitioner to gauge whether and in what direction the changes from status quo conditions will be.

A radiation baseline assessment for an operation is usually different from a radiation background assessment: a radiation baseline assessment is an assessment of radiation-related conditions and impacts without the existence of the new/proposed operation, and usually includes the contributions from all relevant sources, even if these are not of natural background origin. In contrast, a radiation background assessment quantifies the contributions due to the different components of natural background radiation.

To illustrate: a baseline radiation assessment for a new uranium mine usually includes the potential radiation exposure to people and the environment from background and existing operations in the region. This may contribute to the exposure of workers at the newly proposed operation, as well as of members of the public and the environment adjacent to such operations.

14.2 Background Radiation

An assessment of the background radiation includes all radiation sources that exist in each environment, and therefore include man-made radiation sources.

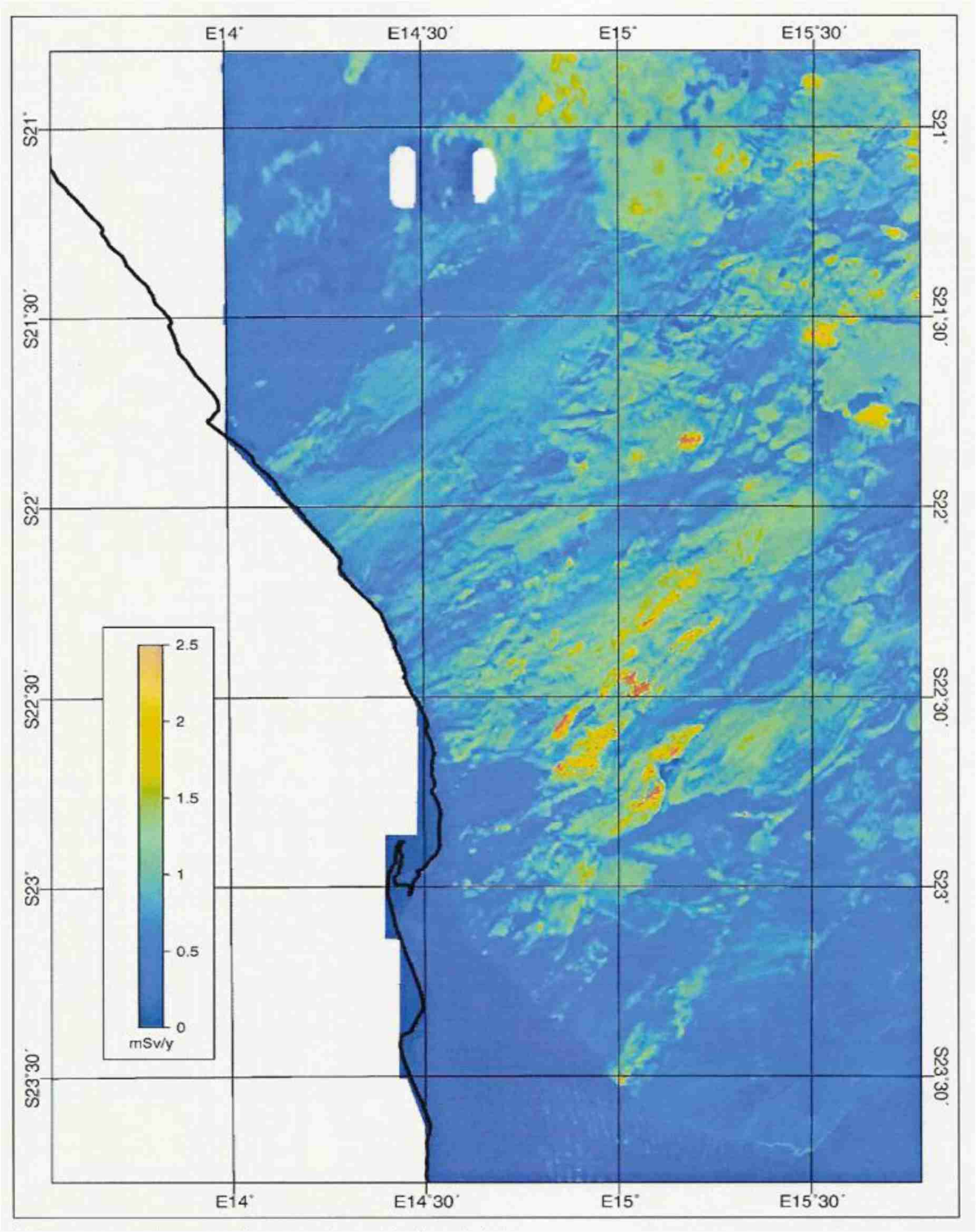
In a radiation impact assessment, man-made sources that are already part of the background radiation field are not considered separately, as these have already been extensively studied by organisations including UNSCEAR and others, to which reference can be made, if needed.

14.3 Gamma Radiation

To quantify the contribution of gamma radiation to the background radiation field in an area, it is useful to quantify and map the gamma dose rates in the area. For this purpose, aerial survey data is useful.

Alternatively, or to ground-truth aerial information, a ground-based monitoring grid can be used to quantify the prevailing gamma dose rates in the area under investigation, noting that the contributions of cosmic radiation must be considered as well. Figure 149 illustrates the annual average exposure dose due to natural terrestrial gamma radiation in Namibia's Erongo Region [33].

Figure 149: Natural terrestrial radiation in the Erongo Region, converted to a dose, in mSv/a [33]



14.4 Atmospheric Pathway

A radiation baseline assessment usually includes the elements of the atmospheric pathway relating to the inhalation of radioactive dust and radon, as may be contained in the ambient atmospheric air in the area under consideration.

14.4.1 Atmospheric Dust

Many regions in the world experience intermittent high wind speed events, which are often associated with the transport and dispersion of considerable amounts of atmospheric dust.

A baseline assessment of the ambient concentration of atmospheric dust in an area must therefore take meteorological realities as well as ambient dust concentrations into account. Usually, such measurement data must be available for at least one full year, to cover the wide range of atmospheric conditions occurring in a typical year. Often, information gathered over several years may be more representative of average conditions than data from a single year only. It is also important to recognise that weather conditions vary significantly from one location to the next. This implies that extrapolations from one specific location to 'the remainder of the area' may not be justified, and their validity must be checked. Despite such uncertainties regarding the input data, one often uses atmospheric modelling software to forecast dust distributions across an area, based on input data from a handful of locations only. This can lead to absurd predictions and must therefore be validated taking actual empirical data into account.

Figure 150 shows an example of the predicted baseline PM_{10} dust concentration in the Erongo Region [33]. It is based on the inputs from four measuring stations, located at Swakopmund, Gobabeb, Etango and Trekkopje, thus leading to a limited data set which was used in an air dispersion model. The result is the average PM_{10} concentration across the Erongo Region. Based on this prediction, the average atmospheric PM_{10} dust concentration in areas that are coloured in orange, including the town of Arandis, exceeds 50 $\mu g/m^3$. In contrast, and based on data collected over a decade, the empirical PM_{10} concentration determined at Arandis found average annual concentrations of the order of 10 $\mu g/m^3$. The discrepancy of a factor 5 between a modelled and empirical ambient dust concentrations emphasises the necessity to base radiation impact assessments on empirical data, whenever available. It also emphasises that data verification in form of ground-truthing is critically important, to ensure that modelled results do indeed correlate with actual in-field data.

14.4.2 Atmospheric Radon

For atmospheric radon concentrations, similar considerations as is the case for dust concentrations apply: for a realistic baseline assessment, sampling must extend over at least one full year, preferably longer, and the distance between individual sampling stations must be sufficiently small to allow for the meaningful extrapolation across stations.

Figure 151 shows the results of a radon survey at the Rössing Mine and surroundings, using radon cups across a grid spaced between one and two kilometres, at one metre above ground level. Cups were exchanged every three months during the monitoring program which took place over three years. The results show that the atmospheric radon concentration due to mining activities does not extend for more than 10 km beyond the main on-site radon sources, such as the pit, waste rock dumps, and tailings storage facilities.

Figure 150: Predicted annual average baseline PM_{10} concentrations in the Erongo Region [33]

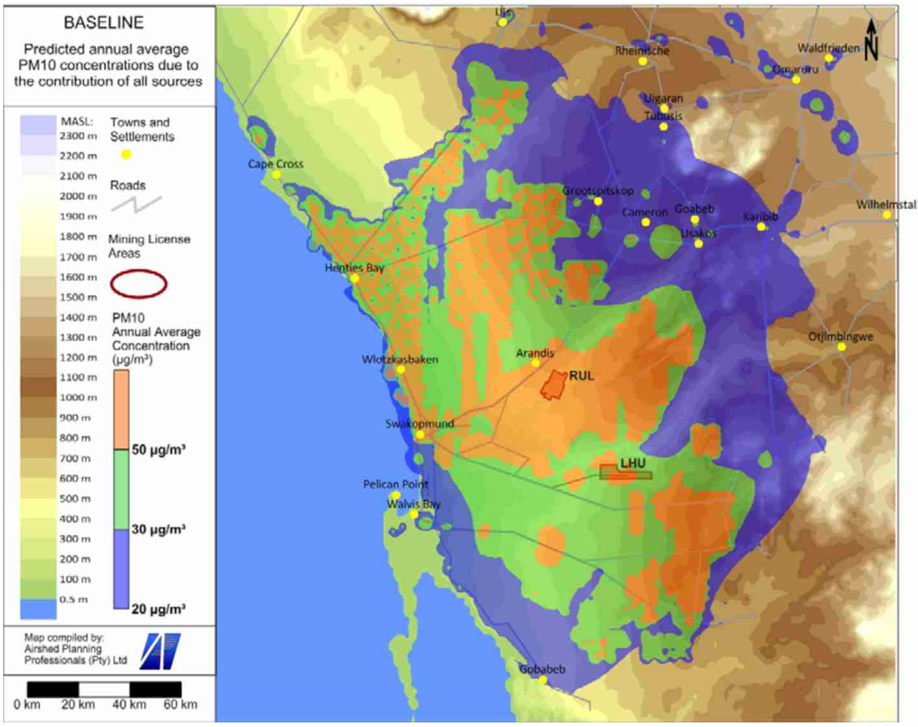
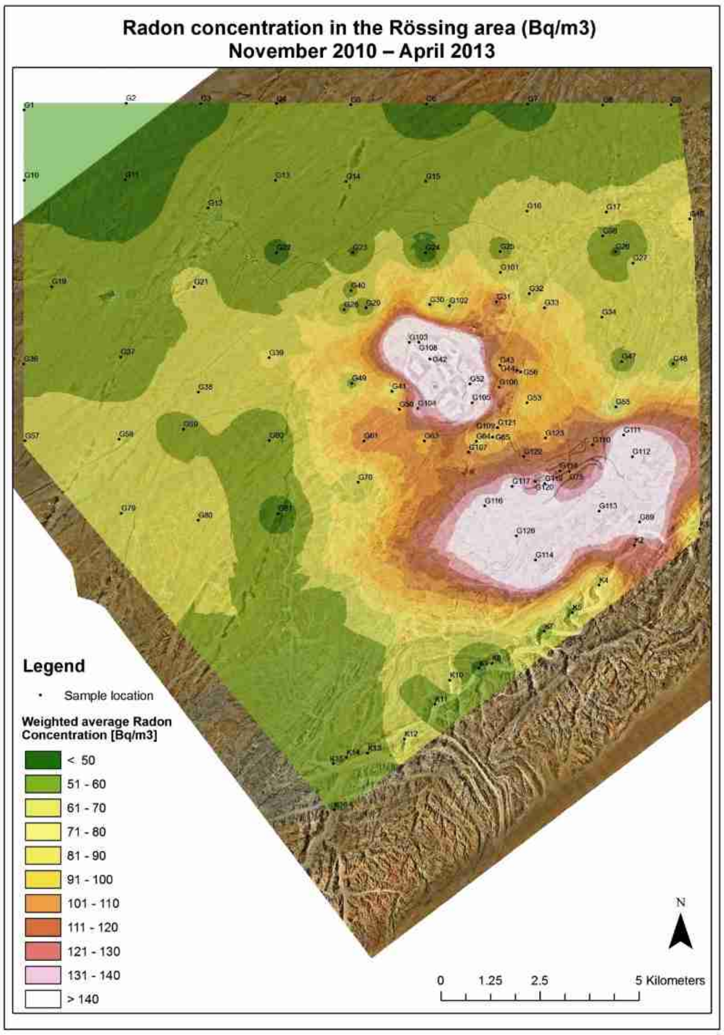


Figure 151: Empirical radon concentrations from a 3-year monitoring program at Rössing [127]



14.5 Aquatic Pathway

Radiation exposures from the aquatic pathway depend on several factors, including radionuclide discharge rates, evaporation, mixing rates, radionuclide intake rates, and how wet/dry an area is. In a dry and sparsely populated environment, radiation exposures from the aquatic pathway are usually small.

Sources that may contribute to radiation exposures include the degree of radionuclide contamination of groundwater, which may arise when water from tailings facilities seeps into the groundwater. Other factors include the quantity of water consumed, by people, and animals and crops used for human consumption.

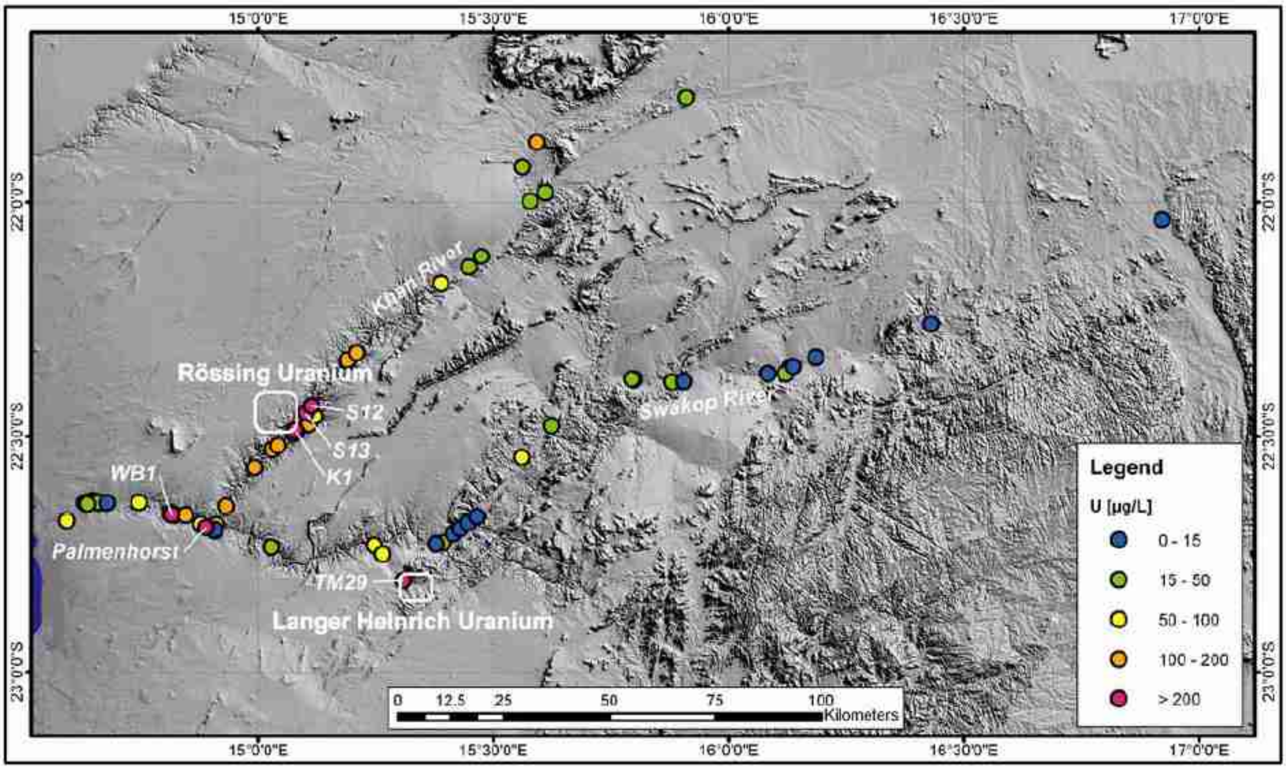
The radionuclide concentration in groundwater sources of both the Swakop and Khan Rivers in Namibia's Erongo Region are highly variable, and they depend on the surrounding substrate, its permeability, recharge frequency and rates, abstraction rates, as well as the actual evaporation rates over the dry years.

Some of these groundwater sources are highly saline, and unsuitable for public consumption. In such cases, the potential impacts from the uptake are limited to such water used for animals and crops.

Groundwater in dry rivers often exists in individual non-continuous aquifers. Such separate water compartments are small and disconnected pockets containing water. Their replenishment, due inflows from one compartment to the next, only occurs during periods of upstream rainfall. This implies that – in arid lands – the recharge of such underground water storage areas is sporadic and infrequent.

As part of the Strategic Environmental Assessment undertaken in the Erongo Region [33], the groundwater quality in aquifers was assessed [148]. Figure 152 depicts the uranium concentration in select boreholes along the main waterways in the Region. These show a significant variability, both up- and downstream of existing uranium mines, and is the result of the factors identified at the beginning of this section.

Figure 152: Uranium concentrations in the Swakop and Khan Rivers, Erongo Region, in µg/L [148]



15 Occupational Radiation Protection and Radiation Safety

This Chapter introduces the foundation of applied radiation protection and radiation safety in the workplace.

15.1 Occupational Dose Limits

Occupational radiation protection is underpinned by the ICRP principles of justification, optimisation, and limitation [45]. Today, these principles are universally adopted, and define the framework within which radiation protection measures are undertaken.

The principle of limitation refers to exposure dose limits, which are based on ICRP recommendations, and which are implemented in the IAEA Safety Standards [1]. Since its publication, many nations have adopted them into their respective national regulations.

The Namibian occupational dose limits for adult workers are summarised in Box 21 [3].

It is reiterated that the equivalent dose to the lens of the eye has, since the publishing of the Namibian Regulations, been adjusted downwards by the IAEA. This implies that the local regulations in regard to this limit are not in agreement with the IAEA Safety Standards [1], as highlighted in section 9.6.

In sectors other than the medical sector, the whole-body dose, and the equivalent dose to the lens of the eye, can in most instances be assumed to be the same. However, in select practical settings, for example where radiation sources with narrow beams are used, the equivalent dose to select parts of the body, such as the eye, can differ from the effective whole-body dose.

15.2 Occupational Exposure Pathways

In occupational settings dealing with radioactive source materials, the principal occupational exposure pathways include some or all the following:

- Direct external exposure to penetrating radiation, e.g. from gamma radiation, X-rays, and ultra-violet radiation;
- Internal exposure from the inhalation of long-lived radioactive dust;
- Internal exposure from the inhalation of radon and its decay products; and
- Internal exposure from the ingestion of radioactive materials.

In practices using electrically-powered sources of ionising radiation, the principal exposure pathway is the direct external exposure to penetrating radiation in form of X-rays and/or ultra-violet light.

15.3 Radiation Protection Controls

Radiation protection controls are used to keep occupational exposure doses as low as reasonably achievable, and to ensure compliance with the legal dose limits.

As discussed in section 7.4, radiation protection controls must follow the hierarchy of controls. They range from engineering controls, which are the most effective ones from amongst the suite of control measures. Thereafter, administrative controls are applied. If the above is insufficient, the use of personal protective equipment is necessary. It is noted however that the latter controls have the lowest effectiveness of the measures in the hierarchy of controls.

15.3.1 Engineering Controls

To ensure that engineered controls are in place, and are afforded the highest priority, it is important that design criteria for buildings, plant and equipment explicitly include and address radiation safety requirements.

Considerations of relevance to engineering controls as applied to radiation safety requirements are essential whenever there are changes or replacements to existing buildings, plant, and equipment, as well as when a greenfield project is planned.

Common engineering controls applied to reduce the risk of exposure to ionising radiation include the

- use of structures, buildings and covers to limit dust emissions, as illustrated in Figure 153;
- use of liners for stockpiles, dams, and tailings facilities, to minimise the seepage of contaminants into the groundwater, as illustrated in Figure 154;
- seepage recovery and control systems, to minimise the seepage of contaminants into the soil and groundwater resources;
- incineration of waste, to limit the need for environmental disposal of contaminants;
- area zoning; and
- forced ventilation in underground settings and locations with limited natural ventilation.

Figure 153: Covered ore stockpile as an example of engineering controls [170]

Figure 154: Large-scale lined tailings storage facilities as an example of engineering controls [8]

15.3.2 Administrative Controls

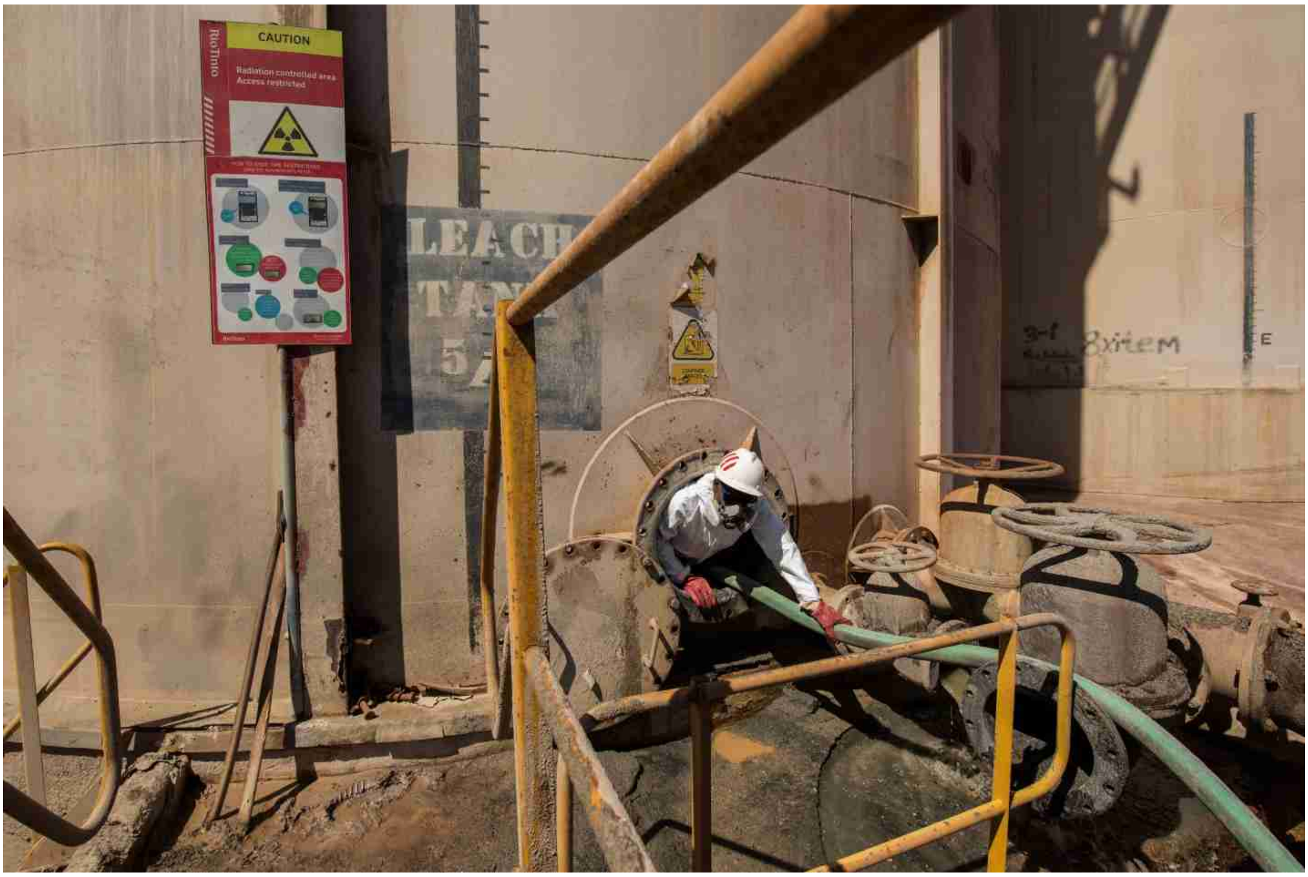
Where engineering controls are insufficient, or ineffective, administrative controls are needed. Administrative controls include inductions, area-specific instructions, workplace rules, standard operating procedures, training, and others.

Often, administrative controls are less effective than controls that have been engineered. This is because administrative controls necessitate an almost continuous and ongoing effort to ensure that messages reach the relevant audience, are properly understood, are and can be effectively enforced, and are complied with. This necessitates training, re-training, management, and supervision, as well as the commitment by end-users to adhere to rules.

Common administrative controls that aim to reduce radiation hazards include

- Induction training, including area- and task-specific inductions;
- Provision of instructions regarding health, safety, and hygiene;
- Workplace rules, including area-specific time limitations and time restrictions, as illustrated in Figure 155;
- Signage to indicate area-specific requirements, including how specific workplace rules are to be implemented, as illustrated in Figure 155;
- check sheets for hazardous materials, tools, and equipment;
- standard operating procedures, as well as area-specific procedures, such as lock-out procedures;
- training and instruction about the implementation of workplace rules;
- clearance procedures with appropriate checks to ensure that the spread of contamination through people, and/or on tools and equipment is controlled; and
- emergency preparedness and emergency responses, which necessitates planning and regular drill exercises.

Figure 155: Signage explaining time restrictions as an example of administrative controls [34]



15.3.3 Personal Protective Equipment

If both engineering and administrative controls are insufficient or inadequate, the use of PPE is necessary. In other words, PPE is used when all other control options have been exhausted and do not provide sufficient or adequate protection.

In most cases, radiation dose rates encountered in the uranium mining industry do not necessitate the use of PPE for the control of penetrating radiation. However, PPE is often necessary to provide for respiratory protection, for example to limit inhalation and ingestion risks. In addition, suitable work clothes are often required to minimise contact between the body and radioactive substances and/or contaminated objects.

The selection of respiratory protection is based on the suitability to control a risk, and on the user's wearing comfort, as illustrated in Figure 156.

Effective respiratory protection relies on the implementation of a clean-shaven policy, except in cases where forced-air respirators are used. Re-usable respirators must be regularly and rigorously cleaned, and inspected, to ensure that such equipment provides effective and ongoing respiratory protection. The responsibility for checking respirators, replacing filter cartridges, and arranging for fit-testing must be defined, and adhered to. Any person who is obliged to use respiratory protection must undergo fit-testing to identify the type and size of respirator that must be worn when relevant.

Induction, area-specific training, as well as signage must be used to communicate the type of PPE that is required in each work area, Figure 156 shows an example of the PPE requirements in the fine crushing work area at Rössing Mine.

Figure 156: Personal protective equipment used in final product recovery at Rössing [34]

Figure 157: Area-specific signage showing PPE requirements for a work area at Rössing [34]

15.4 Work Area Classification

Work areas are classified according to their inherent risk profile.

Three main radiation-relevant work area classifications are utilised, as introduced below.

15.4.1 Controlled Work Areas

The Namibian radiation protection Regulations define *controlled work areas* as:

> *'…any area in which specific protective measures or safety provisions are or could be necessary for*
>
> *a) controlling normal exposures or preventing the spread of contamination during normal working conditions; or*
>
> *b) preventing or limiting the extent of potential exposures.'* [3]

Sound judgment is required to decide what constitutes a sufficient risk to declare a specific work area as a controlled area. Such decisions are best based on area-specific risk assessments. In addition, and as regulatory provisions are meant to influence operational practices, the Namibian Regulations stipulate the following:

> *'Licensees must*
>
> *a) determine the boundaries of any controlled area on the basis of the magnitude and likelihood of expected exposures and the nature and extent of the required protection and safety measures;*
>
> *b) delineate controlled areas by physical means or, where this is not reasonably practicable, by some other suitable means;*
>
> *c) where a source is brought into operation or energised only intermittently or is moved from place to place, delineate an appropriate controlled area by means that are appropriate under the prevailing circumstances and specify exposure times;*
>
> *d) display a warning symbol, recommended by the International Organisation for Standardisation (ISO), and appropriate instructions at access points and other appropriate locations within controlled areas;*
>
> *e) establish occupational protection and safety measures, including local rules and procedures that are appropriate for controlled areas;*
>
> *f) restrict access to controlled areas by means of administrative procedures, such as the use of work permits, and by physical barriers, which could include locks or interlocks, the degree of restriction being commensurate with the magnitude and likelihood of the expected exposures; and*
>
> g) *provide at entrances and exits of controlled areas appropriate means for change of clothing, contamination monitoring and personal decontamination.* '[3]

When a radiation risk assessment indicates that the risk of exposure in a work area is 'high', such a work area is a '*high risk radiation area*' and accordingly classified as a controlled work area.

This implies that the area must be mapped, demarcated using physical barriers, and properly signposted. In addition, the zoning of an area as a controlled area must be communicated to all relevant operational staff and include a description of the requirements that must be met when entering, working, and leaving such an area. In addition, suitable area-specific protection and monitoring activities must be initiated, to provide the necessary indications that exposures are kept as low as reasonably achievable at all times.

An area classified as a '*high risk radiation area*' has the following characteristics:

1. High dose rates from penetrating radiation, potentially leading to high direct external exposure doses of persons active in such an area. In this context, dose rates of 3 µSv/h or more, leading to annual exposure dose of 6 mSv/a or more, as proposed by the ICRP [45], are classified as '*high dose rates*'.

2. High levels of radioactive contamination, which can potentially be spread, and thereby cross-contaminate previously clean areas. This risk also applies in work areas with high concentrations of radioactive dust in air.

3. High risk of potential exposure to radiation from incidents or accidents, for example in the use of sealed radioactive sources, when operating in confined spaces with potentially high levels of radon, or in areas where the risk of inhalation and/or ingestion of radioactive materials is high.

The controlled area classification applies to areas, in terms of specific rules applying to access and work in such areas, and to workers, in terms of specific controls and personal monitoring requirements.

Operational staff who are active in controlled areas must have the necessary PPE, as specified for the area, and need to have their exposure to radiation individually monitored. Here it is noted that 'regular monitoring' does not necessarily mean that monitoring is to be undertaken continuously, but it is important that representative and statistically valid exposure monitoring is undertaken, thereby resulting in the quantification of an annual dose, based on actual monitoring activities.

In cases where a radiation risk assessment indicates a high-risk potential, dose assessments over periods shorter than a year may be necessary to ensure that overexposure is avoided. In this regard, a monitoring period of one to three months may be more appropriate, but the decision must be guided by area- and work-specific exposures and practices.

In some operational settings, controlled areas are referred to as '*designated areas*', and staff who work in such areas are called '*designated workers*', or simply '*radiation workers*'.

It is important to note that a strict definition of the term 'radiation worker' does not exist and is site and activity-dependant. In other words, the term 'radiation worker' may only refer to persons active in controlled area, or to persons active in both controlled and supervised areas.

There are many examples where area-specific demarcations are ineffective, or plainly non-sensical. An example of a controlled area that is not effective in its execution is depicted in Figure 158. It shows a controlled area, which is a stockpile containing thorium-rich titanium ore, stored for further processing at a titanium mine. Because of the gamma dose rate on and at this stockpile, which exceeds 10 µSv/h, it was declared a controlled area, as indicated by signage. However, no demarcations exist, and it is not possible to know from the signage where the physical boundary of the area is meant to be. Also, there are neither access controls nor physical barriers in place. as the stockpile consists of fine sand, which is readily spread by the wind, radioactive contamination is readily spread across the operational site, and beyond. This is most undesirable, and therefore serves as an example of how not to go about area classifications, and the pronouncement of a controlled area.

Figure 158: Example of a controlled area lacking proper controls [8]

15.4.2 Supervised Work Areas

The Namibian radiation protection Regulations define *supervised work areas* as:

> *'… any area not already designated as a controlled area, but where occupational exposure conditions need to be kept under review even though specific protection measures and safety provisions are not normally needed.*
>
> *Licensees must delineate and identify the supervised areas by appropriate means, taking into account the nature and extent of radiation hazards in those areas.*
>
> *Licensees must periodically review conditions to determine the possible need to revise the protection measures or safety provisions, including the boundaries of controlled and supervised areas.'* [3]

As per this definition, a supervised area is characterised by occupational exposure conditions that necessitate regular review, but may not require permanent and specific protection measures, and/or other safety provisions.

Supervised work areas must have control measures exceeding those applied in non-classified or non-designated work areas, but less so than those applied in controlled areas. This implies that work areas that regularly or occasionally require a radiation-related risk assessment, or a review thereof, and necessitate specific risk reduction and control measures, are likely to be classified as supervised work areas.

Persons who are active in a supervised work area do not necessarily need to be monitored regularly, nor do they need to be monitored continuously. However, a monitoring program must be in place to allow for the assessment of occupational exposures which is commensurate with the exposure risks, and the determination of an annual exposure dose must be based on actual monitoring activities.

15.4.3 Non-classified / Non-supervised Work Areas

Non-classified work areas, which are also called *non-supervised work areas*, are those areas in an operational setting that do not need any radiation-related controls, except those that have been included in the design of the area, i.e. engineering controls.

Because the radiation-related classification of work areas is based on the results of a radiation risk assessment, an area that is found to be a non-classified or non-supervised work area is characterised by low or very low radiation-related risks, taking all relevant exposure pathways into account.

Persons who are active in non-supervised areas may be classified as '*non-occupationally exposed persons*', and do not require an annual dose assessment. However, potential exposures may change in time. It is therefore considered best practice that areas that are classified as non-supervised are subjected to occasional dose assessments, to ensure that occupational exposures of persons active in such areas are at or below the public dose limit. This is to confirm that the area classification applies, and that annual exposure doses are limited to those from natural background radiation.

15.5 Radiation Exposure Dose Monitoring

An essential part of every radiation protection program is the *radiation exposure dose monitoring* program, which must include regular area and personal exposure dose monitoring.

The purpose of a radiation exposure dose monitoring is three-fold, namely to:

a) confirm that the controls that have been put in place are effective and sufficient; and
b) ensure that workplace exposure doses are ALARA; and
c) ensure that the occupational dose limits as specified by the regulatory authorities are being complied with.

Often, the classification and zoning of work areas into controlled, supervised, and non-supervised work areas informs and supports the design of the radiation exposure dose monitoring program.

Figure 159: Personal radiation monitoring equipment for gamma radiation, radon, and dust [34]

15.5.1 Occupational Exposure Dose Monitoring

An *occupational exposure dose monitoring program* is best underpinned by the classification of work areas into 'controlled', 'supervised', and 'non-supervised' areas.

It is important to understand what is meant by an '*occupational exposure*'. This book uses the following definition:

> '*occupational exposure means all exposures of workers incurred during their work…*'

Note that occupationally exposed persons will also incur an exposure dose, albeit small in many cases, from natural background radiation sources. Often, and as practiced in Namibia, the exposure dose from natural background radiation is excluded from occupational exposures, because exposures to natural background radiation is not subject to regulatory control.

An occupationally exposed person is therefore anyone who is exposed to radiation exceeding the dose due to exposure to natural background radiation. While many workers active at Namibian uranium mines (for example office workers) do not receive an occupational exposure dose that is significantly different from the natural background around the mine, it is often difficult to determine the local natural background in an area. As such workers are not at home, but at a mining site, where the exposure to the natural background is strongly influenced by the underlying geology, which includes a uranium ore body, such persons do receive an exposure dose which is different from the one that they would have received if they had remained at home.

Best practice therefore dictates that all workers at a uranium mining site are classified as occupationally exposed persons, which implies that their annual radiation exposure is subject to assessment. In cases where the exposure dose is due to the natural background radiation field, and the total annual exposure dose is at or below 1 mSv/a, the radiation monitoring program can include such persons in an occasional dose verification program, even if this only happens once every two to three years.

Based on these considerations and keeping in mind that compliance with the regulatory provisions and requirements is essential, an occupational exposure dose monitoring program specifies the groups that must be monitored, the relevant pathways that are to be monitored, and the dose thresholds that are applicable per pathway. An example of a high-level occupational exposure dose monitoring program is summarised in Table 40.

Note that occupational monitoring must include relevant area monitoring, where the results are used to assess the area-specific exposure risk and use these to estimate personal doses of workers active in such areas. However, if worker exposures exceed background levels, personal monitoring is always preferable, as this yields more reliable results of the actual exposure doses of workers and is often more statistically significant.

Table 40: Example of a high-level occupational exposure dose monitoring program

	Exposure to penetrating radiation	**Exposure to radon and its decay products**	**Exposure to long-lived radioactive dust**
Persons in controlled areas	Continuous monitoring if the average area dose rate exceeds 3 µSv/h. If this is not the case, monitor as if a supervised area.	Continuous monitoring if the average ambient atmospheric radon concentration exceeds 600 Bq/m$^{3.}$ If this is not the case, monitor as if a supervised area.	Continuous monitoring if the average area PM_{10} concentration due to uranium concentrate dust exceeds 0.4 Bq/m^3, or 0.7 Bq/m^3 for uranium ore dust. If this is not the case, monitor as if a supervised area.
Persons in supervised areas	Random monitoring, using suitable similar exposure groups.		
Persons in non-classified areas	Random monitoring, using suitable similar exposure groups, and verify results every 2 years.		
Pregnant females	If the person is active in a non-classified work area, undertake a dose assessment as per similar exposure group, else as for workers in controlled areas.		

15.6 Contamination Control

Radioactive contamination occurs in form of *fixed contamination* or non-fixed contamination.

Fixed contamination indicates that radionuclides are either found on the surface of an object, or within the matrix of the material under consideration. This implies that fixed contamination is an integral part of the material.

Non-fixed contamination on the other hand is removable contamination. It consists of radioactive contaminants that may readily become airborne. If this happens, such contamination can be inhaled or ingested by receptors, or it can settle on exposed surfaces in form of loose surface contamination.

While both forms of contamination are undesirable, their respective risk profile is different: the radiation-related risk of fixed contaminants is mostly associated with the emission of gamma radiation from contaminated objects. In contrast, the radiation-related risk associated with non-fixed contaminants results from the mobility of the contaminants, their suspension and re-suspension in air, and their deposition on open surfaces.

Strict controls must be in place to prevent the spread of contamination. Of importance is the spread from contaminated to 'clean' areas, a process known as *cross-contamination*.

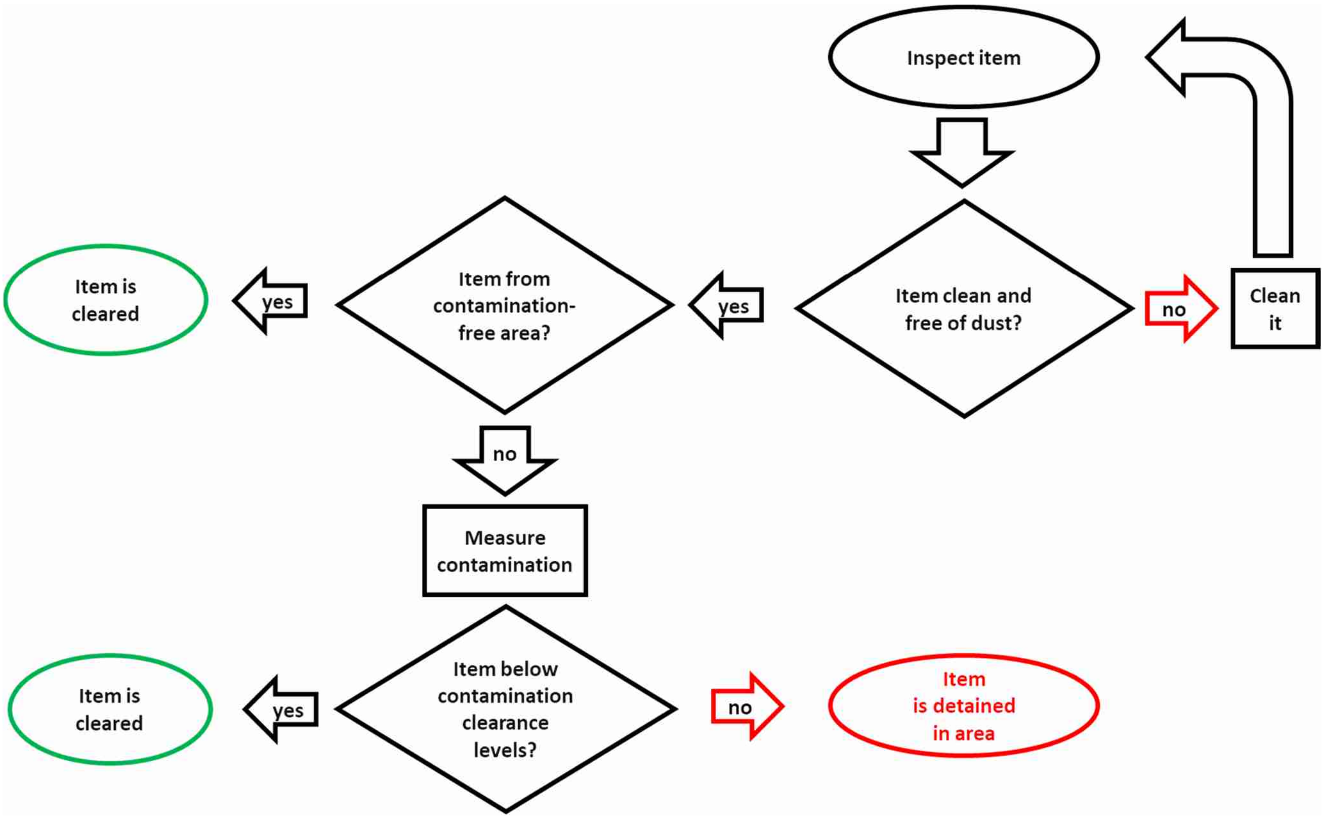
To illustrate: if a specific controlled area is contaminated, measures must be taken to prevent the spread of contaminants to non-contaminated areas. While it is desirable that work areas such as supervised and non-classified work areas are always non-contaminated, it is not a given. In operational environments in which several contaminated work areas exist, the existence of non-contaminated work areas cannot ever be taken for granted and requires permanent vigilance and management effort.

Also, in a work environment with contaminated tools and equipment, it is essential that the movement of contaminated objects both on- and off-site is strictly controlled. To illustrate: when removing metal scrap from a uranium mine it is imperative that only non-contaminated items are cleared for off-site removal.

It is therefore essential that procedures underpin a comprehensive on-site contamination control program, to ensure that all potentially contaminated objects and items are checked for contamination before they are moved off site. Also, the movement of contaminated materials from classified to non-classified areas must be limited, managed, and strictly controlled. If this is not achieved, most on-site areas will eventually be contaminated.

When dealing with large volumes of potentially contaminated objects, it is simply not possible to assess each such object before it is moved to another area, or off site. This is because contamination controls are both labour- and equipment-intensive, and therefore expensive. In addition, the individual control of each potentially contaminated object will result in ineffective work processes and incentivise people to disregard such measures. Therefore, the departure point of an effective contamination control program is best based on a quantitative radiation-related risk assessment, which takes cognisance of and is informed by the area classification (i.e. the origin of individual objects to be cleared) and the uses of the objects under consideration.

Figure 160: Flowchart for the inspection of a potentially contaminated item [8]



15.6.1 Procedural Guide for Effective Contamination Control

It is important that the relevant procedure for effective contamination controls

- are simple to understand, as is for example illustrated in flowchart for the inspection of potentially contaminated objects shown in Figure 160;
- are effectively communicated to every relevant person on site;
- use self-evident language and appropriate signage, as illustrated in Figure 161;
- are regularly evaluated;
- are sporadically blind-tested to ensure that control measures lead to the desired outcomes, as per their design; and are
- executed by suitably trained personnel.

Figure 161: Examples of useful signage to illustrate a clearance process [34]

Not all work areas in a typical uranium mine, not even when dealing with high-grade mineral ores, are necessarily contaminated. As a result, contamination controls can be limited to those areas where the risk of contamination is highest. In such areas, physical barriers must be used to demarcate the area, and in this way assist staff to understand where area boundaries are and at which points contamination checks are done.

Areas that are free of contamination usually include offices, some laboratories, and select workshops. On the other hand, and of relevance to the uranium mining industry, items from the mining and crushing areas must be checked for contamination, even if ore grades are low. Here, it often suffices to ensure that items that must be cleared are clean and free of dust.

Figure 162: Contamination and radiation risk assessment [34]

15.6.2 Rules to Minimise Contamination/Cross-Contamination

Rules to minimise contamination and ensure that cross-contamination is kept to a minimum include the following:

- Ensure that suitably trained staff can distinguish between items that are at risk of being contaminated, such as tools and equipment from a uranium processing plant, and items that are not at risk of being contaminated, such as computers, foodstuffs, and new items delivered to site;

- Ensure that a sufficient number of calibrated contamination monitoring instruments are available, for trained staff to perform contamination checks whenever required;

- Undertake contamination checks at exit points from areas from which contaminated objects are most likely to exit. Avoid creating a central control point to which contaminated objects must be brought to have them assessed and cleared;

- Items that have been in use and/or in direct contact with radioactive contaminants, for example those from the chemical uranium extraction process, including pipes, pumps, and tanks, are almost always contaminated. Here, a principal decision is best taken, which disallows the removal of all such items from site. This simplifies the decision-making process and limits the number of contamination checks that must be undertaken.

- If contaminated items must be moved off site, for example to have them repaired, it is important that these are cleaned, and de-contaminated.

- Clearances for contaminated items that must leave the site may only be issued if the potential off-site exposure dose resulting from contact with such objects leads to trivial doses. If this is not the case, it is only possible to clear contaminated items if the entity/persons receiving such an object are fully aware of the radiation-related risks associated with the item in question.

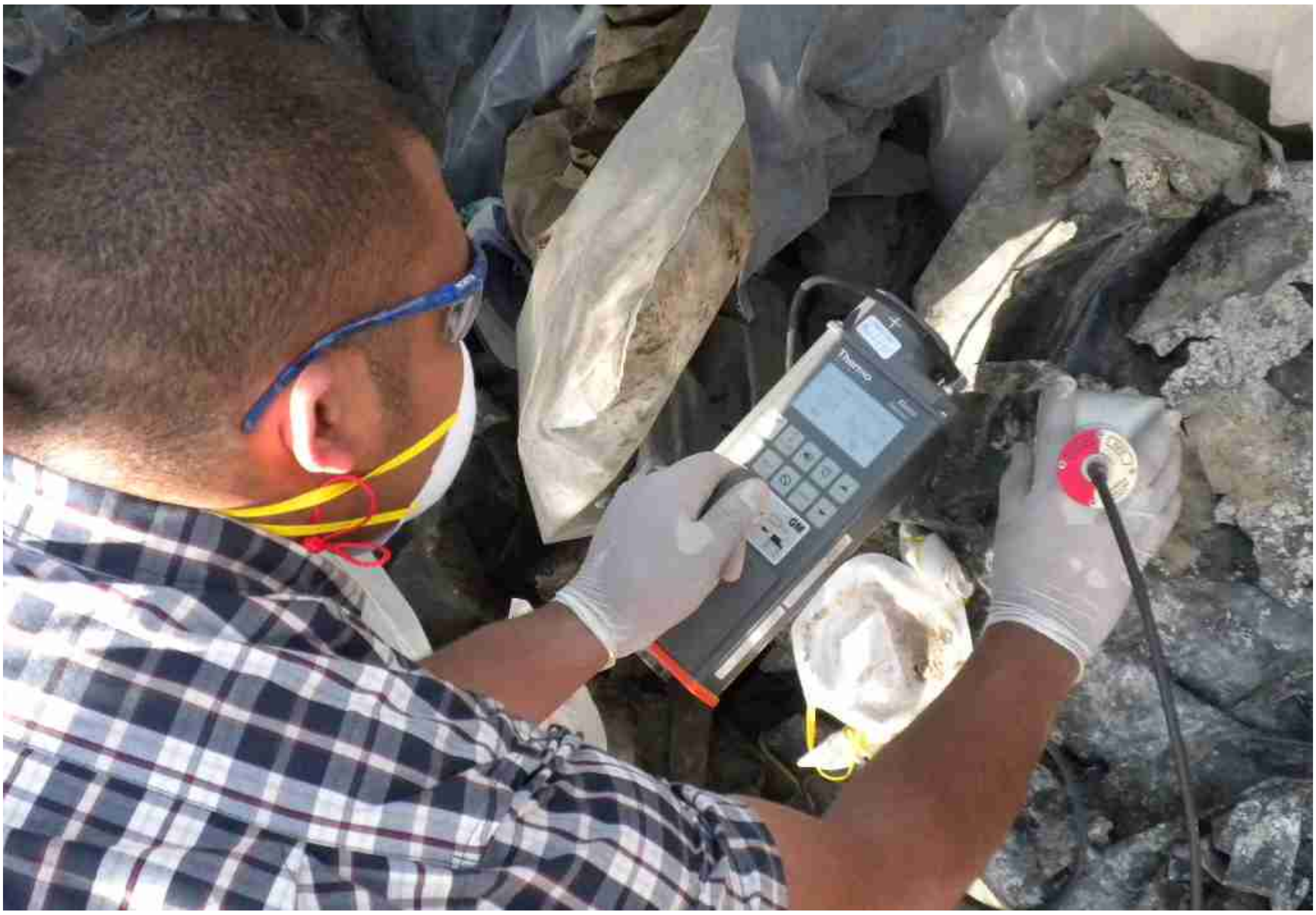
- Ensure that vehicles are not allowed to leave the site unless they are visibly clean, and free of mineral dust.

- The exterior of vehicles is checked, and that dust and/or mud or sludge that may stick to the underbelly of the vehicle, and the inside of the rims and wheels, and other hard-to-find places, are cleaned prior to undertaking a contamination check.

- On-site vehicle washing facilities are to be located close to the exist points in work areas where they are potentially exposed and contaminated with dust, mud, and sludge.

- Items that may have been radioactively contaminated on the inside, for example pipes, pumps, heat exchangers, as well as tools and equipment used in the uranium processing areas, must be thoroughly inspected before they are issued with a clearance. Contamination is often found within such items, which implies that the contamination check must ascertain that objects are clean and free of contamination.

Figure 163: Identifying sources of contamination in waste materials [8]



16 Public and Environmental Radiation Protection and Radiation Safety

This Chapter presents the basics of applied radiation protection and radiation safety to ensure that members of the public and the environment are protected from the potentially negative impacts from exposure to ionising radiation.

16.1 Public Dose Limits

As introduced in section 9.6, internationally applicable dose limits are put forward by the IAEA and implemented as part of the country-specific legislative and regulatory provisions on radiation protection.

Guided by the latest IAEA Safety Standards [1], the relevant Namibian Regulations relating to public exposure dose limits are as summarised in Box 23 (refer to page 152).

Comparing the level of protection through the occupational exposure dose limits (refer to Box 21, page 152) to that of the public dose limits it is noted that these dose limits are indeed different. This is because of the different vulnerabilities that exist in adult workers versus those of ordinary members of the public. An integral part of the cohort of members of the public are unborn children, and babies. It is this group that is most vulnerable to exposure to ionising radiation, and therefore must be protected most. This vulnerability is the result of the very rapid cell replication rate in both foetuses and infants, and the associated sensitivity of such cells when exposure to ionising radiation.

The public exposure dose limit is therefore principally set to protect the most vulnerable members in the group of members of the public. It is for this reason that the public dose limit is significantly below the corresponding occupational exposure dose limit. Here it is also noted that the Namibian occupational dose limits as summarised in Box 21 apply to persons above the age of 18 years, who are declared fit for work by a medical practitioner.

The applicable public dose limit, i.e. 1 mSv/a when averaged over a 5-year period, offers embryos a comparable level of protection as the occupational dose limit of 20 mSv/a offers to adult workers.

Although the public dose limit is intended to optimally protect the most vulnerable members of the public, i.e. unborn and young children, it applies to all members of the public alike. This is because it is neither feasible nor practicable to have a dose limit which applies to children only, as these are an integral and inseparable part of the group of members of the public.

The above also implies that every person who is not an occupationally exposed person is a member of the public, and the above-mentioned public exposure dose limits apply to them.

16.2 Public Dose Constraints

In addition to the public dose limit, the concept of a *public dose constraint* is often used. It is meant as a reference level for protection going beyond the public dose limit. Under certain conditions, a dose constraint can be relevant and required, for example if several practices / operations contribute to the exposure doses of the same critical group(s), and an exact quantification of the dose contribution attributable to each individual operation is not possible or not viable.

In Namibia, the Regulations define the public dose constraint as follows:

1. *'Except for medical exposure, the optimisation of radiation safety measures associated with a given practice must satisfy the condition that the resulting doses to members of the critical group do not exceed dose constraints which are equal to the dose limits specified … or any lower values established by the Director-General.*
2. *In case of any source that can release radioactive substances to the environment, the dose constraints must be established so that the prospective annual doses to members of the public, including people distant from the source and people of future generations, summed over all exposure pathways, including contributions by other practices and sources, are unlikely to exceed the dose limits specified … or any lower values established by the Director-General.'* [3]

However, in early 2018, the regulatory Authority has not defined separate public dose constraints yet. This implies that the Namibian public dose limit and dose constraints are set at 1 mSv/a when averaged over 5 years. South Africa introduced a dose constraint of 0.25 mSv/a, which is regarded as being as stringent as the applicable dose limits.

16.3 Public Exposure Pathways

An exposure of members of the public to ionising radiation can be the result of the direct exposure to penetrating radiation, and/or from internal exposures from the inhalation and/or ingestion of radionuclides. Figure 164 presents a schematic view of the different public exposure pathways, which are further discussed in the subsections below.

16.3.1 Direct External Exposure

Direct external exposures are caused by sources of gamma radiation, X-rays and hard ultraviolet light which are emitted at or close-by the locations where members of the public find themselves.

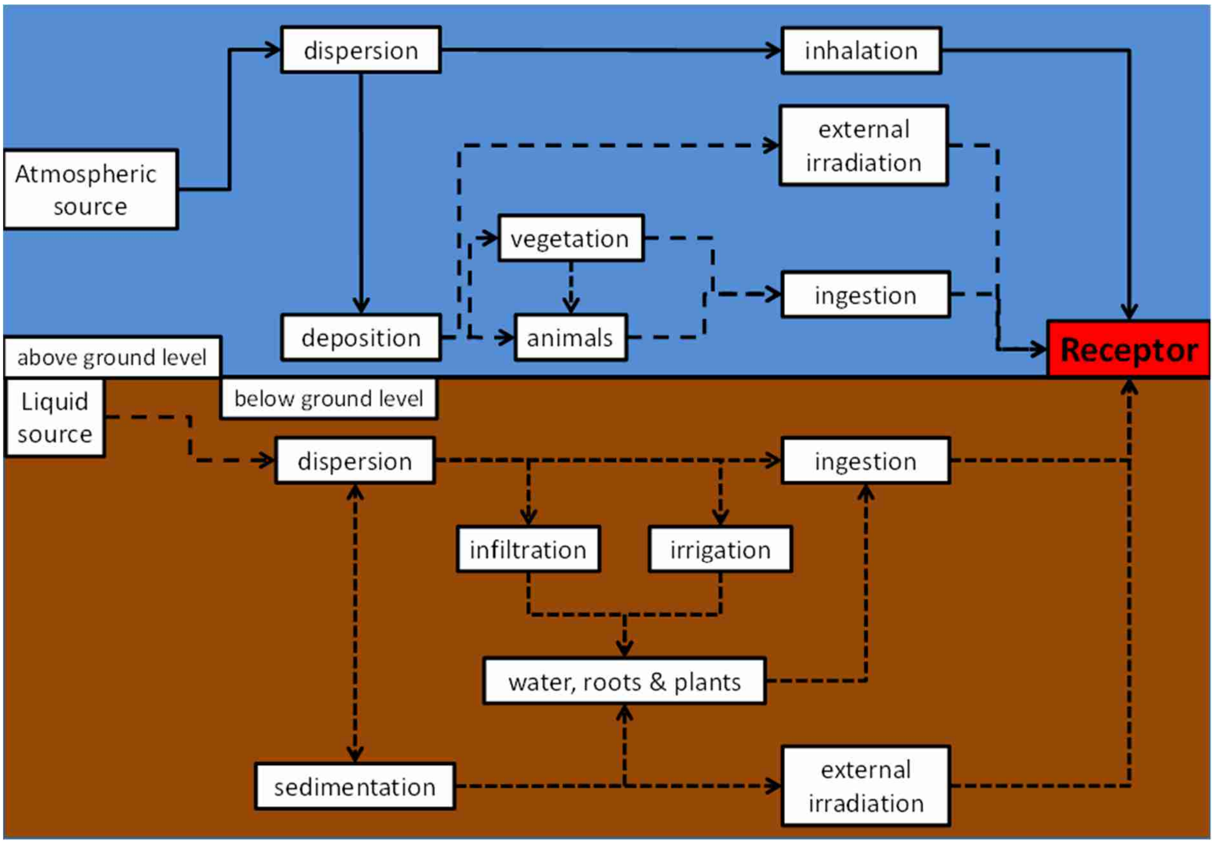
The following potential contributors of direct external exposure may affect members of the public:

- X-ray machines and instruments, including various common laboratory instruments emitting ionising radiation, as well as X-ray scanners which are frequently used at airports and public access points;
- Radiation from sources used for non-destructive evaluation and testing, both from radioactive source materials as well as X-ray sources;
- Transport of radioactive materials, including of sealed radioactive sources, radioactive concentrates, and ore samples of NORM, and their waste products;
- Stores of uranium concentrate, or uranium ore samples in or close to public places;
- Tailings storage facilities, waste rock dumps, and similar concentrations of NORM or processed NORM residues and waste, where these are readily accessible to the public, or part of building / road fill materials used by members of the public;
- Contaminated tools and equipment, waste materials of various kinds originating in the mining and processing sector, as well as radioactively contaminated scrap which may be used by members of the public;

- Ore samples containing radionuclides, used as collectibles by members of the public.

Access to radioactive mineral source materials as listed above is readily controlled by way of limiting public access to sites where such materials occur. This is of importance at uranium exploration and mining sites, where public access restrictions limit the potential exposure to such radiation sources, as well as contaminated mineral and non-mineral waste.

Figure 164: Schematic view of the various public exposure pathways [8]



16.3.2 Atmospheric Pathways

The atmospheric pathways include the inhalation of long-lived radioactive dust (LLRD), and the inhalation of radon and the radon decay products (RDP) that is part of the ambient atmospheric air. As depicted in Figure 164, secondary exposures may result from dust / radon emitted / exhaled into the air, including by way of:

- Deposition of LLRD onto objects, soil, vegetation, and water, which may then be further dispersed by the wind, and remain an ambient constituent in air, or seep into soils and groundwater;
- Deposition of LLRD and RDP on vegetation, and the subsequent ingestion when such materials are consumed by humans and animals;
- ingestion of deposited dust by domestic animals, and the subsequent ingestion of radionuclides when animal products are consumed by humans, including in form of eggs, milk, meat, and other animal products; and
- direct irradiation by way of LLRD in air and related materials which are deposited onto soil, vegetation, and other objects in the environment.

16.3.3 Aquatic Pathway

Groundwater may be contaminated either through seepage from contaminated sites and sources, such as from tailings storage facilities, rock dumps and NORM stores, or indirectly through the deposition of LLRD (and to a lesser extent of RDP) onto the soil, and the subsequent seepage and dissolution into the groundwater.

Contaminated groundwater can also become a source of internal contamination. For example, contaminated water can be a direct contributor to an internal exposure dose, i.e. when used as drinking water. It can also contribute to secondary exposures, which result when contaminated water is used for domestic animals and/or for crop production, followed by the ingestion of such animal products and crops by humans.

16.4 Public Exposure Dose Assessments

All operations that cause and contribute to public exposure doses must comply with the public dose limit as specified by the relevant regulator, and the public dose contributions from all practices must remain below 1 mSv/a. In addition, such entities must demonstrate that exposures are kept ALARA. The exposure dose limits, and dose constraints, refer to incremental dose contributions above those from natural background radiation sources.

The exposure dose from natural background radiation in Namibia's Erongo Region amounts to some 1.8 mSv/a. In most cases, the public dose contributions which are attributable to uranium mining operations are significantly smaller than those from natural background sources.

As the dose contribution from mining operations is part of the total radiation field that receptor groups are exposed to, indirect measurements of public exposures are necessary. In other words, when the signal (i.e. the public dose contribution) is much smaller than the noise (i.e. the natural background radiation), direct measurements are not feasible, and they must be quantified indirectly.

Figure 165: Schematic view of a public dose assessment [8]

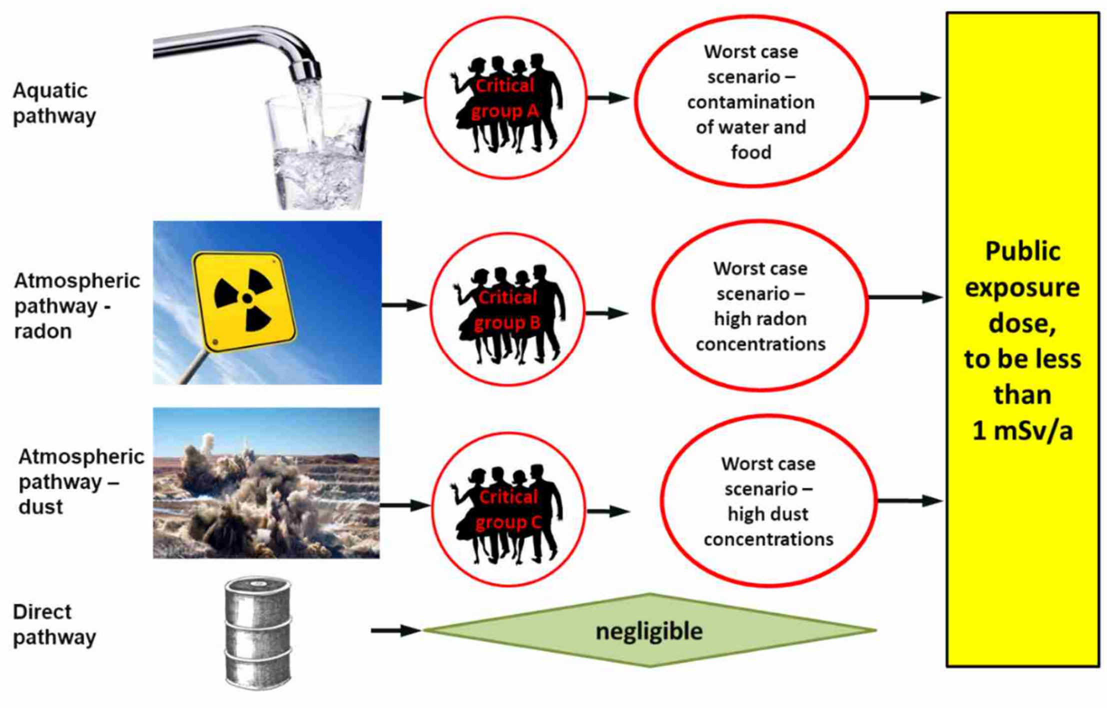


Figure 165 provides a high-level illustration of how public dose assessments are undertaken, and what they need to include:

- each potential exposure pathway must be identified, and each such pathway must be assessed separately;
- for every actual and potential exposure pathway, the relevant critical group/groups must be identified;
- a dose assessment must be performed for each actual and potential exposure pathway and critical group, and preferably be based on empirical (i.e. measurable) evidence and parameters; and
- for each critical group, the cumulative dose from all pathways and all contributing operations must always remain below the relevant dose limit.

If several operations contribute to the dose of a given public receptor, the cumulative dose from all such contributors must be considered. This implies that the public dose limit of 1 mSv/a does not apply for each practice but is the limit that applies cumulatively to all operations that contribute to the total exposure dose of a critical group. If a public dose constraint has been announced, it applies to each contributing practice, and is applicable in addition to the public dose limits as specified in law.

16.5 Example of a Public Exposure Dose Assessment

The following example considers the public exposure dose contribution to inhabitants of the town of Arandis because of the presence of uranium mining operations at the Rössing Mine. Figure 166 shows the town of Arandis (in the left corner of the image), and the Rössing mining site.

Figure 166: Google Earth image showing the town of Arandis and the Rössing Mine [8]

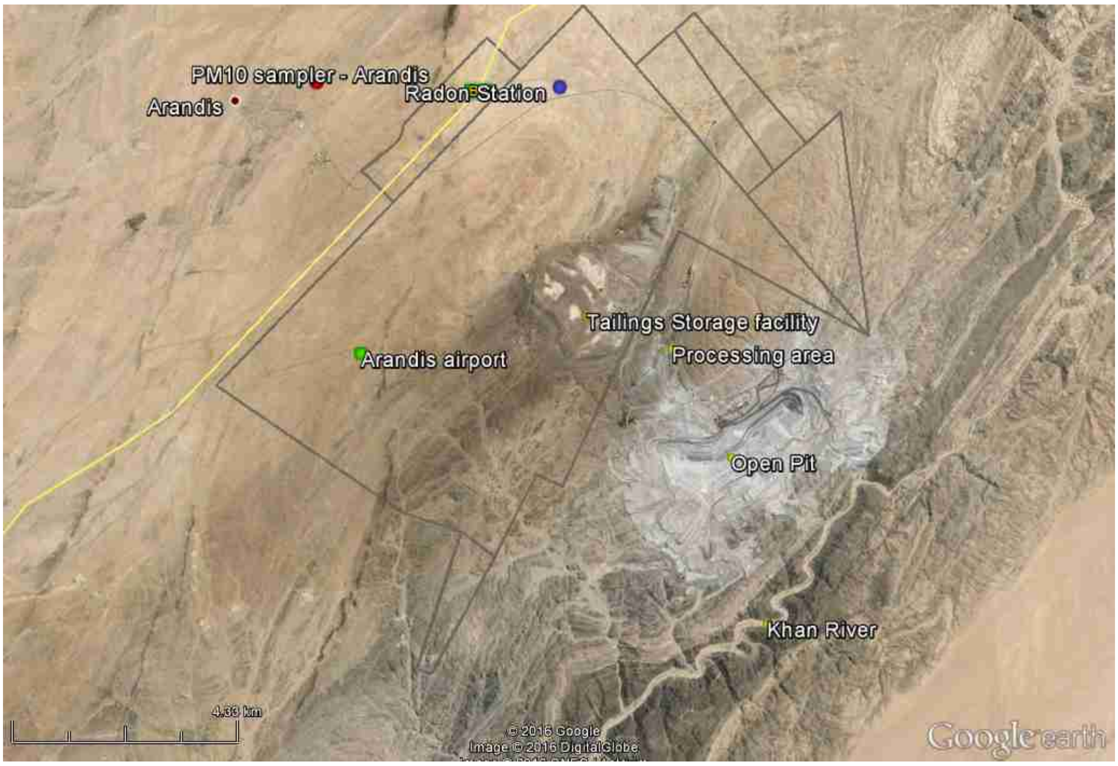
First, the public dose assessment identifies the potential exposure pathways of relevance to the critical group, and assesses each such pathway separately:

- Because access to the operational mining area at Rössing is restricted, it is not accessible to members of the critical group of members of the public residing at Arandis. In addition, the direct distance between Arandis and Rössing exceeds 5 km. These aspects imply that the *direct exposure pathway* is not relevant in the case under consideration.
- The geo-hydrological profile of Rössing shows an incline from the tailings storage facilities towards the south, which does not reach the town of Arandis. Therefore, the *aquatic exposure pathway* is not of relevance to this critical group, and is therefore not considered further in the present dose assessment.
- The *atmospheric exposure pathway* can potentially contribute to this public receptor group, notably through the inhalation of LLRD, and the inhalation of RDP. This exposure pathway must therefore be assessed in further detail. The present example demonstrates the process of a public exposure dose assessment, and therefore focuses on the quantification of the exposure dose due to the inhalation of ambient LLRD.

Next, a dose assessment for each of the relevant exposure pathways must be undertaken. This is best based on empirical (i.e. actually measured) parameters. A monitoring program delivers such input data, and includes a PM_{10} dust monitoring station located at the town of Arandis (red dot in Figure 167), and a radon monitoring station located north of the Rössing tailings storage facilities (blue dot in Figure 167).

The monitoring station at Arandis yields hourly atmospheric LLRD PM_{10} concentrations, as well as the wind direction and wind speed. This meteorological data allows for a correlation of the origin of the LLRD in relation to the mining site, noting that these atmospheric pollutants can originate in mining operations, or be part of the natural background dust in the greater region.

Figure 167: Public receptor group at Arandis relative to the location of Rössing Mine [149]



To quantify the radionuclide content of the PM_{10} dust fraction collected at Arandis, a radionuclide analysis of the com-position of the LLRD must be undertaken. The results of such an analysis are summarised in Table 41.

Table 41: Radionuclide analysis of the PM_{10} dust collected at Arandis [149]

Decay chain	Radio-nuclide	Specific activity [Bq/kg]
Uranium	U-238	494
	Ra-226	756
	Pb-210	7 770
Actinium, *1	U-235	< 34
	Ac-227	< 100
Thorium	Ra-228	220
	Th-228	200
Other	K-40	984

***1:** specific activity values which include the symbol '<' are below detection level.

The following observations are based on the results of the PM_{10} radionuclide analysis as shown in Table 41:

- The analysis did not include all radionuclides of the various relevant decay chains. This implies that the activity contributions of those radionuclides which are not part of the results of the analysis must be predicted, which is done by assuming that the members of the decay chains are in partial secular equilibrium.

- The radionuclide analysis contains K-40, which originates entirely from background sources. As a result, this radionuclide is disregarded in the further analysis, as it is not contributed through mining operations.

- The specific activities of the radionuclides of the actinium decay chain included in the analysis are below the detection limit. One can either decide to disregard these values, or assume the value provided at or close to the detection limit, which may be representative for the most likely value – this example is based on the latter assumption.

- The specific activity of Pb-210 is some 15 times higher than that of its parent U-238. This indicates that this radionuclide is not in secular equilibrium with the remainder of the members of the decay chain. It is to be noted that the elevated occurrence of this radionuclide is due to long-lived radon progeny which has accumulated in the dust samples used for the radionuclide analysis.

Based on the radionuclide concentrations as summarised in Table 41, and the reflections offered above, one now undertakes the dose calculations. Here it is noted that the dose conversion coefficients are different from those used for occupationally exposed persons, as the members of the critical group are members of the public. As a result, the relevant public dose conversion coefficients must be used, as per the IAEA Safety Standards [1], and as provided specifically for adults, and for infants of different ages. The results are presented in Table 42 only focus on the adult exposure dose, as this suffices to illustrate the principles that are applied in this public inhalation dose estimate.

Table 42: Radionuclides and resulting public adult exposure dose from LLRD at Arandis

Decay chain	Radio-nuclide	Lung Absorption Class	Specific Activity [Bq/g]	Adult Public Dose Coefficient [µSv/Bq]	Adult Exposure Dose [µSv/g]
Uranium	U-238	S	0.49	8.0	3.95
	U-234	S	0.49	9.4	4.64
	Th-230	S	0.49	14	6.92
	Ra-226	M	0.76	3.5	2.65
	Pb-210	F	7.77	5.6	53.51
	Po-210	M	7.77	4.3	33.41
Actinium	U-235	S	0.03	8.5	0.29
	Pa-231	S	0.03	34	1.16
	Ac-227	S	0.1	72	7.20
	Th-227	S	0.1	10	1.00
	Ra-223	M	0.1	7.4	0.74
Thorium	Th-232	S	0.2	25	5.00
	Th-228	S	0.2	40	8.00
	Ra-224	M	0.22	3.0	0.66
				Total	**119.1 µSv/g**

Note: Values marked in grey are based on the assumption that secular equilibrium exists.

The average of the empirical PM_{10} dust concentrations found was 11 µg/m^3. Using this average atmospheric dust concentration, and the adult public breathing rate of 0.9 m^3/h, and the exposure time for a full year, i.e. 8 760 h/a, the total adult exposure dose (including the background) resulting from the inhalation of this type of ambient atmospheric LLRD is computed as demonstrated in section 10.2 before:

$$\begin{aligned}\mathrm{Dose_{LLRD}}(\mu\mathrm{Sv/a}) &= \mathrm{Conc_{LLRD}}(\mathrm{g/m^3}) \cdot \mathrm{t(h/a)} \cdot \mathrm{BR}\ (\mathrm{m^3/h}) \cdot \mathrm{DCF_{LLRD}}(\mu\mathrm{Sv/g}) \\ &= 11 \cdot 10^{-6}(\mathrm{g/m^3}) \cdot 8\,760\ (\mathrm{h/a}) \cdot 0.9(\mathrm{m^3/h}) \cdot 119\ (\mu\mathrm{Sv/g}) \\ &\approx 10\ \mu\mathrm{Sv/a}.\end{aligned}$$

The above dose calculation rests on the following assumptions:

The upper limits for the activity concentrations of the radionuclides from the actinium chain were used. The error associated with this assumption is small, and less than 10% of the total result, as is evidenced in Table 42.

Those radionuclides that were not included in the laboratory analysis were assumed to be in (partial) secular equilibrium with the relevant members of their decay chain, as indicated in grey in Table 42.

- The above dose assessment is based on the radionuclide concentrations of ambient PM_{10} dust in air, but it does not allow for any conclusions as to the origins of such atmospheric dust.

Therefore, the above dose assessment is now further refined, firstly by correlating the dust concentration with the direction of the prevailing winds blowing at the time when the measurements were taken. Figure 168 depicts those wind directions that can potentially transport dust from the mining operations at Rössing to Arandis, as indicated by the red wedge.

Based on the wind fields shown in Figure 168, the wind directions are classified into either ‘mining’ or ‘non-mining’ wind fields. This allows for the quantification of the percentage exposure dose related to LLRD which is of mining origin.

As shown in Figure 169, those dust concentrations that are of mining origin are coloured in red, while dust of natural background origin is indicated in blue.

In this example, LLRD originating from the mining operations arises in some 5% of the time during the year. This implies that the public dose from mining origin contributes approx. 5% to the total inhalation dose, while 95% of the dose is from directions other than the mining site, thus originating from background sources of atmospheric dust.

The above approach can be further refined, e.g. by taking several dust contributors into account. In this way, the contribution to the public inhalation dose made by each practice is quantified. This may be important, for example when dose constraints are in place. Also, a similar approach can be used to quantify the public inhalation dose from radon.

Figure 168: Wind directions that may transport mining-related dust to the town of Arandis [149]

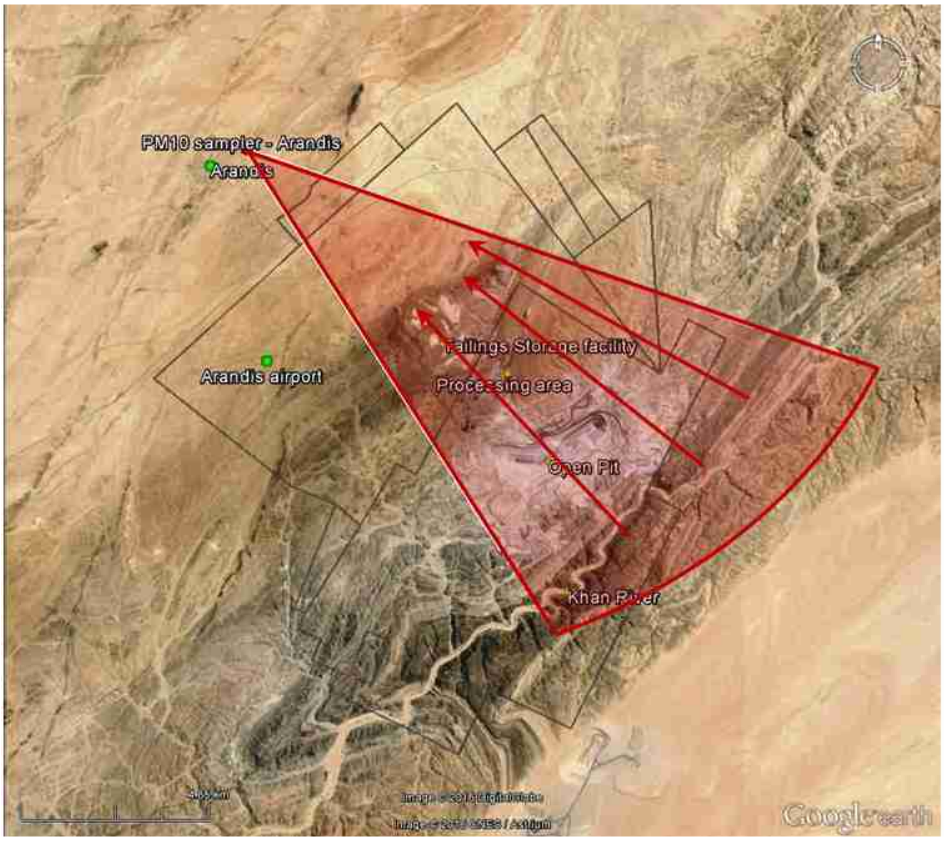
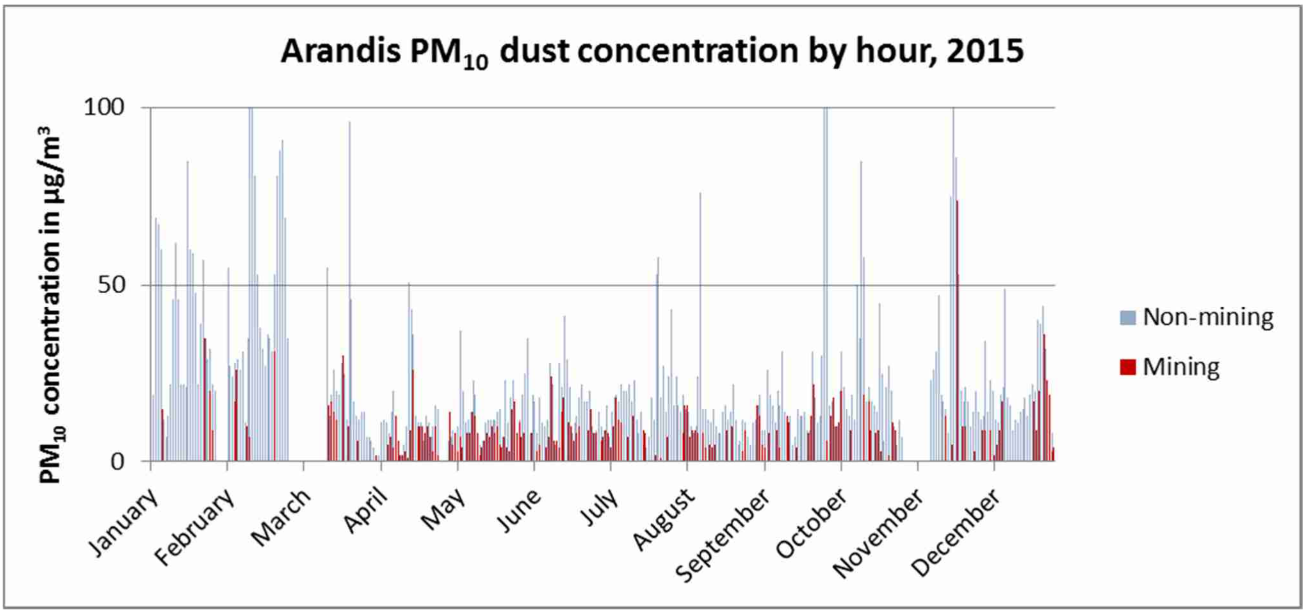


Figure 169: PM_{10} dust concentration with mining and non-mining contributions at Arandis [149]



17 Emergency Preparedness and Emergency Responses

This Chapter describes how to establish emergency preparedness and response capabilities as are relevant when handling and transporting radioactive materials.

17.1 Incidents and Accidents

Although not planned, incidents and accidents happen. This realisation necessitates that plans are in place to confidently, effectively, and swiftly address such unwelcome events.

It is important that the nomenclature used in emergencies is well understood. To this end, one distinguishes between *incidents* and *accidents*, which are defined as follows:

Incident:	an unplanned event which is not part of standard operational practices, resulting in minor injury, and/or minor damage, and/or minor loss, and may cause an accident.
Accident:	an unexpected and undesirable event which is not part of standard operational practices, resulting in injury, death, damage, and loss.

Figure 170: Fire at the final product recovery roasters at Rössing Mine in 2015 [34]

17.2 Emergency Scenarios

Examples of incidents and accidents that have or may occur in the uranium mining industry include

- spills of uranium-bearing ore, drill chips and NORM samples;
- spills of uranium concentrate, for example during loading or transport;
- leaking or bursting pipes or storage tanks containing uranium concentrate or radiation-relevant process solutions;
- leaking X-ray sources;
- leaking or broken sealed radioactive sources;
- unauthorised disassembly of sealed radioactive sources;

- theft of radioactive materials;
- blackmail involving stolen radioactive source material;
- fire, flooding, and storms causing the uncontrollable spread of radioactive materials; and
- acts of sabotage, and terrorism, leading for example the uncontrolled spread of radioactive materials, or the large-scale dispersion of such source materials.

For each conceivable scenario, a judgement call must be made to decide whether an emergency plan is required. In most cases, emergency plans follow a similar approach, as illustrated in section 17.3.

Each scenario-specific plan must address the issues and practices that must be followed to address, manage and being the situation under control.

It is important that emergency plans are readily understood by those who implement them, and enable them to manage such situations safely, effectively and using finite resources.

17.3 Emergency Plan

The responsibility of every operator dealing with sources of radiation which may be involved in incidents/accidents is to develop, communicate, practice, and keep operational an *emergency plan,* that ensures that all radiation sources and their associated risks are and remain under control under all emergency scenarios. This is a tall order.

An emergency plan must define all relevant on-site responsibilities, while also taking the responsibilities of off-site intervening organisations into account. Such entities include, amongst others, the police, firefighting entities, emergency service providers, medical service providers as well as the local authority(ies) of the affected town(s) and relevant national government entities and actors.

An emergency plan must

- ensure that all reasonable protective action is taken to minimise the impact(s) on occupationally exposed persons, members of the public, and the environment;
- characterise the features and extent of potential emergencies based on in-depth analyses of accident situations and emergency scenarios;
- identify the different conditions and thresholds under which an emergency may be declared, should be declared, and must be declared;
- allocate the responsibilities for notifying relevant counterparts, and establish a mechanism of how such communication can be affected, taking the nature of the potential emergencies into account;
- assign the duties and responsibilities to initiate an emergency intervention;
- describe how an accident and its actual/potential consequences are to be assessed, evaluated, and verified;
- spell out the protection and mitigation actions for each emergency scenario, and identify the associated responsibilities for each such action;
- establish an assessment mechanism to enforce and support additional actions, as may be necessary, including communication arrangements with all relevant intervening and supporting entities and persons;
- provide for the regular and systematic training of all persons who may be involved in an emergency; and
- provide for the periodic review, assessment, and update of the plan, to take changing contextual, operational, technical and response capabilities into account.

17.3.1 Responsibilities: Operating Entity

An operating entity must ensure that the implementation of its emergency response plan

- is initiated when protective and remedial actions are justified;
- includes informing the regulatory Authority if an accident requiring additional intervention has or is about to arise;
- does not allow that relevant dose limits are exceeded;
- is communicated without delay to all relevant support services and parties; and
- includes a post-emergency root-cause assessment, of which the findings are shared with all relevant parties once these and any relevant lessons learnt have been summarised.

17.3.2 Responsibilities: Regulatory Authority

Regarding the provision of support before, during and following radiation-related emergencies, the regulatory Authority has the following responsibilities:

- ensuring that every operating entity has an emergency plan that is realistic, kept operational and can be implemented;
- ensuring that the emergency plans of operating entities are periodically reviewed;
- defining all potential emergencies that require interventions;
- providing relevant assistance on demand, which necessitates the availability of human, technical and financial resources, with clear lines of responsibility;
- defining, executing, and enforcing emergency exposure dose limits which are applicable for emergency staff and first responders;
- providing support to operating entities, emergency personnel and members of the public following an emergency;
- initiating any action and/or taking any measures necessary to prevent, eliminate or ameliorate the impacts of a radiation-related emergency;
- ensuring that adequate provision is made for training personnel involved in implementing emergency plans;
- rehearsing emergency scenarios with all relevant stakeholders, including first responders, operating entities, as well as relevant supporting entities and organisations;
- determining the procedures for clean-up and removal operations in case of over-exposures;
- approving the emergency response and clean-up procedures proposed by each licensed operator; and
- determining the method of storage and disposal of any radioactive substance(s) that may arise and result in an emergency and/or clean-up operation.

17.4 Chain of Events in an Emergency

Emergency responses follow a set chain of events, and these must be followed to ensure that the response is optimally executed.

An emergency plan must list all relevant actions that are to be undertaken in case of an emergency, identify the sequence in which these are to be undertaken, and specify the responsibilities of each main action.

A high-level description of the chain of events of an emergency response includes the following main steps:

1. **Notification:**
   The person responsible to deal with a specific incident or accident is notified and informed of the situation and must assess whether an emergency response based on the emergency plan is to be initiated.
2. **Establishing the command-and-control structure:**
   Once it is decided that an emergency response is necessary, the emergency response plan is initiated. Specifically, this implies that a command and control structure is established, which is to be used to communicate with all relevant parties from this point onwards, until the emergency has been fully responded to and has been resolved.
3. **Assessing and classifying the event(s):**
   Based on the intelligence of the emergency, which must include all relevant information gathered from the point of notification onwards, the situation at hand is assessed. This must lead to decisions about the emergency response measure(s) which is(are) best to be initiated. To this end, the scale, scope, and severity of the event must be classified. This initial judgment call determines the urgency, importance and most appropriate initial response measures that are taken.
4. **Dispatch of first responders:**
   Depending on the classification of the emergency, first responders are notified, and informed of the specific requirements at the emergency site. First responders include those persons who initiate and undertake the first action at an emergency site, and who assess whether the initial response is sufficient to fully address the requirements of the emergency. First responders also communicate all situation-specific needs to the command-and-control centre. To enable first responders to effectively execute such tasks, they must have permanent access to all relevant emergency plans, emergency gear and vehicle support.
5. **On-site action:**
   On arrival at the emergency site, all relevant response measures are initiated. The following activities are undertaken as a matter of top priority:
   a. initiate life-saving actions;
   b. provide first-aid treatment and support;
   c. remove the injured, emergency participants and bystanders from those areas where further injuries or harm may occur;
   d. cordon off the area;
   e. keep non-involved persons out of the immediate emergency area;
   f. call on additional emergency service providers, including medical emergency services, the police, fire brigade, radiation experts, and others, as may be required;
   g. prevent, as far as possible, the spread of radioactive contamination. For example, cover dry spills of uranium oxide to prevent dispersion by the wind, or prevent seepage of contaminated liquids into groundwater by speedy removal of materials.

Once the above has been accomplished, the clean-up and recovery process must commence. As the clean-up is substance-specific, the next subsections deal with specific clean-up requirements.

The process of responding to emergencies includes communication with affected stakeholders, members of the fire brigade and police who support the emergency recovery, and persons involved in the emergency response actions, as well as members of the public who may be bystanders.

It is imperative that first responders understand the nature of the material(s) that must be dealt with. It is also critical that they can effectively communicate the substance-specific hazards to all parties that participate in the emergency response and clean-up operation.

To illustrate: if the fire brigade is called to support efforts to extinguish a fire in a uranium roasting plant, they must be made aware of the risks of radioactive contamination that exists in such an area, and the risk of uncontrollably spreading radioactive contamination if firefighting efforts are not carefully managed.

Questions by the media and members of the public who are not immediately affected by the emergency are best referred to the entity's top management and communication section.

6. **Post clean-up activities:**
   Once the emergency has been cleared, relevant stakeholders must be informed of the outcome, the actions taken, and the consequences of the emergency.

7. **Reporting and lessons learned:**
   Each emergency must be followed up by an analysis of the causes of the event, as well as an assessment of the effectiveness of the response actions, to optimise future responses. These are best reported to key stakeholders, including the regulatory Authority and other relevant government entities.

17.5 Clean-up of Uranium Ore Spills

Clean-up operations must be prioritised according to the risk associated with the spilled material.

The clean-up of spilled uranium-bearing ore, drill chips, NORM samples and drill cores entails the following steps:

1. Use PPE, including long-sleeved work clothes, safety shoes and glasses, and dust masks;
2. Cover the spill, if possible, to prevent that the wind spreads the material, and minimise wind-blown dust;
3. As required, wet the material slightly, using spray water;
4. Rake up and sweep up the coarse material, but avoid sweeping areas covered in fine dust as this will generate more airborne dust;
5. Place the raked-up and swept-up material into plastic bags, drums or similar sturdy containers, and seal these;
6. Once the area is cleaned up, thoroughly wash the hands, face, and other exposed body parts, and clean all clothes and equipment used in the clean-up.

17.6 Clean-up of Uranium Concentrate Spills

Clean-up operations must be prioritised according to the risk associated with the spilled material.

The clean-up of spills involving uranium concentrate, such as uranium oxide and dry yellowcake, entails the following:

1. Use appropriate PPE, including disposable overalls, respirators, gum boots and gloves;
2. If the spill occurred outdoors, cover the material with a tarpaulin or large plastic sheets to avoid it being spread by the wind, and avoid generating excessive dust;
3. Rake up and collect the spilled material using shovels, rakes, and brooms;
4. Fill the spilled material into heavy-duty drums, and seal all drums prior to their removal off site;
5. Clean the remaining areas using a vacuum cleaner and hand-held brooms;
6. Assess the remaining contamination levels, using an alpha contamination monitor;
7. Decontaminate the area if indicated by the contamination assessment;
8. Ensure that contamination levels correspond to natural background levels before completing the decontamination efforts;
9. Once cleaned up, thoroughly wash the hands, face, and other exposed body parts;
10. Decontaminate all tools and equipment and dispose of contaminated PPE.

Figure 171: Contaminated area where a yellowcake spill occurred [34]

17.7 Clean-up of Sealed Source Material

Accidents involving sealed radioactive sources may release high-activity contaminants into the environment. This necessitate immediate and urgent action.

The clean-up involving spilled materials from sealed radioactive sources entails the following:

1. Use PPE including disposable overalls, respirators, gum boots and gloves;
2. Use appropriate shielding, such as lead aprons, if available;
3. Avoid any unnecessary movements into or through the area in which sealed source material may be located;
4. Under all circumstances, minimise the time and maximise the distance to any source material;
5. Ensure that as few persons as possible are directly involved in the clean-up;
6. Assess the radiation-related risk by undertaking a dose rate assessment of the area in which the accident happened. The use of a hand-held dose rate meter is sufficient to undertake a rapid high-level assessment;
7. Locate the radioactive material, using the finder mode, as is available on various contemporary gamma dose rate meters;
8. If available, use lead shot and/or lead aprons to cover any remaining radioactive material until it can be removed from the site of the accident;
9. If possible, grab the source material using long tongs;
10. Place the source material into a lead casket, which must be closed and removed to a controlled area as quickly as possible;
11. Place the remains of the damaged sealed source container into a box with lead casing, and move it to a controlled area as quickly as possible;
12. Once a first clean-up has been completed, undertake a radiation assessment of the affected area;
13. Clean-up all areas in which source remnants remain, or which show higher-than-background radiation levels;
14. Once the decontamination activities have been completed, undertake a final radiation assessment of the area. Ensure that the affected area is only vacated once all source remnants have been removed from the accident site;
15. Once the clean-up has been completed, and before leaving the site, thoroughly wash the hands, face, and other exposed body parts;
16. Decontaminate all tools and equipment; and
17. Dispose of all PPE that may have been in contact with source material.

Figure 172: Emergency response measures put to a test in Botswana in 2015 [150]

17.8 Emergency Clean-up Kit

The following items are included in a radiation emergency clean-up kit which is to be used for cleaning up spills of uranium-bearing ore, ore samples and drill cores, uranium concentrate, as well as in accidents involving sealed radioactive sources, as described above:

1. mobile personal radiation detector, such as a RadEye PRD, or FH 40, or similar;
2. surface contamination monitoring instrument with suitable alpha / beta probe, such as a RadEye SX with probe, or similar;
3. two-way radio or similar location-independent communication tool;
4. digital camera (mobile phones should not be used as they may be contaminated during the clean-up operations);
5. note pad and pens, in sealable see-through plastic pouches;
6. depending on the type and quantify of spilled material:
    a. heavy-duty plastic bags, and cable ties (for a few kg to a few tens of kg of NORM samples or similar); and/or
    b. heavy-duty sealable plastic containers (for tens of kg of to-be-removed NORM, or uranium concentrate);
    c. sealable steel drums (for tens to hundreds of kg of to-be-removed NORM, or uranium concentrate);
    d. lead-lined box (for damaged sealed sources), as illustrated in Figure 173;
    e. lead casket (for sealed source material), see e.g. Figure 173;
7. shovels, brooms, and hand brooms;
8. disposable overalls;
9. dust masks (for NORM and related spills), and respirators (for spills of uranium concentrate and sealed source material);
10. heavy-duty gloves;
11. heavy-duty long pliers, adjustable spanner (e.g. a vice grip);
12. screw driver set;
13. heavy-duty tongs of 1 m and 2 m length (for the recovery of sealed source material only);
14. rubber boots;
15. area demarcation band;
16. road-safety cones, bright orange;
17. drinking water;
18. water cans;
19. water to suppress dust;
20. waste bins for contaminated disposable waste and contaminated PPE.

Figure 173: Various lead lined caskets as are useful when retrieving sealed source material [151]

18 Safety and Security of Radiation Sources

This Chapter describes the essential safety and security provisions required when dealing with sources of ionising radiation.

18.1 Introduction

In the context of this book, the *safety and security of radiation sources* is aimed at

- protecting people and the environment against radiation risks; and
- ensuring the safety of facilities and activities that may or does give rise to such radiation risks.

Radiation protection, as it pertains to the safety and security of radiation sources, encompasses the full spectrum of measures to ensure the safety of radiation sources, including radioactive material, nuclear material as well as electric sources of ionising radiation. As such, radiation protection encompasses all measures to make and keep radiation sources safe, and secure. This includes the safety of radioactive material, radioactive waste, safety during the transport of such radioactive material, as well as the security of facilities and equipment, and includes the management of protective measures to ensure the security of radiation sources.

Although important, this book does not concern itself with safety and security measures other than those which are a necessary or desirable part of radiation protection.

Given the focus of this book, *safety* is concerned with radiation risks that arise under normal circumstances, as well as those arising because of incidents and accidents. Therefore, *safety measures* include actions to prevent incidents and accidents, as well as those required to mitigate their consequences if they were to occur.

In contrast, and keeping the focus of this book in mind, *security* means the prevention and detection of, and response to, theft, sabotage, unauthorised access, illegal transfer, or any malicious acts involving radiation sources, specifically including nuclear material and other radioactive material, and the facilities in which these are kept and/or used.

Safety and *security* as well as their corresponding measures, both aim to protect life, health, and the environment.

For safety measures to be actionable, *safety standards* are established. They guide the activities that result in excellent, acceptable, or poor security. Because of the close link between safety and security, one often speaks of *security for safety measures* – these contribute to and foster both safety and security, and typically include

a. deliberate and appropriate provisions in the design, construction, and operation of facilities that house radiation sources or in which they are used, including those for nuclear material and associated nuclear installations, and radioactive material;

b. multi-layered controls to prevent the loss of, and the unauthorised removal, possession, transfer and use of, any radiation source, including nuclear material and other radioactive material;

c. arrangements for and pro-active management to minimise and mitigate the consequences of incidents and accidents, including those resulting from malicious acts, and facilitate measures to prevent and deal with breaches in security that give rise to radiation risks; and

d. measures for the security and management of radioactive sources and associated source material.

18.2 Definitions

When this book refers to *safety*, it means the achievement and maintenance of proper operating conditions, prevention of incidents and accidents, and the mitigation of their consequences, resulting in the protection of people and the environment from undue radiation hazards.

When this book refers to *security*, it means the prevention of, detection of, and response to unauthorised acts involving or directed at radiation sources, including nuclear material and other radioactive material, as well as facilities and associated activities.

Deliberate, successive, and mutually supporting measures that improve the safety and strengthen the security are referred to as *defence in depth*.

The *effectiveness of safety and security measures* rely on how well these remain undisclosed to those who are not immediately entrusted with their implementation, management, and control. Therefore, safety provisions and security measures should not be casually shared or unnecessarily divulged, as the wider knowledge of the *system of safeguards* leads to an overall weakening of the very processes and instruments that underpin the safety and security of an operating environment.

As this book is centred around applied radiation protection and radiation safety, it is important to mention the specific role and repercussions when dealing with *nuclear material*.

The IAEA defines *nuclear material* as:

i. *plutonium except that with isotopic concentration exceeding 80% in Pu-238;*
ii. *uranium enriched in isotope U-235 or U-233;*
iii. *uranium containing the mixture of isotopes as occurring in nature other than in the form of ore or ore residue; and*
iv. *any material containing one or more of the foregoing,* [1].

The Namibian Act defines *nuclear material* as:

'*(a) plutonium (except Pu with isotopic concentration > 80% in Pu-238);*
(b) uranium enriched in isotope U-235, or uranium containing the mixture of isotopes as occurring in nature other than in the form of ore or ore residue; and
(c) any substance or device that may be necessary or useful in the manufacture of nuclear weapons, prescribed to be nuclear material, any mixture or compound that contains nuclear material, except any naturally occurring mineral containing uranium that has not been processed in any manner to concentrate the uranium contents or change the isotopic mixture of the uranium.' [2]

Of note are items iii. and (b): these imply that both yellowcake and uranium concentrate are defined as *nuclear material*.

18.3 Safety and Security of Nuclear Material

The *IAEA Safeguards* are intended to minimise and deter the spread of nuclear weapons, nuclear materials and technologies that can be used for purposes other than peaceful ones.

The safeguards entail multiple approaches and systems to detect the diversion, misuse or otherwise non-compliant dealings involving nuclear materials and associated technologies. In this way, the IAEA focuses on ensuring that states honour their obligations regarding the use of nuclear and associated materials.

The safeguards are a set of technical measures applied by the IAEA, resulting in the independent verification of nuclear facilities. When states accept these measures, which is signalled through the conclusion of a safeguards agreement, they accept that early detection and various monitoring measures are applied to verify that nuclear material is not illegally or clandestinely diverted from their nuclear facilities.

The IAEA Safeguards are a critical constituent of the current *international nuclear security system*. At its centre is the *Treaty on the Non-Proliferation of Nuclear Weapons*, which is often abbreviated as NPT, guiding the global efforts to prevent the spread of nuclear weapons. Under Article 3 of the NPT, each *non-nuclear weapon state* is required to conclude a safeguards agreement with the IAEA.

The agreement between Namibia and the IAEA for the application of safeguards in connection with the NPT was signed on 19 March 1998 and came into force on 15 April 1998 [152].

A *Protocol Additional* between Namibia and the IAEA for the application of safeguards in connection with the Treaty on the NPT was signed on 22 March 2000, and came into force on 20 February 2012 [153], [154].

The *African Nuclear Weapon Free Zone Treaty*, known as the *Treaty of Pelindaba*, establishes a nuclear weapon free zone across the entire continent of Africa [155]. It entered into force on 15 July 2009, prohibiting the research, development, manufacture, stockpiling, acquisition, testing, possession, control, or stationing of *nuclear explosive devices* in the territories of its signatories. It also prohibits the dumping of radioactive waste originating from outside Africa anywhere within the continent's nuclear-weapon-free zone. It requires signatories to maintain the highest standards of physical protection of nuclear material, facilities and equipment, and their use for peaceful purposes only [156]. In early 2018, 39 states and one non-UN member state are parties to the Treaty.

18.4 Classification of Radioactive Sources

The IAEA provides a classification scheme of radioactive source material based on their radiation risk [157].

This classification system uses the ratio of the activity *A* of a source, and the so-called dangerous source value *D,* which is tabulated in the IAEA categorisation scheme for such sources.

It must be noted that the classification system refers to radioactive sources other than NORM sources.

18.4.1 Category 1 Source

An example of a Category 1 source is a Co-60 source, e.g. as used for food sterilisation, with an activity of $5.6 \cdot 10^4$ TBq.

- **Individual sources:**

  Extremely dangerous: This amount of radioactive material, if not safely managed and securely protected, would be likely to cause permanent injury to a person who handled it, or were otherwise in contact with for more than a few minutes. It would be fatal to be close to unshielded source material for a period of a few minutes to an hour.

- **Dispersed radioactive material:**
  This amount of radioactive material, if dispersed by a fire or explosion, could possibly — but would be unlikely to — permanently injure or be life threatening to persons in the immediate vicinity.

There would be little or no risk of immediate health effects to persons beyond a few hundred metres away, but contaminated areas would need to be cleaned up in accordance with international standards.

The size of the area to be cleaned up would depend on the size and type of the source, whether and how it had been dispersed, and the prevailing weather. For large sources, the area to be cleaned up could be a square kilometre or more.

It would be highly unlikely for a Category 1 source to contaminate a public water supply to dangerous levels, even if the radioactive material in question was highly soluble in water.

18.4.2 Category 2 Source

An example of a Category 2 source is a Cs-137 source as used for the irradiation of blood, having an activity of 37 TBq.

- **<u>Individual sources:</u>**

  Very dangerous: This amount of radioactive material, if not safely managed and securely protected, could cause permanent injury to a person who handled it, or were otherwise in contact with for a period of some minutes to hours. It would be fatal to be close to unshielded source material for a period of a few hours to days.

- **Dispersed radioactive material:** This amount of radioactive material, if dispersed by a fire or explosion, could possibly, but would be very unlikely to permanently injure or be life threatening to persons in the immediate vicinity.

  There would be little or no risk of immediate health effects to persons beyond a hundred metres or so away, but contaminated areas would need to be cleaned up in accordance with international standards.

  The size of the area to be cleaned up would depend on many factors (including the size and type of the source, whether and how it had been dispersed, and the weather), but would not exceed a square kilometre.

  It would be virtually impossible for a Category 2 source to contaminate a public water supply to dangerous levels, even if the radioactive material in question was highly soluble in water.

18.4.3 Category 3 Source

An example of a Category 3 source is a Ir-192 source, e.g. as used for brachytherapy, having an activity of 0.4 TBq.

- **<u>Individual sources:</u>**

  Dangerous: This amount of radioactive material, if not safely managed and securely protected, could cause permanent injury to a person who handled it, or were otherwise in contact with it, for some hours. It could possibly – although it is unlikely – be fatal to be close to this amount of unshielded radioactive material for a day to weeks.

- **Dispersed radioactive material:** This amount of radioactive material, if dispersed by a fire or explosion, could possibly, but is extremely unlikely to permanently injure or be life threatening to persons in the immediate vicinity.

There would be little or no risk of immediate health effects to persons beyond a few metres away, but contaminated areas would need to be cleaned up in accordance with international standards.

The size of the area to be cleaned up would depend on many factors (including the size and type of source, whether and how it had been dispersed, and the weather), but would not exceed a small fraction of a square kilometre.

It would be virtually impossible for a Category 3 source to contaminate a public water supply to dangerous levels, even if the radioactive material in question was highly soluble in water.

18.4.4 Category 4 Source

An example of a category 4 source is an Am-241 source, e.g. as used for calibration, at an activity of 0.2 TBq.

- **Individual sources:**

  Unlikely to be dangerous: It is very unlikely that this amount of radioactive material would permanently injure anyone. However, this amount of unshielded radioactive material, if not safely managed or securely protected, could possibly — although it is unlikely — temporarily injure someone who handled it or were otherwise in contact with it, or who were close to it for a period of many weeks.

- **Dispersed radioactive material:** This amount of radioactive material, if dispersed by a fire or explosion, could not permanently injure persons.

18.4.5 Category 5 Source

An example of a category 5 source is a H-3 source, e.g. as used to detect electron capture, at an activity of 0.01 TBq.

- **Individual sources:**

  Not dangerous: this amount of radioactive material could permanently injure persons.

- **Dispersed radioactive material:** This amount of radioactive material, if dispersed by a fire or explosion, could not permanently injure persons.

  Radioactive sources that are typically used for level detection and/or density measurements in commercial and industrial applications, such as in the mining sector, fall into this latter category, as they often have activities of up to a few GBq.

18.5 Security Controls

The approach to site-wide security must be based on an *integrated security system* that aims to detect, prevent, and respond to breaches of all on-site security matters.

It is important to note that the *security controls* applied at a given site must depend on the specific security classification and concerns that may, can and will arise.

Public access areas require the lowest level of security control. They are usually limited to ensuring that persons coming to site have the necessary clearances and have attended all relevant inductions. In addition, persons wishing to leave a site, even those who have only visited public access areas while on site, should be subjected to a high-level search to ascertain the presence of radioactive materials.

Supervised areas are those areas that are, as a minimum, delineated and signposted. They must include notices on the required personal protective measures relevant to the area. It is good practice to name the area and provide the contact details of the relevant area manager, i.e. the so-called *area owner*.

Controlled areas are specially demarcated areas and can only be accessed through specific access points. Such access and egress points are either staffed by security personnel, and often located at vehicle boom gates or pedestrian turnstiles, or similar physical barriers. It is essential that controlled area signage includes the name of the area, provides the contact details of the *area owner*, specifies all compulsory PPE requirements, and describes any specific actions and measures that apply in the area (e.g. disposal requirements for contaminated PPE, and decontamination rules for tools and equipment). Area induction and registration requirements, as well as high-level emergency procedures, are also important.

18.6 Communication

Access control points must be in constant two-way radio contact with the site-wide security operations and control centre. This ensures that unauthorised activities can be readily reported and can be acted upon efficiently and effectively.

18.7 Signage

Sites and work areas at which radiation sources are stored or used must display signage to indicate specific entry and personal protective clothing requirements.

It is good practice to ensure that site-wide access procedures exist, and that all supervised and controlled areas are equipped with signage that include a description of the required PPE that is to be worn prior to entry to such areas. In addition, signage to controlled areas must alert persons wishing to enter such areas of area-specific check-in requirements, and the contact details of the area owner. It must describe location-specific actions and measures that apply, which often include decontamination rules for persons, disposal requirements for contaminated PPE, and decontamination requirements for tools and equipment. Specific induction and registration requirements, as well as high-level emergency procedures, e.g. decontamination processes, evacuation route map and assembly points are useful to include.

18.8 Access and Egress Controls

Any radiation source that could give rise to dose levels that significantly exceed the natural background levels must be placed in areas that are access-restricted. Such restrictions in turn imply that access to these areas must be controlled.

Access restrictions must apply to areas in which industrial radiation sources, such as radioactive gauges, X-ray and some ultraviolet light equipment, radioactive mineral ore concentrates, and select NORM-based sources are located.

Sealed radioactive sources must only be in controlled work areas. They are best equipped with a lockup cage, also called *bird cages*, as shown in Figure 174. These provide additional layers of control for access to the source, while they also reduce the probability of incidents, tampering and malicious acts.

In terms of public access, any source that could lead to significant public exposure doses must be managed to ensure that access to such sources is restricted. This includes radioactive waste rock dumps, tailings storage facilities, as well as exploration and mining areas involving the handling and processing of radioactive minerals.

In mineral sands operations that are characterised by high concentrations of radioactive minerals, access controls must include the stockpile and mining areas if it is found that radiation levels significantly exceed the natural background radiation levels in the area.

Figure 174: Lockup cage around a sealed radioactive source used for density measurements [8]

18.8.1 Perimeter Controls

Good practice necessitates that a site that requires access controls is fully fenced. In addition, perimeter controls should include the active control and supervision of the perimeter, by way of motorised control rides, closed-circuit television cameras, motion detectors and sporadic aerial controls by way of surveillance drones.

It is important that access to a mining site is limited to one or a few main entrance points. These must be permanently staffed with trained security personnel able to identify and detect incidences in which radioactive material is illegally or unintentionally removed from the site, and they must be equipped to ensure that only contamination-free items can be taken off site.

18.8.2 Main Access Point(s)

Access to a site must only be possible through the official main access point(s).

Access must be controlled by ways of access authorisations, e.g. access permits. This ensures that individuals wishing to enter the premises are issued with an access badge or other means by which they identify themselves prior to being allowed on site.

Good practice dictates that persons wishing to enter a site for the first time must familiarise themselves with the safety procedures applicable on site. A compulsory site induction is recommended and must include aspects relating to radiation protection and safety as per site requirements.

Access to radiologically classified areas, i.e. supervised and controlled areas, must be limited to operational and maintenance persons active in such areas. All areas have specific PPE requirements, and only persons meeting such requirements are permitted to proceed, provided they have the necessary area clearances.

All personnel regularly working in a radiologically classified area must be registered as *occupationally exposed persons*. Visitors to such areas are considered *non-occupationally exposed persons*, and can only enter if they have been issued the necessary authorisation by the Radiation Safety Officer or his/her authorised representative.

Vehicles are only permitted to enter a classified area when the driver and any passengers have the relevant area access authorisation.

18.8.3 Access to Radiologically Classified Areas

Access to radiologically classified areas must be strictly limited at all times. To this end, *multi-layered access controls* are useful: they often include limiting access to radiologically classified areas to persons having the required level of authorisation, and/or a special security clearance, and include one or several physical measures, such as gates or turnstiles, as well as written access permissions by the responsible area owner.

Entry requirements to radiologically classified areas must ensure that persons have undergone the necessary area-specific induction training and fulfil the relevant exposure group classification. Persons should only be able to enter such an area by passing one or several physical barriers. To illustrate: a controlled area can be secured by way of a system of electronic badges that all persons must wear to be able to pass a pedestrian turnstile that limits access to a given area. Access by way of fingerprint or facial recognition may also be viable. By equipping such access points with closed-circuit television equipment, which is permanently monitored in an on-site security surveillance room, individual access to such areas can be maximally controlled.

If vehicles need to enter radiologically classified areas, such access must be strictly limited and controlled. For example, a system of gates and/or boom gates can be used, at which all persons wishing to enter or leave the area must be authorised, for example by way of carrying a security badge, or by way of fingerprint identification, or similar. Here it is noted that security badges may end up in the hands of unauthorised persons, which is less likely if personal access controls are exercised by using fingerprint or facial identification.

18.8.4 Egress from Radiologically Classified Areas

On leaving a controlled site, all persons must be searched at random. This is to deter, and it is to ensure that illegally diverted radioactive material is detected. To this end, security controls must include all necessary measures to identify whether any person is radioactively contaminated or is carrying radioactive materials when attempting to leave the site.

Egress controls can only be effective if security personnel are trained, including in the operation and use of hand-held instruments which are necessary to locate radioactive material on persons and vehicles leaving the area.

Vehicles leaving radiologically classified areas must be assessed to ensure that they do not convey any radioactive materials, which may be legal, or may be an attempt to illegally divert such material.

Vehicles must also be assessed for surface contamination. Such assessments must be undertaken by security personnel at the respective egress control point(s). If surface contamination levels exceed those specified in the site's contamination control procedure, vehicles must be cleaned, before returning to be re-assessed.

18.8.5 Non-staff Access

Persons who are not staff members, but must enter a controlled area, for example to render installation and maintenance services, must be authorised to do so. This is achieved by for example issuing an entry permit, which is signed by an authorised staff member such as the area owner. In addition, such persons should be issued with an individual access card. It is good practice to ensure that all non-staff persons who enter the site undergo an induction, which must include the relevant radiation-related safety aspects for the areas that are to be visited. It is common practice that an authorised staff member accompanies non-staff members when on site, and this is of critical importance in supervised and controlled radiation areas.

18.8.6 Visitor Access

Visitors wishing to enter a controlled site must be required to be in possession of a valid and time-limited site access permit. This serves as a first control measure when entering the site. Visitors who are not service providers must only be allowed to enter a restricted site when accompanied by an authorised staff member always. The staff member remains responsible for the safety of such person(s) until they leave the site.

18.9 Theft Protection

Conditional access restrictions to all areas where sealed radioactive sources, and radioactive materials that can readily be diverted, are necessary, and constitute a first step to reduce the potential of theft.

Further to such access measures, a site where such source material is handled or used must have in place thorough security protocols. These are to ensure that all items that are to be removed from site are checked. Authorisations for the removal of any radioactive substances and sources must be regulated, which is achieved by way of a system of clearance and removal permits, signed by the relevant area owner(s), as well as other relevant and authorised site personnel, such as the Radiation Safety Officer.

These principles also apply when safeguarding uranium concentrate from the unintended removal from a site. The use of radiation detection devices that can be used in finder mode, such as the RadEye PRD, for searching all persons and vehicles leaving a site, is one of the more effective tools to minimise the loss of material that is subject to strict controls and the country's safeguards requirements. In this regard, the reader is reminded that references [152] and [153] describe the agreements relating to the safeguards of nuclear materials as they relate to Namibia.

18.10 Radiation Source Inventory

For radioactive sources, such as industrial sealed radioactive sources used for flow, density, and level measurements, and calibration sources, a source inventory must be established and kept current, as described in section 0.

Such an inventory serves to keep track of the whereabouts of such individual radioactive sources and reduces the complexity of ensuring that such sources must remain controlled always.

18.10.1 Sealed Source Inventory

A *sealed source inventory* must include the details of all radioactive sealed sources on site, including

- source type and model;
- serial number;
- source characterisation;
- name of the manufacturer;
- source activity at production;
- radionuclide(s) and their half-life(s);
- date when source was imported;
- location of source; and
- summary of all relevant control and monitoring activities undertaken per source, including all leak and/or integrity tests undertaken, as well as the dates, times, and person(s) who undertook such tests, and the test results;
- registration and license number, as issued by the regulatory Authority; and
- relevant license expiry date.

Sealed radioactive sources must be subjected to an *integrity test* at least twice per year, which must include a leak test. The results of such tests must be included in the annual report to the regulatory Authority.

18.10.2 Radioactive Source Inventory

Radioactive sources other than sealed radioactive sources include uranium concentrate, radioactive material, and NORM, and must when viable, be tracked by a *radioactive source inventory*.

At a uranium mine, a *uranium concentrate inventory* must be kept by the metallurgy and/or production section. This is to entail a detailed and up-to-date summary of uranium concentrate on site, based on a product accounting system that accounts for processed ore, the losses per production step, delivered final product, and drummed product.

A uranium concentrate inventory is an accounting system that must allow for the identification and tracking of unaccounted for product, for example product that is missing because of process losses, and deliberate illegal product diversion. In this way, a uranium concentrate inventory serves to determine process (in)efficiencies, while also providing indicators of possible unauthorised or otherwise unaccounted for product removals in the concentration process.

Inventories for NORM and related radioactive mineral ore must include the run-of-mill rock and ore dumps, tailings storage facilities, waste rock dumps, ore samples as well as radioactive pulps and sludges.

All radioactive ore samples are unsealed radioactive sources, which are readily discharged and spread into the environment. However, it is noted that the radiological risk associated with most radioactive mineral ore samples is low, especially when compared to the radiological and toxicologic risks from sealed radioactive sources and uranium concentrate. As introduced in section 4.6, this is because of the low uranium concentration of most NORM and related materials, which therefore implies that their activities are low or very low when compared to uranium concentrate, and the radioactive material that is contained in sealed sources.

18.10.3 Non-Radioactive Radiation Source Inventory

In addition to the radioactive source inventories described in the previous sections, an *inventory of non-radioactive radiation sources* must be kept, and include

- source serial number;
- source characterisation;
- source type and source model;
- name of the manufacturer;
- location of the source;
- license numbers, for import, ownership, use as applicable;
- import date;
- license expiry date for each license held per source; and
- summary of relevant control and monitoring activities undertaken per source, including relevant leak tests undertaken, date and times when such tests took place, and person(s) who undertook such test(s).

18.11 Security in Controlled Areas

Controlled areas must be secured using multi-layered controls. This is achieved by measures that allow security staff to record and assess the movements and activities of individuals entering, operating, and leaving such areas.

Controlled areas are best secured by way of closed-circuit television (CCTV). Such systems should be enabled by motion sensing and detection, which serves to raise an area-specific alarm, if needed.

As a second-tier measure, 24/7 surveillance of controlled areas must be undertaken, which ensures that alarms are captured and acknowledged on the CCTV data system, and prompt rapid and effective action in case breaches occur.

As a third-tier measure, video surveillance data should be captured on secured servers, which should be regularly assessed. It is also useful to have security provisions regularly and independently audited.

18.12 Personal Protective Equipment

Sites where radioactive source material is stored and/or handled have specific requirements regarding personal protective equipment that is needed before specific areas can be entered.

Area-specific PPE requirements are best displayed on signage boards at the entry points to demarcated work areas.

Contamination of PPE is likely to happen in radiologically controlled areas. Such radioactively contaminated gear may only be disposed of into special radiological waste bins, which must be placed in work areas in which radioactive contamination is likely. The disposal of contaminated PPE must be undertaken regularly and must be guided by the site-specific contaminated waste disposal standard operating procedure.

18.13 Emergency Routes and Assembly Points

On-site work areas must be assessed in terms of their specific risk profile, and their design and layout must make provision for routes that are to be followed in an emergency. Secure assembly points and routes to such points must be available, including in emergency situations. These provisions are particularly relevant in the final product processing plant of a uranium mine, the calcining plant, drumming and packing areas, and other radiologically relevant work areas.

18.14 Wash-down Facilities

Select work areas in which persons may be radioactively contaminated must be equipped with wash-down facilities, to allow for the rapid removal of contaminated persons. The area owners of work areas in which the risk of radioactive contamination exists must ensure that all persons entering such areas are trained to be able to operate the wash-down equipment in case of contamination. wash-down facilities should, however, not be used for the routine decontaminations of radiologically contaminated tools and equipment, as this may limit the availability of such facilities in case of an emergency.

18.15 Contamination Controls

A mining site where radioactive ore is mined and processed would normally have numerous work areas where the risk of surface contamination exists.

Such areas include the pit and tailings areas, where vehicles and equipment are likely to be contaminated with dust, mud and sludge containing radionuclides.

Also, the processing and final product plant of a uranium mine, and maintenance areas in which plant and machinery is maintained, are areas where contamination with uranium oxide, uranium dust and/or jarosite are likely to occur.

Contamination controls, as have been elaborated in section 15.6, are essential whenever people, plant and equipment may be radioactively contaminated, necessitating both area- and activity-specific radiological contamination controls.

Decontamination measures must be established and kept operational always. They must be designed such that they allow staff to decontaminate others, as well as tools, equipment, and vehicles, as and when required.

Contaminated goods that are to be removed from any radiologically classified area must be decontaminated, to minimise any risk of cross-contamination.

Decontamination is best undertaken at workshops within the processing plant area, and the salvage yard, which should be equipped with suitable decontamination facilities. Once contaminated objects have been decontaminated, their fixed and non-fixed contamination levels must be assessed, as described in section 12.6. Only those objects that are below the relevant contamination thresholds may be removed from a radiologically classified area.

If contamination cannot be reduced to levels below the site-specific contamination thresholds, objects must be detained in the work area where they were last used, or they must be transported to a special contaminated salvage yard for intermediate storage, or they must be conveyed to a disposal site which is authorised for use and the final disposal of radioactive waste of the type as must be disposed of.

18.16 Decontamination Facilities

Decontamination facilities are an important control element to minimise the potential spread of radioactive contamination across work areas, and the processing or mining site. Decontamination facilities for vehicles must be available close to where such contamination may occur.

Vehicles must be visually inspected for dust contamination before they are permitted to leave a contaminated area.

When vehicles do not to meet the contamination control requirements, as must be summarised in site-specific decontamination procedures, they must be cleaned.

Radioactively contaminated tools and equipment must be decontaminated before they are cleared. Only thereafter may they be removed from a contaminated work area.

Decontamination facilities must be available at work areas and workshops where the risk of contamination exists. This may include areas such as the special waste salvage yard, and waste transition yard where equipment such as contaminated pipes, pumps, heat exchangers, valves and others are temporarily stored. The decontamination facility at Rössing is shown in Figure 175.

Figure 175: Decontamination facility at Rössing [34]

18.17 Change Houses

Change houses are required whenever site- or area-specific PPE requirements are in place, and require staff, contractors, or visitors to change from their casual workwear into area-specific PPE, or vice versa.

Change houses are best equipped with lockers in which clean clothing is stored, washing areas, as well as drop-off areas for contaminated PPE. Change houses must be designed to have a clean and a dirty area. Under no circumstances should persons be able to move from the dirty into the clean section of the facility without having washed themselves and exchanged their clothing. As such, the movement of persons in a change house must always be one-directional, from clean to dirty, and from the dirty to the washing facility, and from the to the clean area.

At the beginning of a shift, persons working in a radiologically classified area remove their private clothes and replace these with area-specific PPE. Then they enter the work place. At the end of a shift, or when a worker needs to leave the work area for other reasons, they enter the dirt side of the change house, take off their protective work clothing, store or surrender it for disposal or washing in demarcated containers provided, wash themselves, and then proceed to their personal locker to get dressed in their private clothes, before leaving the change house.

It is important that the design of a change house is such that a strict separation between dirty and clean sides can be maintained, and allow for the active control of contamination, while minimising cross-contamination from the dirty to the clean side. Under operational conditions, wash houses are often amongst the first work areas where poor contamination management approaches and sloppy housekeeping can be found.

18.18 Security Breaches

Security breaches, for example the unauthorised entry into a controlled area, or the illegal removal of radioactively contaminated items, must trigger immediate security responses. There can be numerous reactions to such breaches: for example, an alarm should be triggered if a person enters a restricted area without the necessary permissions. If this happens, a recording system should automatically activate, and should continue to document the event until it is deliberately stopped. It should not be possible to erase such recordings for some months, to allow for an in-detail analysis of the different ways in which the surveillance mechanism was triggered.

All security breaches must be recorded, and individually assessed, to investigate how such breaches occurred, and whether the unauthorised entry may also have resulted in the unauthorised removal of source material.

The illegal removal of radioactive material from restricted areas must be minimised. This can be achieved by subjecting all persons existing such areas to a radiation scan. Often, these assessments can only be applied to a select number of persons in each shift. When this applies it is important that the persons to be scanned are selected randomly, to ensure that it remains difficult to predict when personal scanning will happen.

18.19 Removal Permits

All radiation source removals from controlled or supervised areas must be authorised and must result in the creation of a physical or electronic record. It should be possible to cross-check entry/exit records to identify who and when a certain source was removed. The completion of a check-out sheet at the entry/exit point can be useful and should result in a permanent record of the timing and movement of a source, together with a removal permit number.

18.20 Radiation-related Security Training

Radiation-related security approaches must be trained, and they must be practiced. This is best achieved by way of targeted security induction and training courses, which must be compulsory for all security-relevant persons active on site.

18.21 Diversion of Radioactive Sources, Sabotage and Radiological Terrorism

The chapter on the safety and security of radiation sources would be incomplete without touching on malicious acts involving radioactive source material, including the intentional and illicit diversion of radioactive material, sabotage, and radiological terrorism.

While important, this book will not dwell on the safety and security aspects related to enriched and weapons-grade uranium, and their uses for nuclear explosive devices by terrorist organisations [158], [159]. This section only focuses on safety and security breaches at facilities at which radioactive source material is produced and/or stored, including radioactive material produced in the uranium mining sector and radioactive sources used in medicine, industry, and related endeavours. Such breaches can occur because of criminal intent, for example when diverted source material is stolen to be sold, or with the intention to carry out acts of sabotage, or for terrorist purposes.

Source inventories for radioactive material are meant to account for the whereabouts of such material. However, inventories are merely indicators, and do not actively reduce or prevent the deliberate and illicit diversion of radioactive source material. This is achieved by employing multi-layered safety and security approaches which prevent unauthorised access to source material, use alerting mechanisms for when safeguards are deliberately weakened or subverted, as well as by way of measures to identify illicit activities close to or at such sources. Still, and despite such measures being employed, one can be certain that attempts of unauthorised diversions of radioactive material have taken place and will take place in future.

In a uranium mining environment, two types of radioactive source material are of concern: a) radioactive materials, for example as contained in sealed sources, and b) uranium concentrate. Their commercial value – beyond what is achievable by way of a credible procurement process – is limited. However, police sting operations can create a demand, and incentivise the illegitimate diversion of source material, as can be persons with a malicious and terrorist intent. The radioactive source material mentioned here cannot, without elaborate modification, be used in a conventional nuclear bomb. However, such material can be used in so-called dirty bombs. These are devices where conventional explosives are combined with radiological source material, to disperse radioactive material, and thereby radioactively contaminate an area. Unlike a nuclear weapon, a dirty bomb is characterised by a low explosive yield, with the aim to maximally disperse radioactive material, to sabotage, disrupt, and cause fear.

Globally, and in an age of international terrorism, radiological dirty bomb attacks continue to constitute a significant risk [160], [161]. It is realised that countless radioactive sources are not adequately protected, and can therefore be readily diverted, often without having to overcome meaningful security measures or related obstacles. Main risk factors include poorly regulated and secured source materials, especially those in disused facilities, source bunkers and often unprotected storage spaces, as well as a variety of potent radiological sources which are commonly used in medicine, the mining industry, research, agriculture, and food science. An often-ignored source of radiological material includes those used in the health sciences: for example, radioisotopes such as caesium-137, are frequently used in medical equipment such as blood irradiators in hospitals. The ease of availability of such source material, including those used in commercial sealed radioactive sources (refer to Table 43), render them vulnerable to theft [162].

Table 43: Selection of commercially available radioactive source material and their uses

Radioisotope	Typical Application	Form
Cobalt-60	Teletherapy, industrial radiography, and for instrument sterilisation purposes	Solid, metal
Strontium-90	Thermo-electric generators	Solid, oxide powder
Caesium-137	Teletherapy, blood irradiations, industrial sealed sources for level and density gauges, and used in instrument sterilisation facilities	Solid, powder
Iridium-192	Industrial radiography and low dose brachytherapy	Solid, metal
Plutonium-238	Heat source for pacemakers; various research uses	Solid, oxide powder
Americium-241	Well logging, thickness, moisture and conveyor gauges, smoke detectors	Solid, oxide powder

Often, such sources are in unsecured locations, including in the mining and industrial sectors, and with limited or no active security measures and controls. This implies that the probability of a terrorist group detonating a radiological explosive dispersion device is likely to be much higher than that associated with the cumbersome and expensive assembly of an improvised nuclear explosive device.

A dirty bomb attack could radioactively contaminate an area, and would also likely cause large-scale disruption, fear, and panic. Depending on the type of source material used, clean-up of contaminated areas could be costly, and would halt or at least severely constrain most ordinary activities taking place in an affected area. This feature has earned dirty bombs the name weapons of mass disruption, in contrast to weapons of mass destruction, which include nuclear, chemical, and biological weaponry, which remain in the arsenals of many of the world's militaries. Unlike a nuclear weapon however, radiological explosive devices do not cause catastrophic levels of death and injury. However, depending on its composition, application, and location, it could bring about massive costs, including for evacuation, coping, and managing panic and mass hysteria, as well as for the relocation and decontamination of the affected area.

Risk is the probability of an event multiplied by its consequences. The probability of a terrorist act leading to the explosion of a dirty bomb is much higher than that associated with such groups laying their hands on nuclear material that can be used to construct an improvised nuclear bomb. In contrast, the consequences of a conventional nuclear explosion will – in most cases – be catastrophic, while the properties of the radioactive material dispersed by a dirty bomb determine its impacts and repercussions. However, the objectives of a terrorist movement may not always imply that an attack that is easier to accomplish is preferred, and it is important to note that the probability of an attack also depends on how its consequences serve the ultimate purpose of such an act.

From the radiological terrorism perspective, only a few of radioisotopes are of primary concern. For this reason, security risk assessments focus on sources that contain those particular radioisotopes. Not all radioisotopes and radioactive sources present a high security risks. The key properties that determine the security risk are their energy, type of radiation, half-life of the radioisotope in question, the amount of material, its shape and size, the degree of shielding applied, the portability of the source material; prevalence of use and accessibility to the source; and how dispersible the source material is. Using many of these characteristics, the IAEA has categorised a large variety of radioactive sources by their associated radiation safety hazards, a high-level discussion is presented in section 18.4, and Table 44.

As many radiological sources exist, often in unsecured locations, and because of the potential impact that such attacks would have, it is essential that entities that deal with radiological source materials ensure that these are and remain secure. This must include strict access and stock controls, as well as several mutually reinforcing safety approaches to safeguard sensitive materials. In addition, emergency response measures must include scenarios where radioactive sources would be used in acts of sabotage or terrorism. Security measures must protect against the most plausible threats, including the deliberate and malicious diversion of radioactive material, as well as appropriate procedures to ensure that responses can be triggered following an actual act of diversion, sabotage, or terrorism. Here it is important to note that response measures must include those taken even if a threat cannot be verified or turns out to be a hoax. Today, terrorists may often find it easier to unleash the pervasive force of social media rather than focus on the use of physical violence only, which implies that response measures must include preparations for events that may remain mere figments of the imagination.

Table 44: Risk classification of radioactive sources as are used in medicine and industry

Risk Classification	Typical Application	Radioisotope	Typical Activity Range
Category 1: extremely dangerous, would likely cause permanent injury to persons handling it, or who are otherwise in contact with it for more than a few minutes	Thermoelectric generators utilising radioisotopes	Sr-90	330 - 25 000 TBq
		Pu-238	1 - 10 TBq
	Irradiators to sterilise instruments and for the preservation of food	Co-60	190 - 560 000 TBq
		Cs-137	190 - 190 000 TBq
	Self-shielded irradiators	Cs-137	93 - 1 600 TBq
		Co-60	56 - 1 900 TBq
	Blood and tissue irradiators	Cs-137	37 - 440 TBq
		Co-60	56 - 110 TBq
	Multi-beam teletherapy sources	Co-60	150 - 370 TBq
	Teletherapy sources	Co-60	37 - 560 TBq
		Cs-137	19 - 56 TBq
Category 2: very dangerous; could cause permanent injury to persons handling it, or who are otherwise in contact with it for some minutes to hours	Industrial radiography	Co-60	0.4 - 7.4 TBq
		Ir-192	0.19 - 7.4 TBq
		Se-75	3 TBq
		Yb-169	0.093 - 0.37 TBq
		Tm-170	0.74 - 7.4 TBq
	Calibration sources	Co-60	0.02 – 1.2 TBq
		Cs-137	0.056 - 110 TBq
Category 3: dangerous, could cause permanent injury to persons handling it or who are otherwise in contact with it for some hours	Level gauges	Cs-137	0.037 – 0.19 TBq
		Co-60	0.0037 – 0.37 TBq
	Calibration sources	Am-241	0.19 – 0.74 TBq
	Conveyor gauges	Cs-137	0.00011 - 1.5 TBq
		Cf-252	0.0014 TBq
	Well logging sources	Am-241/Be	0.019 - 0.85 TBq
		Cs-137	0.037 - 0.074 TBq
		Cf-252	0.001 - 0.004 TBq
Category 4: Unlikely that anyone would be permanently injured by such a source, but a temporary injury is possible	Thickness gauges	Kr-85	0.0019 - 0.037 TBq
		Sr-90	0.00037 - 0.0074 TBq
		Am-241	0.011 - 0.022 TBq
	Fill level gauges	Am-241	0.44 - 4.4 GBq
		Cs-137	1.9 - 2.4 GBq
		Co-60	0.19 - 1.9 GBq

19 Transport of Radioactive Material

This Chapter describes the provisions governing the transport of radioactive material.

19.1 Introduction

The United Nations Recommendations on the Transport of Dangerous Goods, which cover the transport of dangerous goods by all modes of transport except by bulk tanker, have gained a wide degree of international acceptance, although they are not legally binding [163] - [166]. Today, the Recommendations form the basis of various international agreements, and underpin many a national law.

The transport hazards identified in the Recommendations are grouped into nine classes. Often, these are further segregated into divisions and packing groups. The most common dangerous goods are assigned a United Nations number, which is a four-digit code, and is an internationally recognised goods identifier.

The nine classes into which the transport hazards are grouped are:

(1) Explosives

(2) Gases

(3) Flammable liquids

(4) Flammable solids

(5) Oxidising substances

(6) Toxic and infectious substances

(7) Radioactive material

(8) Corrosive substances

(9) Miscellaneous dangerous goods

Of relevance to this book is the transport of radioactive material. Based on the nine classes into which transport hazards are grouped, radioactive material is classified as *class 7 material* [163].

Internationally, the *IAEA Regulations for the Safe Transport of Radioactive Material* (SSR-6) guide the transport of radioactive material [96]. Advisory Material is provided to support the application of the regulations [97].

19.2 IAEA Regulations for the Safe Transport of Radioactive Material

The *IAEA Regulations for the Safe Transport of Radioactive Material* defines the legal framework conditions for the conveyance of radioactive material [96]. In the remainder of this book, the above regulations are abbreviated *IAEA Transport Regulations*.

Chapter 10 of the Namibian Regulations explicitly refer to the IAEA Transport Regulations. It is to be understood that the latest version of these regulations is the applicable version in the country.

19.2.1 Objectives of the IAEA Transport Regulations

The objectives of the IAEA Transport Regulations as they relate to the conveyance of radioactive material are identified in Regulation 104, which states:

> *'The objective of these Regulations is to establish requirements that must be satisfied to ensure safety and to protect persons, property and the environment from the effects of radiation in the transport of radioactive material.*
>
> *This protection is achieved by requiring:*
>
> *a) Containment of the radioactive contents;*
> *b) Control of external radiation levels;*
> *c) Prevention of criticality;*
> *d) Prevention of damage caused by heat.'*

19.2.2 Key Definitions and their Interpretation

The IAEA Transport Regulations provide important definitions which are of relevance to the terminology used in the transport of radioactive material [96]. These include:

- **Radioactive material (Reg 236):** *'Radioactive material shall mean any material containing radionuclides where both the activity concentration and the total activity in the consignment exceed the values specified in paras 402 – 407.'*

  Paragraphs 402 to 407 refer to 'Table 2', which has four columns, namely 1) A1 in TBq; 2) A2 in TBq; 3) Activity concentration limits for exempt material in Bq/g; and 4) Activity limits for exempt consignments in Bq.

  The definition states that material is radioactive if *both* the activity concentration and the total activity exceed the values specified in 'Table 2'.

  To illustrate: for uranium (natural), 'Table 2' provides the following values: 1 Bq/g and 1 000 Bq, which refer to the head of the radionuclide chain only. In the case of uranium (natural), the head of chain member is U-238. Therefore, material with an activity concentration exceeding 1 Bq/g *and* a total activity exceeding 1 000 Bq from radionuclide U-238 is defined as being radioactive.

For uranium or thorium concentrates, i.e. products from naturally occurring radionuclides, the values for A1 and A2 as per 'Table 2' are specified as being 'unlimited', which implies that they are not relevant.

- **U(natural):**
  U(natural) is uranium ore, regardless of its activity concentration. As per 'Table 2', and the associated footnote (b), U(natural) includes the parent radionuclide (U-238) and its '…*progeny included in secular equilibrium…: Th-234, Pa-234m, U-234, Th-230, Ra-226, Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, Po-210*'.

  This definition implies that material that includes U-238 plus all its decay products in secular equilibrium is defined to be U(natural). Note that this definition disregards the actinium chain (U-235 and its decay products), because it only contributes some 4% to the total radioactivity of natural uranium.

- **U-238:**
  As per 'Table 2', and the associated footnote (b), U-238 includes only Th-234 and Pa-234m as decay products in secular equilibrium, which appear in secular equilibrium with U-238 some 100 days after extraction.

- **Natural uranium (Regulation 247):**
  'Natural uranium shall mean uranium (which may be chemically separated) containing the naturally occurring distribution of uranium isotopes (approximately 99.28% uranium-238 and 0.72% uranium-235, by mass).'

  This definition implies that any material in which the naturally occurring ratio of uranium isotopes exists is defined to be *natural uranium*. Therefore, natural uranium includes uranium ore, freshly extracted and concentrated uranium, and the tailings material arising from uranium mining, milling, and processing.

  Uranium concentrate, which is also sometimes referred to *uranium oxide concentrate (UOC)*, is therefore 'natural uranium'. UOC is *not* U(natural), as the latter includes the parent plus progeny in equilibrium.

  Because uranium concentrate is natural uranium, the exemption limits that apply are those for U-238. These are ten times higher than the corresponding exemption limits for U(natural).

- **Low toxicity alpha emitters (Reg 227):**
  'Low toxicity alpha emitters are: natural uranium, depleted uranium, natural thorium, uranium-235, uranium-238, thorium-232, thorium-228 and thorium-230 when contained in ores or physical and chemical concentrates; or alpha emitters with a half-life of less than 10 days.'

  This definition implies that uranium concentrate, uranium ore, and uranium tailings material are defined as low toxicity alpha emitters.

- **Contamination (Reg 214):**
  'Contamination shall mean the presence of a radioactive substance on a surface in quantities in excess of 0.4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters, or 0.04 Bq/cm^2 for all other alpha emitters.'

  This definition implies that – for the uranium mining industry – contamination refers to the presence of radioactive contaminants of more than 0.4 Bq/cm^2 for alpha, beta, and gamma emitters. Here it is noted that this definition applies for each radiation type separately and must therefore not be added or assessed jointly. In practice, in a uranium mine, one focuses in many areas on monitoring for contamination from alpha decaying radionuclides, s.a. U-238.

- **Non-fixed contamination (Reg 214):**
  '…shall mean contamination that can be removed from a surface during routine conditions of transport.'

  This implies that non-fixed contamination is such contamination as can be readily removed by way of (often thorough) cleaning.

- **Fixed contamination (Reg 215):**
  '…shall mean contamination other than non-fixed contamination.'

  This implies that contaminants that are not readily removed from a surface are regarded as fixed contamination.

- **Surface contaminated object (SCO) (Reg 241 and 412):**
  'Surface contaminated object (SCO) shall mean a solid object that is not itself radioactive, but which has radioactive material distributed on its surface.'

  SCO objects are differentiated into two groups, namely SCO-I and SCO-II.

  SCO-I is defined as

  'A solid object on which:
  (i) The non-fixed contamination on the accessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed 4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters, or 0.4 Bq/cm^2 for all other alpha emitters.

  (ii) The fixed contamination on the accessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed 4 × 10^4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters, or 4 000 Bq/cm^2 for all other alpha emitters.

  (iii) The non-fixed contamination plus the fixed contamination on the inaccessible surface averaged over 300 cm^2 (or the area of the surface if less than 300 cm^2) does not exceed 4 × 10^4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters, or 4 000 Bq/cm^2 for all other alpha emitters.'

- **Low specific activity (LSA) material (Reg 226):**
  'Low specific activity (LSA) material shall mean radioactive material that by its nature has a limited specific activity, or radioactive material for which limits of estimated average specific activity apply. External shielding materials surrounding the LSA material shall not be considered in determining the estimated average specific activity.'

  As per Regulation 409, LSA materials are differentiated into three groups. For the purposes of this book, the definition of LSA-I suffices:

  'LSA-I:

  Uranium and thorium ores and concentrates of such ores, and other ores containing naturally occurring radionuclides.

  Natural uranium, depleted uranium, natural thorium or their compounds or mixtures, that are unirradiated and in solid or liquid form. '

  This definition implies that all forms of uranium as occur in the uranium mining industry are LSA materials. In other words, the NORM, uranium (natural), natural uranium and uranium-poor tailings materials are all classified as LSA-I.

- **Transport index (TI)**
  The transport index assigned to a package, overpack or freight container, or to unpackaged LSA-I or SCO-I,

  '…shall mean a number that is used to provide control over radiation exposure.'

  Section 19.3 demonstrates how the TI is determined in practice and used.

19.2.3 Applicability of the IAEA Transport Regulations

As per Regulation 107(f) of the latest IAEA Transport Regulations , they do not apply to:

> *'Natural material and ores containing naturally occurring radionuclides, which may have been processed, provided the activity concentration of the material does not exceed 10 times the values specified in Table 2, or calculated in accordance with paras 403(a) and 404–407.*
>
> *For natural materials and ores containing naturally occurring radionuclides that are not in secular equilibrium the calculation of the activity concentration shall be performed in accordance with para. 405.'*

This definition, which is also called the *factor 10 rule*, implies that, although a certain material is radioactive, as per 'Table 2', it can still fall outside the ambit of the IAEA Transport Regulations.

To illustrate: uranium ore with an activity concentration and total activity exceeding 1 Bq/g and 1 000 Bq respectively but having an activity concentration of less than 10 Bq/g, is radioactive. However, the IAEA Transport Regulations, as per regulation 107(f) for radioactive material, do not apply.

Based on Regulation 107(f) and 'Table 2' of the IAEA Transport Regulations, Table 45 provides a summary of the main exemption levels and classifications of select uranium compounds.

Table 45: Exemption levels and classifications of select uranium compounds [96]

	Exemption level for specific activity to be defined as radioactive	**Exemption level for specific activity for the application of the IAEA Transport Regulations**	**Exemption level for total activity for being radioactive, *and* the application of the IAEA Transport Regulations**	
Material	**[Bq/g]**	**[Bq/g]**	**[Bq]**	**Defined as**
Uranium ore	1 from U-238	10 from U-238	1 000 from U-238	U(natural), natural uranium, LSA, low toxicity alpha emitters
Uranium concentrate	10 from U-238	100 from U-238	10 000 from U-238	U-238, natural uranium, LSA, low toxicity alpha emitters
Uranium tailings	1 from Th-234 / Ra-226	10 from Th-234	1 000 from Th-234	natural uranium, LSA, low toxicity alpha emitters

In tailings from uranium mining operations, the concentration of the leading radionuclide, i.e. U-238, is reduced through the extraction process. This implies that one cannot use the exemption levels for U-238 for such material but must use the first daughter in the decay chain, which is Th-234, or Ra-226, from the remaining U-238 decay chain. However, in practice, and because the grade of the original ore is known, its activity and activity concentrations are used to assess the applicability of the IAEA Transport Regulations.

19.2.4 Licensing / Permitting Requirements

As per the Namibian Regulations, the following licensing and permitting requirements relating to the transport of radioactive material apply [3]:

- A license is required for the possession of any radiation source or nuclear material, except for the purpose of transporting such material as an agent for a licence holder;
- An import / export permit is required to / from Namibia for any radiation source or nuclear material;
- A transport permit is required for the conveyance of any radiation source or nuclear material in Namibia;
- A license is required for the use of all radiation sources and nuclear material provided they are not exempted under the Regulations;
- A license is required for the disposal of any radiation source or nuclear material; and
- A license is required for storage of a radiation source and nuclear material.

In practice, it is firstly important to ascertain whether the stipulations of the IAEA Transport Regulations apply. As per section 19.2.3, materials may well be radioactive, as per 'Table 2' in the IAEA Transport Regulations, but they can still fall outside of their ambit. If this is the case, an import / export permit, as well as a license for the possession of such material is needed provided it is above the exemption levels specified for them to be considered radioactive, as is further illustrated in Box 58.

Box 58: Application of the IAEA Transport Regulation's factor 10 rule to uranium-bearing ore

For uranium-bearing ore, the applicable exemption criteria for them to be considered radioactive are those for U(natural), i.e. 1 Bq/g and 1 000 Bq, as per 'Table 2' in the IAEA Transport Regulations. Here the following applies:

$$\textit{Activity concentration} = (\textit{U-ore grade in ppm} / 10^6) \cdot 12\,350\ \textit{Bq/g}.$$

To illustrate: uranium-bearing ore with a uranium concentration of 80 ppm, and using the above formula for the activity concentration implies that

$$\begin{aligned}\textit{Activity concentration} &= (80 / 10^6) \cdot 12\,350\ \textit{Bq/g} \\ &\approx 0.99\ \textit{Bq/g} \\ &\approx 1\ \textit{Bq/g},\end{aligned}$$

i.e. this implies that the activity concentration of uranium-bearing ore that has a uranium concentration of 80 parts per million is approximately 1 Bq/g and is therefore radioactive.

However, as per section 19.2.3, the provisions of the IAEA Transport Regulations for natural material and ores containing naturally occurring radionuclides only apply if the activity concentration exceeds 10 times the value specified in 'Table 2'.

For uranium-bearing ore, the IAEA Transport Regulations imply that the exemption levels for the activity concentration are 10 Bq/g, and those of the activity are 1 000 Bq. This implies that the IAEA Transport Regulations only apply for uranium ores that have a mineral concentration exceeding 800 ppm, and where the total activity exceeds 1 000 Bq.

It must be noted that the *factor 10 rule* under the IAEA Transport Regulations applies *only* to the activity concentration, and not to the maximum activity of a consignment.

Box 59: Maximum amount of uranium-bearing ore below the transport exemption limits

For uranium-bearing ore with a uranium concentration of 80 ppm, what quantity is needed before it is considered radioactive?

Box 58 has demonstrated that the activity concentration (specific activity) of uranium-bearing ore of approx. 80 ppm is 1 Bq/g. It therefore remains to calculate how much material is needed for a total activity of 1 000 Bq.

The activity is the product of the specific activity (activity concentration) times the mass, i.e.

Activity = activity concentration · mass.

This relationship is used to calculate the mass associated with an activity of 1 000 Bq, i.e.

mass = activity / activity concentration = 1 000 Bq / 1 Bq/g = 1 000 g = 1 kg.

This implies that 80 ppm uranium-bearing ore is considered radioactive if its mass exceeds 1 kg.

Box 60: Calculating the mass of uranium concentrate with an activity of 10 000 Bq

How much uranium concentrate is needed before the material is considered radioactive?

For uranium concentrate, 'Table 2' of the IAEA Transport Regulations stipulate the exemption levels for the specific activity (activity concentration) and activity for U-238, which are 10 Bq/g, and 10 000 Bq, respectively.

Pure uranium concentrate, i.e. U_3O_8, contains 84.5% uranium. This implies that its activity concentration is 84.8% of that of pure uranium as contained in natural uranium, i.e. 12 350 Bq/g. Using the relationship between the mass, activity and activity concentration, as introduced in Box 59, the mass is calculated as follows:

$$\text{mass} = \frac{\text{activity}}{\text{specific activity}} = \frac{10\ 000\ \text{Bq}}{0.848 \cdot 12\ 350\ \text{Bq/g}} \approx 0.95\ g\ \ \approx 1\ \text{g}.$$

An amount exceeding 1 g of uranium oxide is therefore considered radioactive, which necessitates a license for the possession and use, as well as a permit for its transport, import and export.

Box 61: Maximum amount of uranium concentrate below the transport exemption limits

What mass of uranium concentrate can be transported without requiring a transport permit?

The exemption threshold for the activity concentration as per the IAEA Transport Regulations is given in 'Table 2' of these regulations. For uranium concentrate, i.e. U-238, the specific activity threshold is specified as 100 Bq/g, noting the applicability of the *factor 10 rule*, as per Table 45.

However, the specific activity of freshly extracted uranium concentrate is 25 kBq/g, refer to Table 5 (page 61). This implies that the activity concentration threshold specified above is not relevant when computing the maximum mass of uranium concentrate that can be conveyed without requiring a transport permit, as 25 kBq/g always exceeds the exemption threshold of 100 Bq/g.

Consequently, and as computed in Box 60, uranium concentrate with a mass of more than 1 g exceeds both the specific activity and activity thresholds specified by the IAEA Transport Regulations. This value therefore also defines the maximum mass of uranium concentrate that can be transported without a transport permit.

19.3 Transport Index

The radiation levels occurring outside a package containing radioactive material indicates the level of risk of exposure to people close to such a package. This risk is quantified by the *transport index (TI)*.

Based on the IAEA Transport Regulations, and with reference to Regulation 523, the transport index is calculated as follows:

'(a) *Determine the maximum radiation level in units of milli-Sievert per hour (mSv/h) at a distance of 1 m from the external surfaces of the package, overpack, freight container or unpackaged LSA-I and SCO-I. The value determined shall be multiplied by 100 and the resulting number is the TI. For uranium and thorium ores and their concentrates, the maximum radiation level at any point 1 m from the external surface of the load may be taken as…0.02 mSv/h for chemical concentrates of uranium, other than uranium hexafluoride.*

(b) *For tanks, freight containers and unpackaged LSA-I and SCO-I, the value determined in step (a) shall be multiplied by the appropriate factor from Table 7* (as reproduced in Table 46).

(c) *The value obtained in steps (a) and (b) shall be rounded up to the first decimal place, except that a value of 0.05 or less may be considered as zero.'*

Table 46: Multiplication factors for tanks, freight containers & unpackaged LSA-I and SCO-I [96]

Size of load, *1	Multiplication factor
size of load ≤ 1m^2	1
1 m^2 < size of load ≤ 5 m^2	2
5 m^2 < size of load ≤ 20 m^2	3
20 m^2 < size of load	10

*1: largest cross-sectional area of the load being measured.

Box 62: Transport index of a 200-litre drum containing NORM

Determine the transport index for a 200-litre drum containing NORM, with a dose rate of 0.2 μSv/h when measured at 1 m from such a drum.

The dose rate of 0.2 μSv/h corresponds to 0.0002 mSv/h. Therefore, TI = 100 · 0.0002 = 0.02. As per the IAEA Transport Regulations, Reg 523 (c), a TI < 0.05 or less may be considered as zero. Therefore, the TI for this specific load is 0.

Box 63: Transport index for a drum of uranium oxide

Determine the transport index for a drum which contains uranium oxide. A dose rate of 2 μSv/h is measured at one metres from such a drum.

The above dose rate corresponds to 0.002 mSv/h, therefore TI = 100 · 0.002 = 0.2.

Here it is useful to refer to the IAEA Transport Regulations, Reg 523 (a), which state that '*…for uranium and thorium ores and their concentrates, the maximum radiation level at any point 1 m from the external surface of the load may be taken as…0.02 mSv/h for chemical concentrates of uranium*'. This implies that the corresponding TI = 0.02 · 100 = 2.

The TI is an indication of risk, and international customs officials tend to check whether it has been applied correctly. An over-estimation of risk is mostly not a problem. However, if the indicated TI is smaller than the actual value, this may have significant repercussions. It is therefore good practice to use a standard value that represents the 'worst case TI', and apply this to loads having such characteristics. For example, for uranium oxide drums, a common standard value for the TI is 0.4.

Box 64: Transport index for a freight container of uranium oxide

Determine the transport index for a freight container which is packed with drums containing uranium oxide, based on a dose rate of 20 µSv/h when measured at 1 m from the long side of a 20-foot freight container.

As per Table 46, and realising that the containment is a freight container which has a surface area of between 5 and 20 m^2, one must use a multiplication factor of 3 when computing the TI, i.e.

$$TI = 0.02 \cdot 100 \cdot 3 = 6.$$

The same TI results when using the standard dose rate value of 0.02 mSv/h, as per the IAEA Transport Regulations, Reg 523 (a).

19.4 United Nations Classification Numbers

Radioactive material is classified according to a system of numbers which are provided by the United Nations. This is done according to the type and properties of the material, as further described in 'table 1' of the IAEA Transport Regulations.

For uranium, i.e. a low specific activity material, the classification numbers are:

- UN 2912: RADIOACTIVE MATERIAL, LOW SPECIFIC ACTIVITY (LSA-I), non-fissile or fissile-excepted
- UN 2910: RADIOACTIVE MATERIAL, EXCEPTED PACKAGE — LIMITED QUANTITY OF MATERIAL
- UN 2913: RADIOACTIVE MATERIAL, SURFACE CONTAMINATED OBJECTS (SCO-I or SCO-II), non-fissile or fissile-excepted
- UN 2908: RADIOACTIVE MATERIAL, EXCEPTED PACKAGE EMPTY PACKAGING

Whether material is classified as UN 2912, or UN 2910, depends on the quantity and TI of the material in question.

Based on Regulations 424 of the IAEA Transport Regulations, classification UN 2910 is used if

> *'Radioactive material in forms other than as specified in para. 423 and with an activity not exceeding the limits specified in column 4 of Table 4 are classified UN 2910, RADIOACTIVE MATERIAL, EXCEPTED PACKAGE — LIMITED QUANTITY OF MATERIAL, provided that:*
>
> *(a) The package retains its radioactive contents under routine conditions of transport.*
>
> *(b) The package bears the marking "RADIOACTIVE" on (i) An internal surface in such a manner that a warning of the presence of radioactive material is visible on opening the package; or (ii) The outside of the package, where it is impractical to mark an internal surface.'*

It is to be noted that excepted packages must also comply with Regulation 516, i.e.

> *'The radiation level at any point on the external surface of an excepted package shall not exceed 5 µSv/h.'*

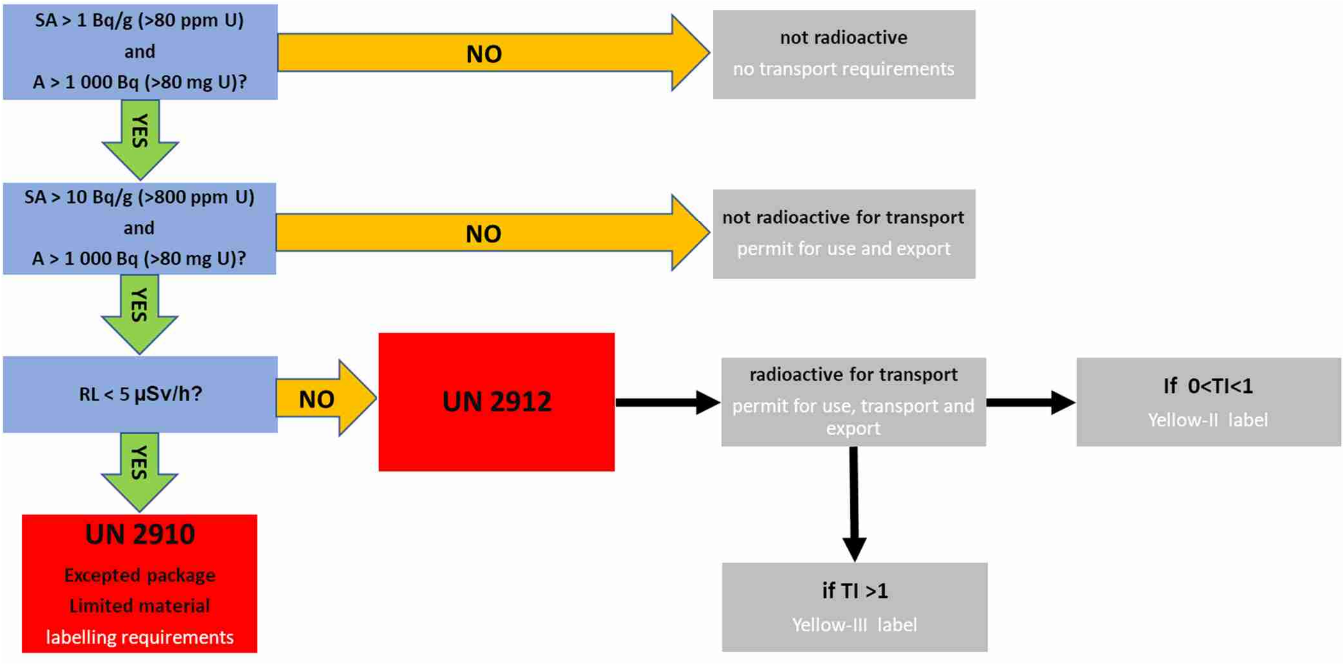
19.5 Labelling and Marking

Packages must be labelled according to their contents, radiation levels and activity. This implies that the material to be packaged must be classified.

Figure 176 illustrates an assessment flowchart to assist with the classification for uranium-bearing material, where the following abbreviations are used:

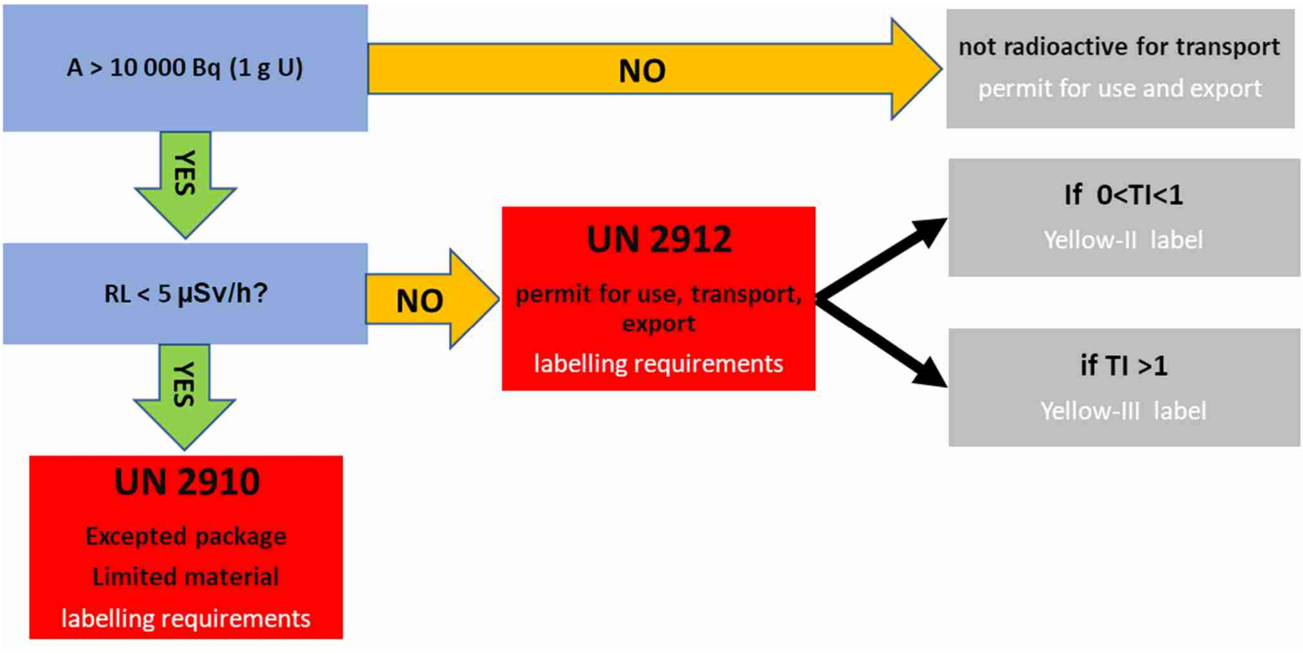
- **SA** for specific activity;
- **A** for activity; and
- **RL** for radiation level.

Figure 176: Flowchart to assist with the classification for labelling of uranium-bearing materials [8]



For uranium concentrate, the specific activity always exceeds the applicable exemption threshold for radioactive material, i.e. 10 Bq/g. In addition, the corresponding exemption level as per the IAEA Transport Regulations, i.e. 100 Bq/g, refer to Table 45, is also always exceeded. This implies that uranium concentrate must be classified according to the quantity to be transported, and the dose rate associated with the package. This is illustrated in the assessment flowchart depicted in Figure 177.

Figure 177: Flowchart to assist with the classification for labelling of uranium concentrate [8]



'Table 8' of the IAEA Transport Regulations specifies the labels that are to be used when transporting uranium ore and concentrates. These depend on the TI, and the radiation level on the external surface of the package. For ores or concentrates with a radiation level RL < 5 µSv/h, the conditions for packages of UN 2010 (excepted package, limited material), as well as UN 2912, TI = 0 are both satisfied. It is therefore often more convenient, and cheaper, to use the UN 2910 classification, with the label for excepted packages as shown in Figure 178, rather than the UN 2912 classification with the WHITE-I label as illustrated in Figure 179.

Figure 178: Label for excepted package, limited material [96]

Radioactive Material, Excepted Package

This package contains radioactive material, excepted package and is in all respects in compliance with the applicable international and national governmental regulations.

UN 2910

The information for this package need not appear on the Notification to Captain (NOTOC)

As per Regulation 424 of the IAEA Transport Regulations, materials which are to be transported as 'excepted – limited material' must be labelled on the external surface using the excepted label, as well as a label indicating 'radioactive material' on an internal surface of the package.

For materials that are subject to the provisions of the IAEA Transport Regulations, i.e. require to be transported as radioactive material, the following markings are required on the outside of packages:

- Identification of consignor or consignee or both (Reg 531);
- UN number on the outside of the package, and the word 'overpack' for containers (Reg 532);
- Gross mass if > 50 kg (Reg 533); and
- 'Type IP-1' if applicable (Reg 534).

Further, Regulation 540 of the IAEA Transport Regulations, the radioactivity labels used as marking must stipulate the:

- Contents (LSA-I for uranium ore and concentrate, otherwise the radionuclide(s));
- Maximum activity of the consignment (from all radionuclides); and
- Transport Index (only relevant if labels YELLOW-II or YELLOW-III are used).

Table 47: Labelling requirements of radioactive packages, overpacks and freight containers [96]

Transport Index	Maximum radiation level at any point on the external surface	Category of Label
0 *1	≤ 0.005 mSv/h	White-I
> 0 but < 1 *1	> 0.005 but ≤ 0.5 mSv/h	Yellow-II
> 1 but < 10	> 0.5 but ≤ 2 mSv/h	Yellow-III
> 10	> 2 but ≤ 10 mSv/h	Yellow-III *2

*1: if the TI ≤ 0.05, use the value TI = 0, in accordance with Reg 523 (c).
*2: shall also be transported under the exclusive use except for freight containers.

If the transport index is between 0 and 1, and the maximum radiation level at any point on the external surface of the package is ≤ 0.5 mSv/h, the label YELLOW-II is used, as shown in Figure 179.

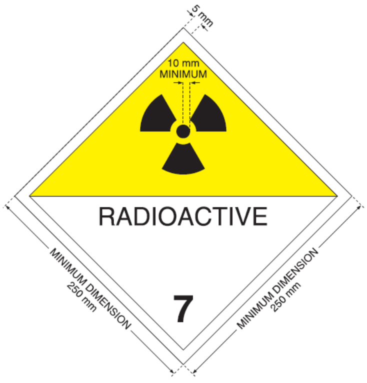
If the TI is greater than 1 ≤ 10, and the radiation level on the external surface is ≤ 10 mSv/h, the label YELLOW-III is used. The labels as shown in Figure 179 are of size 100 mm by 100 mm.

Figure 179: Labels for radioactive packages [96]

WHITE-I Label **YELLOW-II Label** **YELLOW-III Label**

For containers in which radioactive material is to be conveyed, an additional label is needed, as shown in Figure 180, with a size of 250 mm by 250 mm.

Figure 180: Label for containers of radioactive material [96]



Box 65: Determining the label and marking requirements of a drum of uranium concentrate

Determine the transport labels and markings required to transport a drum containing 450 kg of uranium oxide (with 84.8% uranium), having a dose rate of 2 μSv/h at 1 m from the drum.

The TI for such a drum was computed in Box 63, where it was found to be TI = 0.2. This implies that the Yellow-II label must be used, stating 'LSA-I' as contents. As the total mass of the drum plus its contents exceeds 50 kg, the gross mass is used in the marking, as per Regulation 533.

The activity of the drum must be due to all radionuclides, i.e. not only the head-of-chain radionuclide as is used to determine the classification. Accordingly, the activity is calculated as follows:

Total activity = weight (g) · % uranium · specific activity = 450 · 1 000 · 0.848 · 25 000 Bq ≈ 9.5 GBq.

19.6 Contamination Controls when Transporting Radioactive Material

If radioactive material is to be transported in or through public areas, the packages must be free of surface contamination. The definition of surface contamination as it pertains to items which are transported in are provided in the IAEA Transport Regulations, as summarised in section 19.2.2.

These stipulate that packages may not have radioactive materials on their exterior surface areas exceeding an activity concentration of 0.4 Bq/cm^2 for beta, gamma, and low toxicity alpha emitters. For packages exceeding these contamination limits, the classifications SCO-I or SCO-II apply, and items must be marked accordingly.

During routine transport conditions, the surface contamination of any package must remain ALARA, and in any case below 4 Bq/cm^2 for beta emitters, and gamma emitters, and low toxicity alpha emitters, even in case of a leaking package (Regulation 508). This implies that during routine transport, the surface contamination levels may be up to 10 times larger than the relevant levels applicable for clearing objects for public use.

However, it is important to note that this applies to routine transport conditions only, where the integrity of the package is guaranteed, and the package labelling includes a warning about its radioactive content.

As soon as the containment, e.g. a freight container, is no longer used to transport radioactive material, it must be cleared for public use, as per the definition of surface contamination of objects that are to be released into the public. This clearance level is 0.4 Bq/cm^2 for beta, gamma, and low toxicity alpha emitters. In all cases, these limits apply when averaged over 300 cm^2 of any part of the surface of the package under consideration.

Based on the above, best practice implies that packages such as drums, containers or parcels are cleared, to ensure that they do not exhibit non-fixed surface contamination on their external surfaces.

Converters receiving uranium concentrate shipments are under strict regulatory control, which necessitates that all containers must be free from contamination before they can be returned for further public use. If surface contamination levels exceed 0.4 Bq/cm^2, decontamination must take place until the container(s) can be cleared. This is expensive, and leads to unnecessary delays, and is therefore best avoided by ensuring that contamination levels are kept well below the regulatory limits for any such freight. Accordingly, care must be taken to avoid any occurrences of contamination, and to apply strict contamination controls that ensure that surface contamination on packages is detected and removed before the transport activity begins.

19.7 Permits

In Namibia, a license is required prior to the handling, owning, disposal, import, and export of any material that is classified as being 'radioactive' under the Regulations [3].

In addition, a permit is required if the material to be conveyed is subject to the provisions of the IAEA Transport Regulations, i.e. if it is classified as being 'radioactive for transport'. Also, permits are required for the import and export of such material.

Permits must be obtained from the regulatory Authority, using the prescribed license/permit forms, which must be accompanied by a cover letter explaining the requirements, and submission of the Radiation Management Plan or Transport Plan, as relevant.

19.8 Storage During/Following Transport

If radioactive material must be stored prior to or during transport, the owner(s) of the intended storage location must have all the relevant permits and licenses prior to such storage being undertaken.

For the storage of radioactive material, a license is required, which implies that a valid RMP needs to be in place and must be approved by the regulatory Authority prior to the use of the storage facility.

19.9 Planning for the Conveyance of Radioactive Material

The transport of radioactive material must be thoroughly planned. A high-level checklist includes the following:

- Have the responsibilities prior to, during and up to the finalisation of the conveyance been communicated, and confirmed by all relevant parties?
- Are all relevant permits and licenses in place?
- Do the permits and licenses remain valid until the end of the planned transport activity?
- Have all necessary labels and markings been ide notified, and applied?
- Has the Transport Plan of the entity who is to undertake the conveyance been approved by the regulatory Authority?
- Are the transport agent's permits in place, and valid until the end of the planned transport activity?
- Who will be the responsible parties in case of an emergency?
- Have the entities that participate in an emergency response been notified?
- Have all external service providers who are to be called in an emergency confirmed their availability?
- Is there a command-and-control structure in place an emergency arises during the planned conveyance?
- Has the response team been mobilised?
- Is the response team resourced, including reliable vehicles?
- Are the clean-up kits stocked, and available in case of an emergency?
- Is the route clear of obstructions or potential bottlenecks?
- Have alternate routes been identified in case of unplanned developments or occurrences during the planned transport?
- Have all storage locations and potential lay-down areas that may or will be used during transport been assessed for contamination, and have they been cleared?
- Have the local and regional security conditions been considered in planning the route and emergency response measures?
- Is there at least one alternative destination / storage solution in case the planned destination becomes unavailable?

19.10 Exercises

1. As the designated RSO of a company which intends to outsource the transport of uranium-bearing sample material to an external transport provider, what must be kept in mind before the outsourced entity can commence with their services?

2. What are the similarities and differences between "U (natural)" and "natural uranium", as per the IAEA Transport Regulations? Given these, what are the main distinguishing features that explain U (natural) is different from natural uranium?

3. A box of uranium-bearing ore samples needs to be conveyed between Namibia and a mineral analysis laboratory in South Africa. The uranium concentration of the mineral ore is 650 ppm, and the mass of the box is 5 kg. From the options provided below, select the correct response(s):
   a. Ore is not radioactive for transport, so just phone a courier and have it shipped off site.
   b. The ore is radioactive and needs a transport and export permit, as well as labels for UN 2912 and class 7.
   c. This material may not be conveyed as it is a maritime pollutant.
   d. The material is radioactive but exempt for transport purposes, hence needs export permit.

4. A yellowcake sample with a uranium content of 64% and sample mass of 500 g originating at a uranium mine is to be presented as a gift to be displayed at a museum in the capital. As the designated RSO of the mine where the sample originated, select the answer(s) from the options below that best reflects the local requirements:
   a. Label the package UN 2912 and class 7, and obtain a transport permit;
   b. No permit or labelling is needed as the museum is an entity under state control;
   c. The gift must be declared to the regulatory Authority, who must authorise that the museum can rightfully receive, possess, transport, and store the sample;
   d. The quantity in question is small, so one can send it as UN 2910-excepted, limited quantity of material, if dose rate on the exterior surface is less than 5 μSv/h.

5. The transport index for a 20-foot container containing uranium concentrate drums needs to be determined. The following dose rate readings were taken: dose rate at 1 m from container door is 10 μSv/h, dose rate on contact at the long side is 30 μSv/h, dose rate at 1 m from at long side is 15 μSv/h, dose rate on contact of a drum of concentrate is 30 μSv/h, dose rate at 1 m from a drum of concentrate is 5 μSv/h. The TI is:
   a. 0.2
   b. 2
   c. 4.5
   d. 45
   e. 8
   f. 80

20 Waste Management

This Chapter describes the basics that underpin the management of radioactive waste.

20.1 IAEA Classification of Radioactive Waste

The IAEA has introduced a classification system for radioactive waste [157], which is called *radwaste* in the sections below.

The classification system differentiates between three main radwaste categories, i.e. low-, intermediate-, and high-level waste, and introduces secondary categories, including very short-lived and exempt waste, as illustrated in Figure 181.

Exempt radwaste contains very low concentrations of radionuclides, or radionuclides with very low activity concentrations, which imply that radiation protection does not need to be applied.

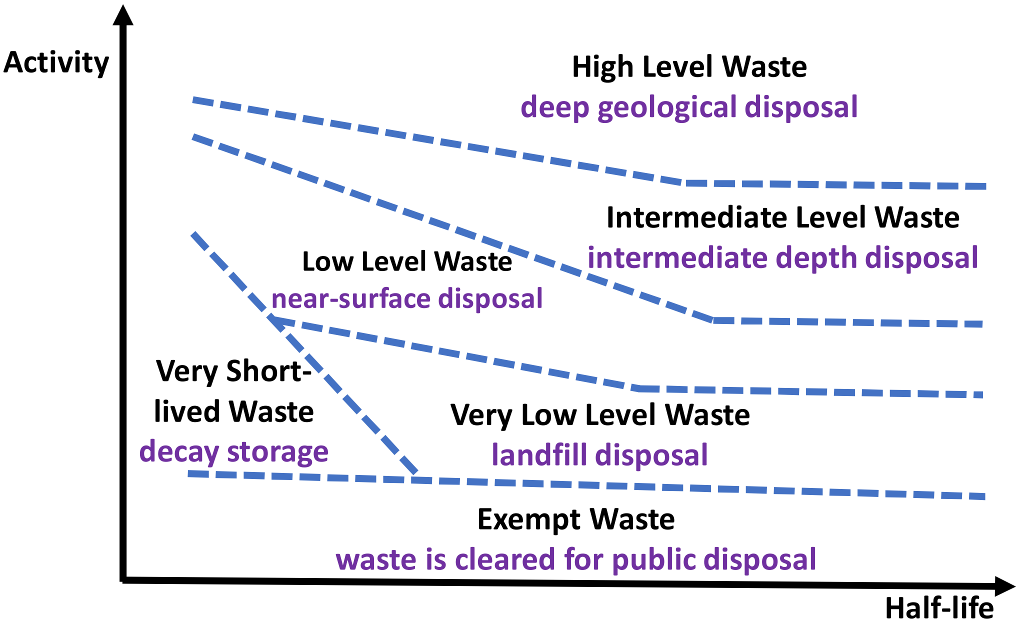
Based on the IAEA concepts of *exclusion, exemption,* and *clearance [167]*, i.e. that *any exposure whose magnitude or likelihood is essentially unamenable to control through the requirements of the IAEA Safety Standards is deemed to be excluded from the Standards*, the exempt waste classification is used to indicate radwaste that is exempt from the application of control measures. In this context, exempt means not being under the provisions of the IAEA Safety Standards.

For radionuclides of natural origin, the activity concentrations of exempt materials are provided in the IAEA Safety Standards and IAEA RS-G-1.7 ([1] and [167] respectively), namely 1 Bq/g for natural uranium, and natural thorium, and 10 Bq/g for K-40.

The factor 10 between the uranium/thorium and potassium exemption levels is because both the latter does not have a decay chain associated with it, while U/Th often occur in secular equilibrium with members in their decay chains, in which case the provisions for U(nat)/Th(nat) apply.

In select cases, and usually involving small quantities only, tailings waste from uranium mines may be classified as EW.

Figure 181: IAEA radioactive waste classification system [8]



Very short-lived radwaste contains radionuclides that are characterised by their short half-lives. Such radwaste originates typically from research and medical facilities. This waste class must be disposed of in engineered landfill-type facilities, to allow for its (rapid) decay, and does not represent longer-term radiation risks.

Low-level waste (LLW) is often characterised by its high total activity, but often contains only limited amounts of long-lived radionuclides.

This radwaste requires robust isolation and containment, often for periods of several hundred years. It is disposed of in engineered near-surface facilities. LLW covers a broad range of radwaste, including various short-lived radionuclides at high(er) activity concentrations, as well as long-lived radionuclides, if the latter are associated with low activity concentrations.

Examples of LLW include radwaste from medical applications in hospitals, laboratories and from industry, usually in small quantities, as well as radwaste associated with activities that are related to the nuclear fuel cycle, including those from mining, conversion, and enrichment activities.

The radiation-related risks associated with LLW are generally low, and this radwaste is mostly not dangerous to handle. Nevertheless, precautions are necessary when contemplating its disposal. A common disposal method is by burying such radwaste in shallow landfill sites, as done for medical and industrial waste, or dedicated bulk disposal facilities, including tailings storage facilities at mines and fuel converters.

Some 90% of all radwaste by volume is classified as LLW, while the radioactivity contributed by this waste type is of the order of 1% of all radwaste that is generated. For medical and industrial LLW, volumes can often be reduced by compaction/incineration prior to final disposal.

Under the IAEA's waste classification system, uranium mining tailings and other radwaste falls under the LLW category.

Intermediate-level waste (ILW) is radwaste that, because of its activity, and long-lived radionuclide content, requires a higher degree of containment and isolation than can be provided in near-surface disposals. However, ILW needs either no provision, or only limited provisions, for heat dissipation during storage and disposal.

ILW may contain long-lived radionuclides that will not decay to a level of activity concentration that are acceptable for near-surface disposal in periods for which institutional controls can (usually) be relied on. Therefore, radwaste of this class requires disposal at greater depths, typically of the order of tens to a few hundred metres below the surface of the earth.

Examples of ILW include radioactive resins, chemical sludges, and reactor components from nuclear reactors, and parts and equipment originating from nuclear fuel manufacturing processes. About 7% of the volume and 4% of the total activity of the world's radwaste is in form of ILW. Often, it is solidified in concrete and/or bitumen, to ensure better containment, before it is disposed of in deep underground disposal facilities.

High-level waste (HLW) is radwaste with activity concentrations that are sufficiently high to generate significant heat because of radioactive decays. HLW also includes radwaste containing significant amounts of long-lived radionuclides. The capacity for heat generation, and requirements of its long-lived constituents inform the design of disposal facilities.

Typically, HLW is disposed of in deep underground and stable geological formations, usually several hundred metres or more below the earth's surface. Examples of HLW include used fuel from nuclear reactors, principal waste from nuclear fuel reprocessing plant, and select waste originating from nuclear accidents.

Some 3% of the world's radwaste by volume is HLW but contributes some 95% of the total radioactivity of all radwaste. HLW is typically vitrified, which is achieved by incorporating it into glass, and sealing it inside steel containers, before its disposal in deep underground facilities.

20.2 Namibian Regulations on Radioactive Waste

Regulation 61 of the Namibian Regulations classifies radwaste into five distinct groups [3], namely:

- **Category I: low-level radwaste,** which is characterised by an activity of less than 10 MBq and containing only short-lived radionuclides with half-lives of less than 50 days, decaying to clearance levels within one year following its generation.
- **Category II: low- and intermediate-level radwaste,** which is characterised by radionuclides with half-lives of less than 30 years, with limited long-lived radionuclide concentrations (limitation of longer-lived alpha emitting radionuclides is 4 000 Bq/g in individual waste packages, and to an overall average of 400 Bq/g per waste package). Such waste is not expected to decay to clearance levels within one year from the time of its generation.
- **Category III: low- and intermediate-level radwaste,** which is characterised by radionuclides with half-lives greater than 30 years, and alpha emitter concentrations exceeding the limitations specified for Category II radwaste.
- **Category IV: high-level radwaste,** which is characterised by a thermal power capacity above 2kW/m^3, and alpha emitter concentrations exceeding the limitations specified for Category II radwaste. Such waste includes, for example, spent fuel from research reactors.
- **Category V,** which is radwaste that has been produced as part of the extraction of radioactive minerals, or a mineral classified as a nuclear material.

Based on the above classification system, the radwaste originating from the uranium mining industry falls into Category V.

Further classification of radwaste is done according to the physical form and appearance of the waste material in question, which includes the following:

- Solid waste;
- Liquid aqueous waste;
- Liquid organic waste;
- Gaseous waste;
- Sealed radiation sources;
- Biological waste (e.g. animal carcasses which might undergo decomposition if not properly treated and stored); and
- medical waste (e.g. syringes, bed linen and contaminated clothing from hospitals).

20.3 Sources of Radwaste in Uranium Mining

Typically, radwaste from the uranium mining and processing sector is either in solid or liquid form, or is a combination of solids and liquids, as well as particulate emissions into the ambient air.

Such radwaste includes:

1. **Solid radwaste**, such as
    - mineral waste, such as tailings materials, as illustrated in Figure 182;
    - waste rock materials;
    - contaminated equipment originating from the processing plant;
    - contaminated materials including soil, building materials, tools and

  equipment originating in the processing plant;
- contaminated materials (e.g. mineral waste) used for construction purposes; and
- filters and filter materials originating from air conditioners, stack scrubbers, mobile machinery, and vehicles.

2. **Liquid radwaste**, such as
   - waste from metallurgical processes;
   - seepage from waste rock dumps and tailings storage facilities, as illustrated in Figure 183;
   - laundry drains and associated sewer systems;
   - laboratory drains and associated sewer systems; and
   - waste from decontamination areas, resulting from the decontamination of tools, equipment, and vehicles.

3. **Particulate emissions**, such as
   - stacks emitting dried and roasted uranium;
   - wind-blown tailings materials;
   - dust from waste rock dumps, ore stockpiles, pit areas, as well as from on-site blasting, mining, haulage, and milling; and
   - dust from uncovered process areas.

Figure 182: Aerial view of the tailings storage facility at Rössing [26]

Figure 183: Seepage from the tailings storage facilities at Rössing [26]

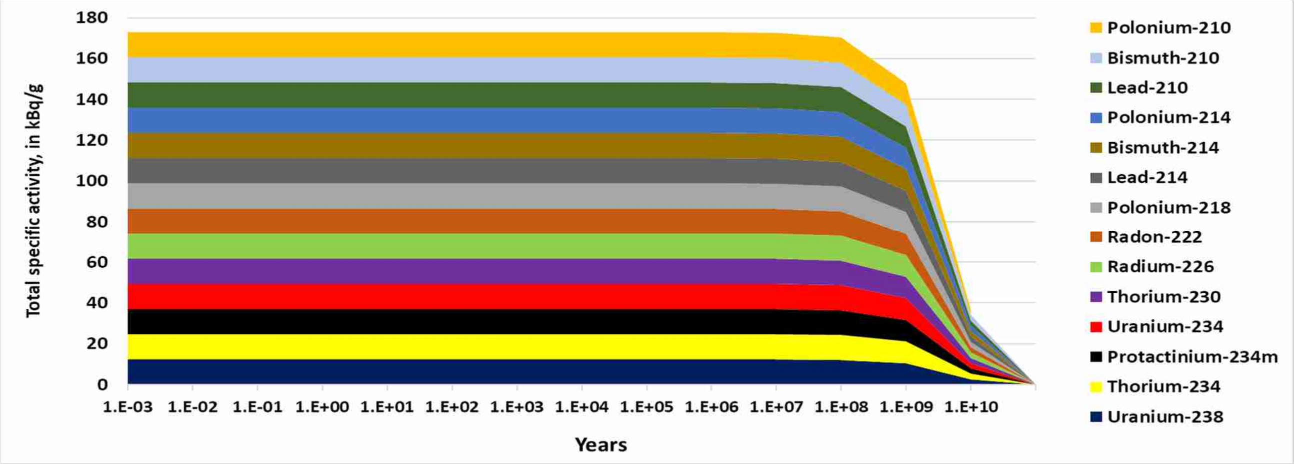
Figure 184: Waste rock dumps and exposed mining pit at Rössing [26]

20.4 Characteristics of Radwaste originating at Uranium Mines

Uranium is naturally occurring radioactive material (NORM) which is characterised by a very long half-life. The solid radwaste associated with the uranium mining and milling processes shares many of the characteristics of the uranium-bearing mineral ore from which such waste originates.

Uranium-bearing ore, and therefore the waste rock dumps associated with its mining process, often contain uranium (and possibly thorium) in secular equilibrium with the members of its decay chain. Unprocessed uranium-bearing material is therefore extremely long-lived, as is illustrated in Figure 185.

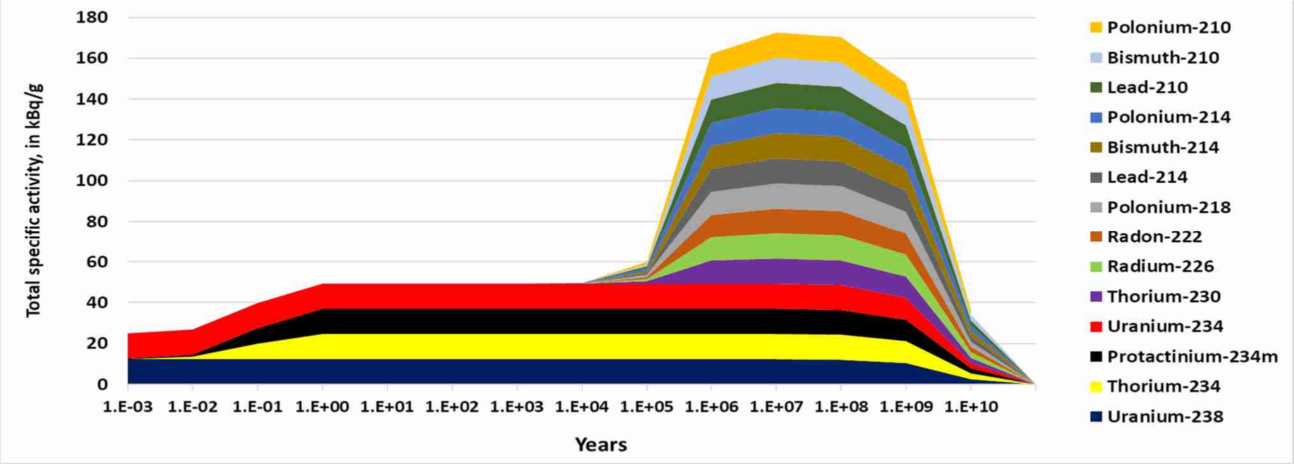
Figure 185: Evolution of the activity concentration of uranium ore as a function of time [8]



Uranium-bearing minerals, and the associated waste rocks and mineral stockpiles decay to lower activity levels within geological timescales, i.e. over billions of years, rather than on human timescales. Areas in which such low-level radwaste occurs must be remediated before they are made available for future public use.

Concentrated uranium, i.e. uranium that is extracted from uranium-bearing minerals, contains only U-238 and U-234, depending on the purity of the product. Its activity concentration as a function of time is depicted in Figure 186. Partial secular equilibrium between the first four radionuclides of the U-238 decay chain re-establishes itself within some one-hundred days following the extraction. Thereafter, it takes more than 1 000 years before other radionuclides from the U-238 decay reappear and contribute to the activity concentration of such radioactive material.

Figure 186: Evolution of the activity concentration of pure uranium as a function of time [8]



Tailings material arising in the uranium mining and milling processes still contain some uranium residues, as the uranium extraction process is never entirely efficient. Typically, between 80% and 90% of the uranium that was originally contained in the ore is removed in the extraction process.

All other radionuclides contained in the mineral ore remain following the extraction of uranium. They continue to exist in the radwaste which is disposed of in tailings storage facilities. The total activity of tailings material is therefore similar to the original mineral ore: given an extraction efficiency of x, the activity of the remaining tailings material is factor $(14 - 2\,x)$ times that of the original head-of-chain concentration as contained in the ore.

Box 66: Radioactivity of tailings material arising in the uranium mining sector

If a given mineral ore is characterised by a uranium concentration of 1 000 parts per million (ppm), determine the activity of the tailings material if the extraction efficiency is x = 90%.

A mineral ore with a uranium concentration of 1 000 ppm has a head-of-chain activity concentration R of $R = 1\,000 \cdot 12\,350\,/\,1\,000\,000\ \mathrm{Bq/g} \approx 12.4\ \mathrm{Bq/g}$.

The total activity concentration of the ore, including all 14 radionuclides contained in the U-238 decay chain is $14 \cdot R = 172.9\ \mathrm{Bq/g} \approx 173\ \mathrm{Bq/g}$. Following the extraction of uranium from the mineral ore, the activity concentration of tailings is $\big(12 + 2 \cdot (1 - x)\big) \cdot R = (14 - 2x) \cdot R$.

Given the extraction efficiency of 90%, the total activity concentration of the tailings material is

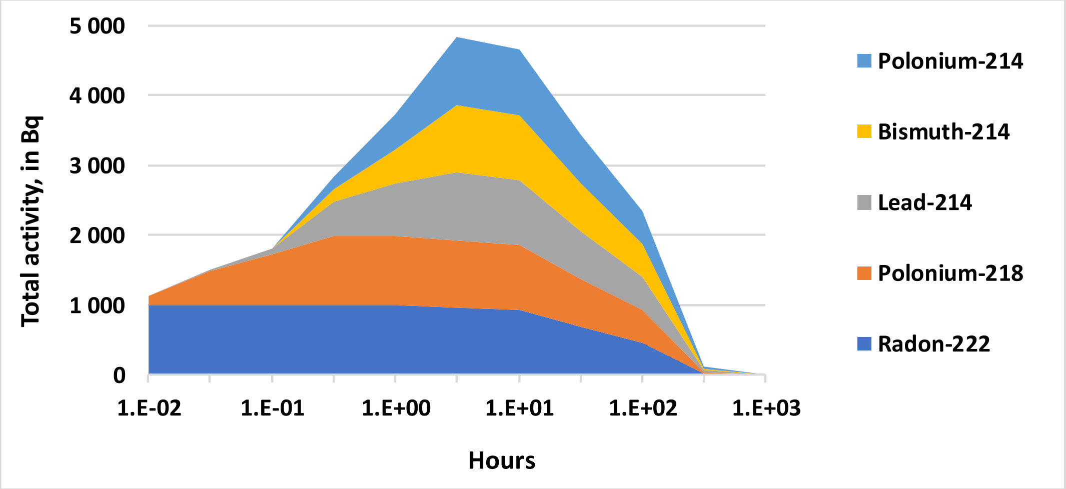
$$(14 - 2 \cdot 0.9) \cdot R = 12.2 \cdot 12.35\ Bq/g\ \approx 151\ \mathrm{Bq/g}.$$

This implies that, given that the initial activity concentration of the ore was approx. 173 Bq/g, the tailings activity concentration is approx. 151/173 ≈ 87% of the unprocessed ore.

Radon is exhaled from uranium-bearing minerals, including the mineral waste produced as part of the uranium mining processes. Radon is short-lived, and so are its immediate decay products, as shown in Figure 187. Unless continuously replenished, these radionuclides disappear as a result of their decay within a few hundred hours once their source is removed.

Radon also has long-lived progeny that accumulate on surfaces that are exposed to air containing high radon concentrations. This may necessitate remediation activities if the risk of inhalation of long-lived progeny, as may be attached to particulates contained in air, is appreciable.

Figure 187: Evolution of the radon activity and its short-lived progeny as a function of time [8]



20.5 Handling Radwaste

Radwaste must be handled and disposed of in a manner that ensures that the resulting exposures are and remain ALARA. In addition, it must be ensured that the current and future risk to receptors is and remains controlled.

Low-level liquid radwaste can often be disposed of by mixing into processing liquids, which then dilutes their concentration. In this way, such liquid waste is usually well contained, and controlled.

If liquid waste cannot be integrated into the processing stream, it may have to be disposed of on the tailings storage facilities, provided this is a licensed radwaste disposal area. In this way, such radwaste is controlled through the provisions existing for such disposal facilities. In dry climates, a considerable proportion of liquid tailings material is reduced by way of evaporation, and the remainder disappears from the exposed surface areas of the facility by seepage.

Solid waste, such as contaminated tools and equipment, soil and building materials, may be disposed of into the tailings storage facility, provided it is a licensed facility for the disposal of this type of radwaste. Its control is achieved through the control mechanisms in place for the tailings facility as a whole.

Contaminated hydrocarbons, contaminated PPE, packaging and other combustible materials can be incinerated, provided that the particulate emissions created in such a process can be controlled. This is achieved, for example, by scrubbing and/or filtering the incinerator's stack emissions. It is noted however that regulatory guidance must be sought when contemplating the incineration of radwaste, to ensure compliance with relevant air quality and emissions standards. Other disposal options must be considered too, to select the disposal method that minimises the overall impact on people and the environment, while remaining cost-effective in the long(er)-term.

The disposal of radwaste must be managed according to the risks posed by such materials. Specifically, disposal must be undertaken in a manner that ensures that the lowest risk arises to receptors, including those receptors who live today as well as future generations. Exposures from disposed of materials must be and remain justified. This also implies that any additional exposure, for example from multiple or excessive handling, transport, relocation, and remediation must be minimised, if such handling is considered at all.

All radwaste other than that classified as exempt waste must be monitored. Control measures must be in place to ensure the long-term stability of the disposal site, in compliance with the radiological protection principles of justification, optimisation and limitation. These considerations must explicitly take the requirements of future generations into account.

20.6 Disposal of Radwaste

The disposal of radwaste necessitates regulatory authorisation. In most cases, the site-specific licence conditions specify the approach by which radwaste is permitted to be disposed of, as well as the siting and design criteria of the disposal facilities, and their associated monitoring and reporting requirements.

Mineral waste disposal includes the disposal in tailings storage facilities. These may be lined, or unlined. Unlined facilities must undergo a rigorous program of tests and checks to ensure that seepage from such facilities is minimised.

The disposal of waste rocks may include mineral radwaste, and hence care must be taken to minimise the successive leaching of radionuclides from such rock dumps. Leaching may take place over tens or hundreds of years, or longer, and may result in radioactive liquids which eventually seep into the groundwater. Such processes contaminate the environment and may take place even when operating in arid or hyper arid environments.

Non-mineral radwaste originating at a uranium mine includes a large variety of radioactively contaminated materials. In many cases, these may be deposited onto the tailings facility, together with the mineral radwaste, provided that the mineral waste disposal site satisfies the provisions of a hazardous waste site and is licensed and managed accordingly.

Figure 188: Challenges associated with the responsible disposal of NORM [8]

An important aspect to consider are radioactively contaminated hydrocarbons and related substances that are contaminated with radwaste. These may not be included in a mineral radwaste storage and disposal site, as hydrocarbons may cause additional contamination and pollution of the receiving environment. This implies that contaminated hydrocarbons must be disposed of differently, for example by way of controlled incineration, as referred to in section 20.5.

When transporting radwaste, care must be taken to prepare and package such waste material, including radioactively contaminated material. Transport activities must conform to the IAEA Transport Regulations, if such conveyance is to take place beyond the license area.

External transport providers that may be used for such conveyance activities must comply with regulatory provisions prior to the commencement and provision of such transport services. This implies that transporters must have a Transport Plan, as discussed in section 19.7, which is approved by the regulatory Authority, and must be in possession of all relevant licenses. The Authority must accept such applications before the conveyance of radwaste can take place.

20.7 Managing Solid Radwaste

Solid radwaste must be disposed of in compliance with the licence conditions of the disposal site. In practice, this implies that the disposal site which is used for the disposal of tailings materials and waste rocks must be mapped and signposted and must have access restrictions.

For waste disposal areas such as tailings and waste rock areas, continuous monitoring is not required. However, a risk assessment must be undertaken to identify and quantify the radiation-related risks associated with such storage sites. This includes, amongst others, that the gamma dose rate and radon exhalation rates of the tailings facility / waste rock dumps must be established. Access restrictions must be applied, to prevent members of the public from accessing such areas, as the public dose limit may be exceeded at such facilities.

A closure management plan must be in place, outlining the remediation actions to be initiated following the closure of the facility. As the site may become accessible to members of the public once it is no longer operational, such a closure plan must include remediation actions that address how the radiation-related risks associated with the facilities will be managed to ensure that public dose limits can be complied with following its closure.

For tailings facilities, mitigation measures may include covering the active tailings area with sufficient uranium-poor soils and/or clay, to reduce radon exhalations to acceptable levels, and to ensure that gamma dose rates are reduced to levels resembling the natural background levels in the area. Long-term monitoring of these indicators may remain a regulatory requirement.

20.8 Managing Liquid Radwaste

Liquid radwaste from uranium mining operations are often contaminated and may contain a cocktail of radionuclides in various concentrations.

Such radwaste includes waste from process overflows, leakages from the processing plant, as well as seepage and contaminants from containment failures of tailings storage facilities.

To a more limited extent than is the case for tailings facilities, waste rock dumps also lead to effluent streams released into the environment, as rainwater leaches uranium and other radionuclides from the waste rock, and then causes seepage into the environment and therefore the groundwater.

The design of a processing plant must take the possibility of minor and major leakages of processing fluids into account and allow for effective collection of such effluents. Passive measures, which do not rely on pumping and active seepage controls, are always preferred.

If tailings facilities are unlined, seepage into the environment is inevitable. This can be controlled by collecting such seepage, for example by the construction of trenches to prevent seepage flows to lower-lying areas. Seepage flows must be monitored regularly, which is best supported by the ongoing monitoring of the adjacent environment which may receive effluents unless they remain carefully managed.

Figure 189: Low-level radioactive waste storage site in Nevada, United States of America [168]

20.9 Radwaste Inventory

Good practice dictates that a radwaste inventory is kept. The Namibian Regulations stipulate that an inventory is a requirement that every licensee must keep.

The radwaste inventory must be regularly updated and included in the annual/bi-annual report to the regulatory Authority. If the approach, site, or conditions in which radwaste is managed change in any material manner, the Authority must be informed about such changes before these are implemented.

The waste inventory must identify the various types of mineral waste materials, such as the tailings and waste rock dumps. Minerals with an average uranium concentration of less than 80 ppm are exempted from this requirement. Also, the inventory must specify the type(s) of contaminated waste included, as well as all other radioactive waste if it is different from the former radwaste types.

If radwaste is removed or otherwise diverted without authorisation from a site, such incidents must be reported to the regulatory Authority within 30 days of such an occurrence.

20.10 Exercises

1. Based on the provisions as contained in the Act and Regulations, is radioactive waste in the form of uranium-bearing waste rocks which is to be disposed of at the tailings storage facilities of a uranium mine considered to be a "radiation source"?

2. Based on the provisions as contained in the Act and Regulations, can defunct tools and equipment which are contaminated with uranium concentrate residues be disposed of at the tailings storage facilities of a uranium mine?

3. Mine management has decided to relocate the waste area which is used for radioactively contaminated waste.

   The operation's RSO has calculated that the exposures associated with digging up the radwaste and relocating it to the proposed area will lead to an increase of the exposure doses of all workers participating in this exercise by an average of 2 mSv.

   Given the incremental exposure dose increase associated with the relocation of the site, are there any other arguments that the operation's RSO should consider before deciding whether to recommend the relocation of the radwaste?

4. Under which conditions will the disposal of radioactive mineral waste material as take place at a uranium mine constitute a *planned exposure situation* as foreseen in the IAEA Safety Standards?

5. Mine management has decided that it is too inconvenient to store radioactively contaminated materials in the temporary contaminated waste yard, which happens to be some 500 metres away from the uranium concentrate drum packing area. Instead, it is recommended that the radwaste and related materials are to be stored close-by the receiving stores, which are some 30 metres away from one of the larger office complexes on the mining site.

   The operation's RSO has calculated that the use of the new laydown area would lead to an annual average external exposure dose of 3 mSv for such office workers, instead of the 0.8 mSv/a which they currently incur, mostly because of the natural background radiation.

   Based on the above, the designated RSO recommends that

   a) the relocation is acceptable, noting that an exposure dose of 3 mSv/a is below the annual dose limit of radiation workers; or

   b) the relocation is unacceptable, because the receiving stores workers are office workers who should not be exposed to more than 1 mSv/a; or

   c) the relocation is neither practicable nor acceptable, because it leads to an increase of the exposure doses of workers which cannot be justified in an operation that claims to keep exposure doses ALARA.

21 Data Management

This Chapter describes the main radiation-related data management requirements.

21.1 Reporting Requirements

In most jurisdictions, operators who own, transport, and use radioactive material which are subject to regulatory control, must annually report on their activities.

In Namibia, the regulatory Authority requires that licensed entities report annually on the progress made in implementing their Radiation Management Plan. The annual report must be accompanied by a summary spreadsheet, using the template provided by the Authority, which summarises the dose records of all exposed persons in each year. such dose records include those from penetrating radiation, the inhalation of radioactive dust (both ore and uranium, if relevant), the inhalation of radon decay products, and the total exposure dose per month, and per year, per exposed person. In addition, radioactive material exports and imports are to be summarised, and an inventory of nuclear gauges, and hazardous waste must be provided.

21.2 Data Analysis

Exposure data obtained for dose assessments must be statistically valid. This means that such data accurately reflects the actual exposure situation as measured and is representative for the period in which it was taken.

Data must be statistically significant and be based on a sample of randomly selected person from within the total persons included in the group of persons that were monitored. Such random sampling of individuals belonging to *similar exposure groups* is necessary to minimise the sampling bias. In other words, when selecting those persons who are to be monitored in each period, the selection process is to resemble a lottery process, and must specifically exclude any preferences or specific allocations to groups or individuals in the overall sample.

The sampling frequency, or number of measurements to be undertaken, must be sufficient to ensure that the data is statistically valid. Here, professional judgement is required. If in doubt, one is better served by over- rather than under-sampling, i.e. monitoring a greater number of persons more frequently rather than a small number of persons in a sample which are monitored in infrequent intervals. If the data follows a normal or lognormal trend, then statistical validity is often assured. However, if the distribution of the data is neither following a normal nor a lognormal trend, then the data range may be too large, or the sampling frequency may not be sufficiently high, or the sampled persons are not representative of a specific group, e.g. when it includes statistical outliers.

For a normal or lognormal distributed set of exposure measurements, between six to ten measurements are usually sufficient to determine a realistic mean and standard deviation. When dealing with less than six measurements, the exposure profile may not be representative, and is not an accurate reflection of the total exposure profile. Often, having more than 10 measurements only provides marginally better results, if at all, and one rapidly approaches the point where the principle of diminishing returns is obvious.

In practice one finds that reasonable approximations of exposure distributions are possible with some ten measurements, but it is also noted that for rigorous goodness-of-fit testing, some 30 measurements or more may be needed.

If it has been determined that exposures are significantly below a given limit, for example the site-specific dose limit or the legal occupational dose limit, and one has statistically significant results to prove it, then the sampling frequency can be reduced, as regular sampling is not required for legal compliance.

21.3 Data Integrity and Verification

A regulatory requirement is that entities that need to report exposure doses must keep and make available records of equipment calibration, and quality assurance, as well as relevant information that allows for retrospective assessments of such doses. This implies that dose records that are used for reporting purposes must include all relevant information that can be used to support the integrity of such data.

A further regulatory requirement is that proper records of monitoring and verification of compliance, including records of the tests and calibrations that were carried out, are kept.

This implies that

- If the data is provided by an accredited dosimetry service provider, the accreditation certificate and original dose records must be kept as a record, and be made available for auditing purposes, as and when required by the regulatory Authority;

- If the data originates from an on-site monitoring program, monitoring instruments must be calibrated as per the manufacturers' specifications, and the calibration records must be kept and made available for auditing purposes, as and when required by the regulatory Authority.

- Records of measurements must include instrument serial numbers, as well as the dates and time when such measurements were taken.

- Records of all secondary information sources which may be of relevance when data is re-analysed during retrospective exposure dose assessments must be kept.

- Information that must be kept with the exposure dose data includes a description of the sampling approach and sampling routine used to gather such data, the approach used to select individuals within similar exposure groups, and a summary of how work areas in which sampling was undertaken were selected and monitored.

- It is of critical importance that full employee details are collected, and kept with exposure dose records, as this data is required when a detailed reconstruction of exposure conditions is necessary in future.

- The integrity of exposure data, and the quality of the data used to calculate exposure doses, must be regularly quality assured by a suitably trained professional.

21.4 Long-term Data Availability and Security

A regulatory requirement is that entities that need to report exposure doses must ensure that a health record in respect of each employee is kept and maintained.

This record, or a copy thereof must be kept until the person to whom the record relates has or would have attained the age of 75 years, but in any event for at least 50 years from the date of the last entry made in it.

In addition, entities must maintain exposure dose records for all workers for whom an occupational exposure assessment has been required. Such records must be preserved for at least until the worker attains or would have attained the age of 75 years, and for not less than 30 years after the last occupational exposure event, whichever date is the latest.

Keeping reliable and accessible health records for 50 years, and exposure records for 30 years after an employee has terminated his/her service necessitates a robust and reliable system for record-keeping. In view of the rapidly changing digital environment in which such data is typically stored, this regulatory requirement is certainly not trivial, and necessitates well-planned succession and reliable data propagation approaches.

It is also considered important that paper-based as well as electronic records are kept. This is to ensure that changing operational realities, including those pertaining to technical changes of the way in which data is stored and retrieved, and human resource policies, do not negatively affect an organisation's ability to preserve past data collections.

21.5 Occupational Exposure Data

As stated in section 21.4, it is the obligation of each practice which collects occupational exposure data to ensure that the minimum data retention periods as specified by the regulatory Authority can be guaranteed. Such exposure dose records must include:

a) Information that allows for an assessment and re-valuation of the general nature of the work in which an occupationally exposed person incurred his/her exposures;
b) A description of the approach used to determine the dose, and overall dose assessment methodology, as well as the resulting exposure doses. This must include a description of the intakes at or above the relevant recording levels as specified by the regulatory Authority;
c) Information on the commencement and completion date of each worker's employment, and radiation-related work/risk area during the employment period;
d) Records of the assessments underpinning the occupational exposure doses; and
e) Records of the assessments of exposures that may have been incurred in unplanned exposure situations, such as incidents, accidents, and emergencies during reach worker's occupational exposure period, including references to assessment and investigative reports, if available.

Individual occupational exposure doses and dose records must be

a) made available to each occupationally exposed person;
b) integrated into the practice's health surveillance records;
c) submitted to the regulatory Authority as part of annual report to the authority;
d) provided to workers leaving the employment at a practice, to enable other practices to determine past occupational exposures of workers who have changed employment;
e) kept for a period as described in section 21.4; and
f) managed in a way to ensure the confidentiality of personal records.

22 Appendix A: Selection of Useful Tools and Some Basic Mathematics

This Appendix offers a selection of tools that are useful and part of the common set of instruments used by practicing Radiation Safety Officers, including some basic mathematics.

22.1 Powers of Ten

In 1977, Charles and Ray Eames produced a movie for IBM, titled '*The Powers of 10*'. Unlike other films made back then, this one can still be viewed, conveniently on *YouTube*, and the reader is urged to do just that at reference [169].

The film demonstrates the immense size of the world we live in, starting at the scale of 1 m, which is the size of many of our everyday experiences in our environment. It then zooms out by a factor of ten, in ten second intervals, to show the successively large and largest structures in the world we live in. This is repeated for small scales, again starting at 1 m, and zooming in by a factor of ten every ten seconds, focusing our view onto the smallest structures in the universe, the atomic nucleus. The movie also demonstrates the use of scientific notation, expressing the scales as powers of ten, as is also demonstrated in Table 48.

Table 48: Examples of some powers of 10 from the world we live in

Scale, [m]	Scientific notation, [m]	Other notation	Description
1	10^{0}		order of magnitude of a human
10	10^{1}		order of magnitude of houses
100	10^{2}		order of magnitude of the largest living organisms, and man-made objects such as buildings and ships
1 000	10^{3}	1 km	size of a neighbourhood or village
10 000	10^{4}	10 km	height of the highest mountain (Mount Everest, almost 9 000 m)
10 000 000	10^{7}	10 000 km	the size of Earth (diameter of approx. 12 700 km)
	10^{13}	10 billion km	diameter of our solar system (diameter of 9 billion km)
	10^{16}	1 light year (distance travelled by light in one year, i.e. $9.4 \cdot 10^{15}$ m)	order of magnitude of the distance to the nearest star (Alpha Centauri is 4.4 light years away from Earth)
	10^{21}	one billion billion km, or 10^{5} light years	size of Milky Way galaxy (diameter of some 100 000 light years, and containing approx. 100 billion stars)
	10^{27}	100 billion light years	size of the universe (estimated diameter of the universe is 93 billion light years, or $8.8 \cdot 10^{26}$ m)
0.1	10^{-1}	10 cm	size of a human hand
0.001	10^{-3}	1 mm	size of creases on human skin
0.000 01	10^{-5}	0.01 mm	size of a white blood cell
0.000 000 01	10^{-8}	0.01 μm	size of individual genes / viruses
	10^{-10}	0.000 1 μm, 1 Å	diameter of hydrogen atom
	10^{-14}	10 fm	size of nucleus of a carbon atom

22.2 Scientific Notation

When using scientific notation, one separates the digits and size of a number. In other words, a number is expressed in terms of its digits, and multiplied by the required powers of ten, to express its size.

For example, instead of writing 5 234, which is five thousand two hundred and thirty-four, one writes it as $5.234 \cdot 10^3$, when using scientific notation. In this way, the first part of the number expresses the relevant numbers or digits, while the second part expresses its size using the powers of ten.

One expresses large numbers using powers of ten, and small numbers using negative powers of ten.

To illustrate: one million = 1 000 000 = 10^6. Or, one-hundredth = 1 / 100 = 0.01 = 10^{-2}.

To express a large number in powers of ten, one counts the number of digits after the first digit and expresses it as the number of powers of ten. For example: the number 65000000 or 65 000 000 has 7 digits following the first one (which is 6), and thus one writes it as 65 000 000 = $6.5 \cdot 10^7$.

The number 65000000 or 65 000 000 also demonstrates another helpful rule: large numbers are easier to read if one separates the clusters containing three zeroes with a space or a comma. To illustrate: instead of writing 000000, one writes it as 000 000, or in some texts 000,000. This book uses the convention that thousands ('000), or millions ('000 000) are separated by a space. It is however a mere convention, and other texts separate the thousands or millions using commas.

It is also very important to note that a 'full stop' or 'dot' is used to denote a decimal and is therefore used to separate full numbers and fractions. To illustrate: the number 6.5 means 6 integers and 5 fractions of one-tenth, or expressing this mathematically, one has:

$$\mathbf{6.5 = 6 + 5 \cdot \frac{1}{10} = 6 + \frac{5}{10}}\,.$$

To express small numbers using scientific notation, one counts the digits between the decimal point up to the first non-zero digit, which is be the number of negative powers of ten associated with the number. To illustrate: the number 0.0000987 has 5 digits after the decimal point up to the first non-zero digit (which is 9) and can thus be written as 0.0000987 = $9.87 \cdot 10^{-5}$.

Table 49 shows some useful examples where the use of scientific notation is illustrated.

Table 49: Examples using scientific notation

Number	Scientific notation
100	10^2
10	10^1
1	10^0
1 / 10 = 0.1	10^{-1}
1 / 100 = 0.01	10^{-2}
687.23	$6.8723 \cdot 10^2$
60 000 000	$6 \cdot 10^7$
60 000 001	$6.0000001 \cdot 10^7$

22.3 Prefixes

Both small and large numbers that are expressed in scientific notation are often abbreviated with prefixes, and thereby replace the relevant power of ten.

For example, 1 000 metres = 10^3 m, and can be written as 1 km using the prefix 'k' (for kilo). In the same way, 1 000 000 Bq = 10^6 Bq, which can be expressed as 1 MBq using the prefix 'M' (for Mega).

Some common prefixes are summarised in Table 50.

Table 50: Common prefixes used in science

Prefix	Abbreviation	Scientific Notation	Multiplier
femto	f	10^{-15}	1 / 1 000 000 000 000 000
pico	p	10^{-12}	1 / 1 000 000 000 000
nano	n	10^{-9}	1 / 1 000 000 000
micro	µ	10^{-6}	1 / 1 000 000
milli	m	10^{-3}	1 / 1 000
centi	c	10^{-2}	1 / 100
deci	d	10^{-1}	1 / 10
deka	d	10^{1}	10
hecto	h	10^{2}	100
kilo	k	10^{3}	1 000
Mega	M	10^{6}	1 000 000
Giga	G	10^{9}	1 000 000 000
Tera	T	10^{12}	1 000 000 000 000

Table 51 provides some typical examples which illustrate how the prefixes introduced above are used in practice.

Table 51: Examples of common prefixes in use

Example	Solution
10^{8} tons	100 Mtons
10^{-8} m	0.01 µm
10^{11} W	0.1 TW
10^{-13} m	0.1 pm
(10^{2} Bq) / ((10^{-1} m^3)	10^{3} Bq/m^3
1 mSv / 2 000 h	0.5 µSv/h
50 Sv / 50 000 Bq	1 mSv/Bq
10^3 µSv	1 mSv

22.4 Units

The result of a measurement is a number with a specific unit. A number without a unit has no meaning. This applies equally to the way we communicate, write, or enter data in a spreadsheet.

In equations, for example y = a · x + b, the units on both sides of the equation must match, otherwise the two sides cannot be equal, and would then not be a valid equation.

To report scientific results, it is important to choose units that are suitable for their purpose. For example, a suitable unit for your wedding anniversary is a day and a month, much likely not minutes or seconds, even though these are all valid units of time.

To illustrate: a suitable unit for the half-life of U-238 is using the unit in billions of years, rather than hours or minutes. And, to expand, a suitable unit for the distance between your home and your place of work is best expressed in km, rather than using mm or µm.

22.5 Adding/Multiplying Numbers using Scientific Notation

When adding two numbers in scientific notation, one must ensure that they have the same power of ten (i.e. the size is the same). To illustrate: say one wanted to add $6 \cdot 10^2 + 3 \cdot 10^2$. In this case, one adds two numbers, i.e. 6 and 3, both of which are multiplied by the same factor expressed as a power of ten, i.e. 10^2. This is permissible, as the power of ten of each of the two numbers to be added is the same. Therefore, $6 \cdot 10^2 + 3 \cdot 10^2 = 9 \cdot 10^2$.

One can generalise the above:

$$(\boldsymbol{x} \cdot \mathbf{10}^{\boldsymbol{A}}) + (\boldsymbol{y} \cdot \mathbf{10}^{\boldsymbol{A}}) = (\boldsymbol{x} + \boldsymbol{y}) \cdot \mathbf{10}^{\boldsymbol{A}}.$$

However, if the powers of ten are not the same, then the numbers cannot simply be added to one another. For example, $6 \cdot 10^2 + 3 \cdot 10^4$ is not a sum that is as straightforward as the example used above. To add these two numbers, one first must ensure that the exponents (i.e. the powers of ten) are the same. This is done as follows:

$6 \cdot 10^2 + 3 \cdot 10^4 = 6 \cdot 10^2 + 300 \cdot 10^2 =$ $(6 + 300) \cdot 10^2 = 306 \cdot 10^2 = 3.06 \cdot 10^4$.

When multiplying two numbers in scientific notation, the powers of ten are simply added. To illustrate: $100 \cdot 1000 = 100\,000$, which could also be expressed as $10^2 \cdot 10^3 = 10^{2+3} = 10^5$.

Again, one can generalise:

$$(\boldsymbol{x} \cdot \mathbf{10}^{\boldsymbol{A}}) \cdot (\boldsymbol{y} \cdot \mathbf{10}^{\boldsymbol{B}}) = \boldsymbol{x} \cdot \boldsymbol{y} \cdot \mathbf{10}^{\boldsymbol{A}+\boldsymbol{B}}.$$

A division by a power of ten is written in form of a negative power of ten. To illustrate: $\frac{1}{10^A} = 10^{-A}$.

One can express a division of number and their powers of ten as

$$(\boldsymbol{x} \cdot \mathbf{10}^{\boldsymbol{A}})/(\boldsymbol{y} \cdot \mathbf{10}^{\boldsymbol{B}}) = (\boldsymbol{x}/\boldsymbol{y}) \cdot \mathbf{10}^{\boldsymbol{A}-\boldsymbol{B}}.$$

Table 52 provides some typical examples which further illustrate the addition and multiplication of numbers when expressed in powers of ten.

Table 52: Adding and multiplying numbers using the powers of ten

Example	Solution
$10^1 \cdot 10^4$	$10^{1+4} = 10^5$
$10^3/10^4$	$10^{3-4} = 10^{-1} = 0.1$
$10^3 \cdot 10^{-4}$	$10^{3+(-4)} = 10^{3-4} = 10^{-1} = 0.1$
$10^3/10^{-4}$	$10^{3-(-4)} = 10^{3+4} = 10^7$
$(6 \cdot 10^3)/(3 \cdot 10^5)$	$(6/3) \cdot (10^3/10^5) = 2 \cdot 10^{3-5} = 2 \cdot 10^{-2}$

Example	Solution
$10 + 10^2$	$10 \cdot (1 + 10^1) = 10 \cdot (1 + 10) = 10 \cdot (11) = 110$
$10^1 + 10^4$	$10 \cdot (1 + 10^3) = 10 \cdot (1 + 1000) = 10 \cdot (1\,001) = 10\,010$
$10^4 + 10^2$	$10^2 \cdot (10^2 + 1) = 100 \cdot (101) = 10\,100 = 1.01 \cdot 10^4$
$10^1 - 10^{-1}$	$10 - 0.1 = 9.9$

22.6 'Dots before Dashes' Rule

The *dots before dashes rule* states that calculations involving dot symbols must be done before those involving dash symbols. *Dot symbols* indicate mathematical operations such as multiplication (·), and division (: or /), and refer to exponentials and trigonometric functions, as well as brackets and percentages (%). *Dash symbols* indicate mathematical operations such as addition (+), and subtraction (–). To illustrate: 5·6 + 10·2 = 30 + 20 = 50, i.e. first multiply (or divide), then add (or subtract).

When using an electronic calculator, it is essential to check that the 'dots before dashes' rule is strictly applied by the calculator.

22.7 Significant Figures

The *significant figures* of a number are those digits that are used to express it to the required degree of accuracy.

The number of digits in each number which are significant are called the significant digits. The significant digits are those numbers in a figure that carry meaning, and therefore contribute to its precision.

Digits that do not contribute to the significant digits include

- Leading zeroes, such as those in 0.000 02;
- Trailing zeroes, which are mere placeholders to indicate a given number's magnitude, e.g. 2000 years;
- Spurious digits that are introduced, for example, by calculations carried out to greater precision than that supported by the original data; and
- Numbers that are reported to a greater precision than is supported by the equipment (e.g. a ruler, or a temperature gauge, or a gamma detector) that was used for the measurement that led to such numbers.

The following example illustrates the use of significant figures: say one travels from A to B. When stopping exactly at B, the distance between A and B is 100 km. However, say that it is not possible to stop right at B, and one must instead stop some 25 metres away from B. In such an instance, the distance between A and B would amount to 100 km plus 25 metres, and therefore would be 100.025 km. However, in most instances, the additional 25 m is insignificant when compared to the distance of 100 km, and there is no significant difference between 100.025 km, and 100 km.

Box 67: Example of significant figures when calculating an annual exposure dose

When reporting measurements, it is important to understand which part of the data is significant, i.e. worth knowing, or even possible to know, and which is insignificant.

To illustrate: say one measures the gamma dose rate in an area to be 1 μSv/h. Based on this measurement, one now calculates that an employee who works in this area for 1 750 hours in each year will be exposed to an annual exposure dose of

$$1\ \mu\text{Sv/h} \cdot 1\ 750\ \text{h/a} = 1\ 750\ \mu\text{Sv/a} = 1.750\ \text{mSv/a}.$$

If one were to report the person's total exposure dose as 1.750 mSv/a, one would make the result look as if the annual gamma dose would be accurately known to 4 digits. This is not the case. The challenge is that one knows one of the numbers to one-digit accuracy, i.e. the dose rate, while the annual exposure time is known to four significant digits. This example illustrates that the final answer can certainly not be known more accurately than the least accurate of the two numbers. Hence, the annual exposure dose should only be provided to one significant digit, which implies that it is 2 mSv/a.

The following rules ensure that significant digits are correctly used:

- Use enough digits to avoid the unintended loss of significance.
- Limit the number of digits used to ensure that the mathematical operations remain manageable.
- The number resulting from a calculation cannot have more significant digits than those of the data used in the calculation.
- Non-zero digits are always significant. For example, 22 has two significant digits, and 22.3 has three significant digits.
- Zeroes placed between other digits are always significant. For example, 4009 kg has four significant digits.
- Zeroes placed before other digits are not significant. For example, 0.046 has two significant digits.
- Zeroes following other digits but behind a decimal point are significant. For example, 7.90 has three significant digits.
- Only round the number in the final answer, i.e. do not round the numbers used in an intermediate calculational step. For example, $1.243 \cdot 20.0 = 24.86$, where the result can be rounded to three significant figures, i.e. 24.9, or two significant figures, i.e. 25.
- A result of a mathematical operation (e.g. a multiplication) cannot have more digits than is justified by the number of significant digits in the original data.
- Use common sense to decide on the level of precision. For example, knowing the time to the nearest tenth of a second makes no sense if we are talking about a person's birthday.
- Keep the raw data in the raw and therefore unchanged format.

A calculation using multiplication, division, exponentials and trigonometric functions, as well as brackets and percentages, i.e. the so-called 'dots' calculations as discussed in 22.6, the number of significant digits shown in the result should be the same as that of the number having the least number of significant digits in the operation. To illustrate: $20 \cdot 3.0001 = 60$.

Table 53 provides examples of calculations where the final answer has the correct number of significant digits.

When numbers are added or subtracted from one another, the number of decimal places (not significant digits) in the result should be the same as that of the number having the least decimal places in the operation. To illustrate: $50 + 0.002 = 50$.

Table 53: Examples of calculations and their significant figures

Example	Final answer
$10 \cdot 12$	1 200
$100 \cdot 1.2001$	120
$100/20.001$	5.00
$90/0.3$	300
$10 + 0.5$	11
10.0 + 0.5	10.5
$10.5 + 11.5$	22.0
10.5 + 11.56	22.1
$10.5 - 10.05$	0.5
$80 - 0.3$	80

Box 68: Decimal places and significant figures

The following examples illustrate the difference between decimal places and significant figures:

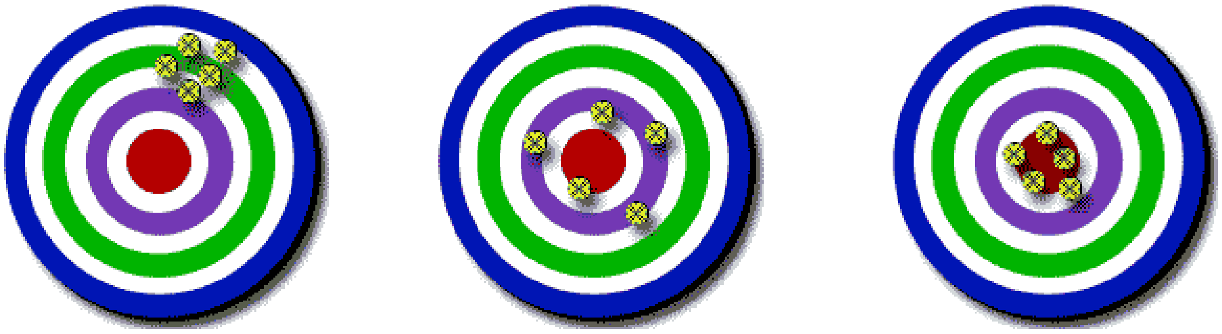
- 5.67 mSv has two decimal places, but three significant digits;
- 1.1 nSv has one decimal place and two significant digits; and
- 0.9378 m has four decimal places and four significant digits.

22.8 Precision and Accuracy

Preferably, one repeats the same measurement several times to ensure the consistency of results. If such repeated measurements yield values that are close to each other, one says that the measurement was *precise*. On the other hand, if the results were close to the true value of the variable that was being measured, one says that the measurements were *accurate*.

The concepts of precision and accuracy are illustrated in Figure 190, using the example of a dart board. Say all darts hit the board close to each other, as shown in A, the person throwing the darts was precise, but not accurate, as he missed the centre of the target. If the darts are clustered around the centre of the target, the person throwing the darts was accurate, as shown in B, but not precise, as there remains some significant scatter amongst the throws. If the darts are all clustered around the centre of the target, and are close to one another, as shown in C, then the person throwing the darts was both accurate and precise.

Figure 190: Precision and accuracy illustrated



A) High precision, low accuracy B) High accuracy, low precision C) High accuracy and high precision

Often, the accuracy of a measurement is not known, as one does not always know what the true value that is to be measured really is. Though, if all systematic errors are avoided, then the measured values should be maximally accurate. On the other hand, if all random errors are avoided, then the measured values should be maximally precise.

Systematic errors are introduced by instrument calibration errors, incorrect measurements, and/or logical errors that arise when combining measured data into a result. Often, such systematic errors tend to show the same trend or direction for all measurements, in that all measurements are either too high, or too low.

Random errors are always present in measurements, and are introduced because of the variability of nature, including but not limited to temperature and/or pressure fluctuations, the natural variability of radioactive decays, and many others. As such, random errors are not trending in a specific direction, but are scattered, as if they are subject to random forces. The randomness of an error allows for the statistical evaluation of the magnitude of the error.

Increasing the number of measurements decreases the random error associated with an average value, as it increases the precision of the results. However, an increase in the number of measurements does not change any systematic errors that may be present, i.e. it does not improve the accuracy of the results.

22.9 Solving Equations for Unknowns

The relationship between a set of variables is often expressed using a mathematical relationship which is in form of an equation. If one of the variables used in the equation is unknown, while all others are known, one can solve the equation for that unknown variable.

A few simple rules allow the successful manipulation of an equation when solving for an unknown variable:

- When multiplying or dividing an equation with/by a specific factor, multiply/divide both sides of the equation with/by the same factor;
- When adding or subtracting values from an equation, add/subtract the value from both sides of the equation; and
- When having to invert an equation, invert both sides.

An equation remains valid if the same mathematical operation (i.e. division, multiplication, inversion, or other) is applied to both sides of the equation.

Table 54 provides a few examples to demonstrate some simple techniques in how to solve an equation for the unknown value x.

Table 54: Solving an equation for the unknown x

Task: solve for x	Technique applied	Solution
$A + B = x + C$	subtract C from both sides of the equation	$x = A + B - C$
$A = x \cdot (B \cdot C)$	divide both sides by $B \cdot C$	$x = \frac{A}{B \cdot C}$
$\frac{A}{x} = \frac{x}{2}$	multiply both sides by 2, and by x, then take the square root on both sides	$2A = x^2$ $x = \sqrt{2A}$
$30 \cdot A \cdot x = 90 \cdot C$	divide both sides by $30 \cdot A$	$x = \frac{90 \cdot C}{30 \cdot A} = 3 \cdot \frac{C}{A}$

22.10 Combination of Errors

If a measurement involves a combination of steps, each step may introduce errors, which could either be random or systematic errors, or a combination of both. The outcome of such a measurement then includes a combination of errors. Typically, errors do not simply add up, but must be combined following a set of rules.

Having a large error in one step, and a small error in the next one does not decrease the overall error as the result is always a reflection of the largest error of the various steps taken. To illustrate: Aunt Nancy was born on 2 October 1940 at 08h45 and started going to school in the year she turned six. Here we do not know anything else of the exact age at which she first went to school, other than that she was six years old, unless we are given the date and time with the same accuracy as was provided for her date of birth.

When adding or subtracting several quantities to/from one another, with each one having an individual error, these errors which are called e_1, e_2 ,… e_n are then propagated into the overall error E, which is computed as follows:

$$\boldsymbol{E = \sqrt{(e_1)^2 + (e_2)^2 + \cdots (e_n)^2}}\ .$$

Note that the squares of the individual errors are added to one another, regardless of whether the underlying operation is an addition or a subtraction.

Box 69: Propagating statistical errors when the result is additive

When determining the annual radiation dose of employees, one considers all the relevant exposure pathways that may contribute to the total exposure dose.

Assume that the following measurements were made:

1. External dose from gamma radiation: $D_e = 0.5 \pm 0.1$ mSv/a;
2. Inhalation dose from long-lived radioactive dust: $D_{LLRD} =$ 0.1 $\pm$ 0.05 mSv/a; and
3. Inhalation dose from radon progeny: $D_{Rn} = 0.3 \pm 0.3$ mSv/a.

Here it is noted that the error for the radon inhalation dose is large when compared to the measured value, while the errors for the other two pathways are much smaller than the associated exposure doses.

For the values given above, the propagated error is calculated as follows:

$$E = \sqrt{(e_1)^2 + (e_2)^2 + (e_3)^2} = \sqrt{0.1^2 + 0.05^2 + 0.3^2} = \sqrt{0.01 + 0.0025 + 0.09} = \sqrt{0.1025} = 0.3 \text{ mSv/a}.$$

The total annual exposure dose is the sum of the doses contributed by the individual pathways:

$$D = D_e + D_{LLRD} + D_{Rn} = 0.5 + 0.1 + 0.3 = 0.9 \text{ mSv/a}.$$

The total annual exposure dose, taking the errors into account, is therefore given as

$$D = 0.9 \pm 0.3 \text{ mSv/a}.$$

If instead, the variables that are measured must be multiplied with one another, the errors e_1, e_2 ,… e_n from the quantities Q_1, Q_2 ,… Q_n are propagated into an overall error E as follows:

$$\boldsymbol{E = Q\sqrt{(\tfrac{e_1}{Q_1})^2 + (\tfrac{e_2}{Q_2})^2 + \cdots + (\tfrac{e_n}{Q_n})^2}}.$$

Box 70: Propagating statistical errors when the result is multiplicative

The area of a square is determined by measuring the lengths of the two sides A and B.

Assume that the following results were obtained by way of separate measurements:

$$A = 10 \pm 1 \text{ cm, and } B = 5 \pm 0.5 \text{ cm.}$$

The area of the square, Q, is the product of the two sides, i.e.

$$Q = A \cdot B = 10\,cm \cdot 5\,cm = 50\,cm^2,$$

While the error is determined as

$$E = Q\sqrt{(\tfrac{e_1}{Q_1})^2 + (\tfrac{e_2}{Q_2})^2 + \cdots + (\tfrac{en}{Qn})^2} = 50 \cdot \sqrt{(\tfrac{1}{10})^2 + (\tfrac{0.5}{5})^2} = 50 \cdot \sqrt{0.01 + 0.01} = 7\,cm^2.$$

The area of the square, taking the measuring errors into account, is therefore given as

$$Q = (50 \pm 7) \text{ cm}^2.$$

22.11 Mean, Median and Range

One often needs to characterise a collection of items with a number that is representative of all of them. For example, when wishing to know the approximate cost of a kilogram of apples, it helps the understanding when one has available the cost charged by several apple vendors on a given day, realising that such costs are likely to vary from one day to the next day.

To illustrate the above, assume that one has a group of 40 adults attending an evening class, and one wants to determine their weight in kilograms (i.e. the mass). An approach to determine their weight would be to measure the weight of each participant, which would yield a data set, in kg, such as the following: 70 73 80 95 78 83 75 95 98 69 80 78 77 73 85 88 90 68 85 79 65 93 95 78 85 78 108 75 73 78 78 90 80 68 80 65 78 75 74 78. While such detailed information may be useful, there are a variety of ways to more concisely convey this information.

One way of analysing the data would be to group it into specific weight bins. Realising that the weights range between 60 and 110 kg, one could sort the data into intervals which are 10 kg apart, starting with 60 kg. in this way one would find the following distribution:

65 65 68 68 69 **(5 data points)**

70 73 73 73 74 75 75 75 77 78 78 78 78 78 78 78 78 79 **(18 data points)**

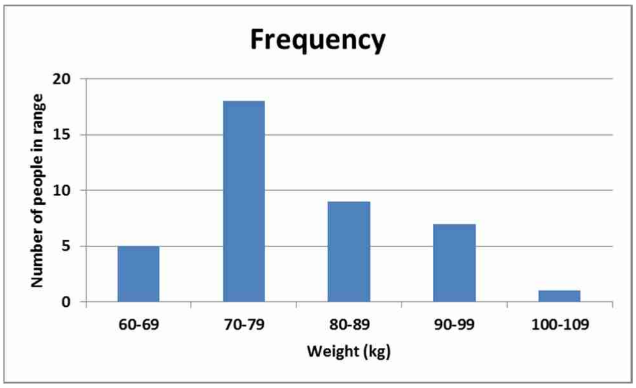
80 80 80 80 83 85 88 85 85 **(9 data points)**

90 90 93 95 95 95 98 **(7 data points)**

108 **(1 data point)**

This reveals that there are 5 people weighing between 60 and 69 kg, 18 weighing between 70 and 79 kg, 9 weighing between 80 and 89 kg, 7 who have a weight in-between 90 and 99 kg, and one person between 100 and 109 kg. Graphically, these results can be illustrated as shown in Figure 191.

Figure 191: Frequency distribution of the weight of 40 adults



A graph such as the one shown in Figure 191 is called a frequency distribution, as it shows how the data is distributed throughout the different weight intervals. The most frequently occurring weight bin, i.e. the showing most people weighing between 70 and 79 kg, is the most representative weight interval of this adult class, even though one realises that there are persons both above and below this specific weight bin.

Seeing that there are 40 individual data points, this data sample does not have an exact midpoint. However, data points 20 and 21 are both in the middle of the data set, and in this case, they happen to have the same numerical value, i.e. 78 kg. The 'midpoint of a data set' is called the ***median***, and is the data point that is in the middle of an ordered data set, ordered meaning that one arranges the numbers from the lowest to the highest value, or vice versa. If there are an even number of data points in each set, then the median is the average of the two midpoints. If the data set has an uneven number of data points, the data point that is exactly in the middle of the ordered data set is the median value of the set.

In Excel, the median of a data set in cells A1, A2, …, An is obtained using the function MEDIAN(A1:An).

If one had a data set such as the one given above, but with the highest value being much larger than the current maximum value (108 kg), for example 200 kg, then the median value for the set remains unchanged, as it remains the value in the middle of the ordered data set, regardless of the values that exist on the 'edges' of the ordered data set. This illustrates that – in some cases – the median may not be representative for the data set. This is particularly true when data is spread across a wide range of values, or if there are individual data points that are significantly different from the remainder of the set. In such cases, a more representative value of the set is obtained by computing the *average* of the values of the data set instead. This number is called the ***mean***, or *mean value*, indicated by $\bar{x}$, and is obtained by summing over all values, and dividing the result by the number of data points in the set. In the example introduced above, there are 40 data points in the data set, and their sum is 3 213 kg. The mean is determined by dividing the sum of all values by the number of data points in the set, i.e. 3 213/40 = 80.3 kg. When rounded to the original number of significant digits of the individual data points, the data set's mean is 80 kg.

In Excel, the mean of a data set A1, A2, …, An is determined using the function AVERAGE(A2:An).

The above shows that the mean and the median are not the same, i.e. 78 kg and 80 kg respectively. But it is noted that the two values are like one another and are specific representations of the data set in question.

Another useful characteristic of the data set is the ***range***, which indicates how far apart the lowest and the highest value of the data set are. In the example introduced above, the range is computed as follows: $108\,kg - 65\,kg = 43\,kg$. It is evident that the range – in this example – is almost one-halve of the median and the mean values. However, if one were to replace the maximum value in the data set, i.e. 108 kg, by a single data point of 200 kg, then the range changes to $200\,kg - 65\,kg = 135\,kg$, and is now almost twice the median, which remains at 78 kg.

If the range is large, the median is not a good representative of the data set, even though it may still be a good indicator if outliers determine the range, i.e. data points that are significantly larger/smaller than the remainder of the data set.

22.12 Weighted Average

When averaging over data, it is important to ensure that all data points carry the same weight, in other words, all data points must contribute equally to the data set. To illustrate: consider a set of sampled radiation exposure doses of workers who belong to two different exposure groups, namely the group of field workers, and the group of plant workers. Assume that an average exposure dose was determined for each of the two groups, as summarised in Table 55.

Table 55: Weighted average illustrated

Group	Average dose for group (mSv/a)	Number of workers per group
Field workers	1.50	100
Plant workers	3.00	20

From Table 55 it is evident that the total average exposure dose is not simply the average of the two group doses. This is the result of the different number of people in each exposure group and implies that the group with more people makes a larger contribution towards the average dose of all workers than the group representing fewer workers. To remedy the difference in the number of members in each group, one allocates a weighting factor to each of the group results, which expresses how many contributors are in each group.

In this way, the *weighted mean* is determined, which is an expression of the average of a sample in which different groups each make their separate (and often quite different) contributions to the mean of the sample.

Using the data provided in Table 55, one computes the weighted average exposure dose of the whole group as follows:

$$\bar{x} = \frac{1.5 \cdot 100 + 3 \cdot 20}{100 + 20} = \frac{210}{120} = \mathbf{1.75\ mSv/a.}$$

Weighted averages are used whenever one is averaging over variables that contribute differently towards the total. For example, if one were to sample the exposures to noise levels for employees during the day shift, afternoon shift and night shift, then the average exposure for the groups must be weighted with the number of people in each group. Therefore, if one samples radiation exposures by similar exposure group, and wishes to compute the site-wide average exposure dose, then such a site-wide average is NOT the average of the exposure doses of all groups (which is the average of averages), but rather, one must weigh the exposure dose of each contributing group to reflect the number of people in each group.

22.13 Normal Distribution

The different data one measures often follow a specific frequency or probability distribution, depending on what law(s) such data is governed by, or the behaviours of the measured variables.

The most commonly obtained distributions followed by many natural variables are the Poisson and the Gaussian/Normal distributions. The Poisson distribution is not necessarily symmetrical, whereas the Gaussian distribution is always symmetrical around a given midpoint, noting that the Gaussian is a special case of the Poisson distribution.

The Gaussian distribution – which is also called the Normal distribution – represents the probability distribution of most natural variables, such as the height and weight distribution of people, the distribution of wealth in a society, and the distribution of radioactive decays of a specific radioisotope in each time interval.

When considering the Gaussian distribution, its values are symmetrically arranged or centred around a midpoint, which is the mean value or expectation value of the distribution, which is indicated using the symbol μ. Of all values that are in the data set described by a Gaussian distribution, 68.3% fall within one *standard deviation*, which is indicated using the symbol σ, of the mean μ. Similarly, 95.4% of all data fall within 2σ, and 99.7% fall within 3σ, as indicated in Figure 193.

Figure 192: Poisson (left) and Gaussian distributions (right)

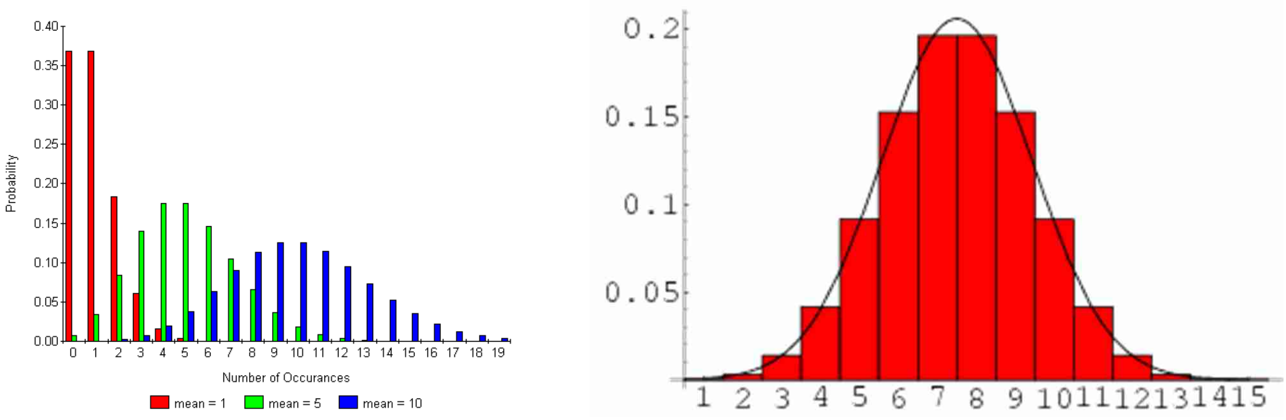
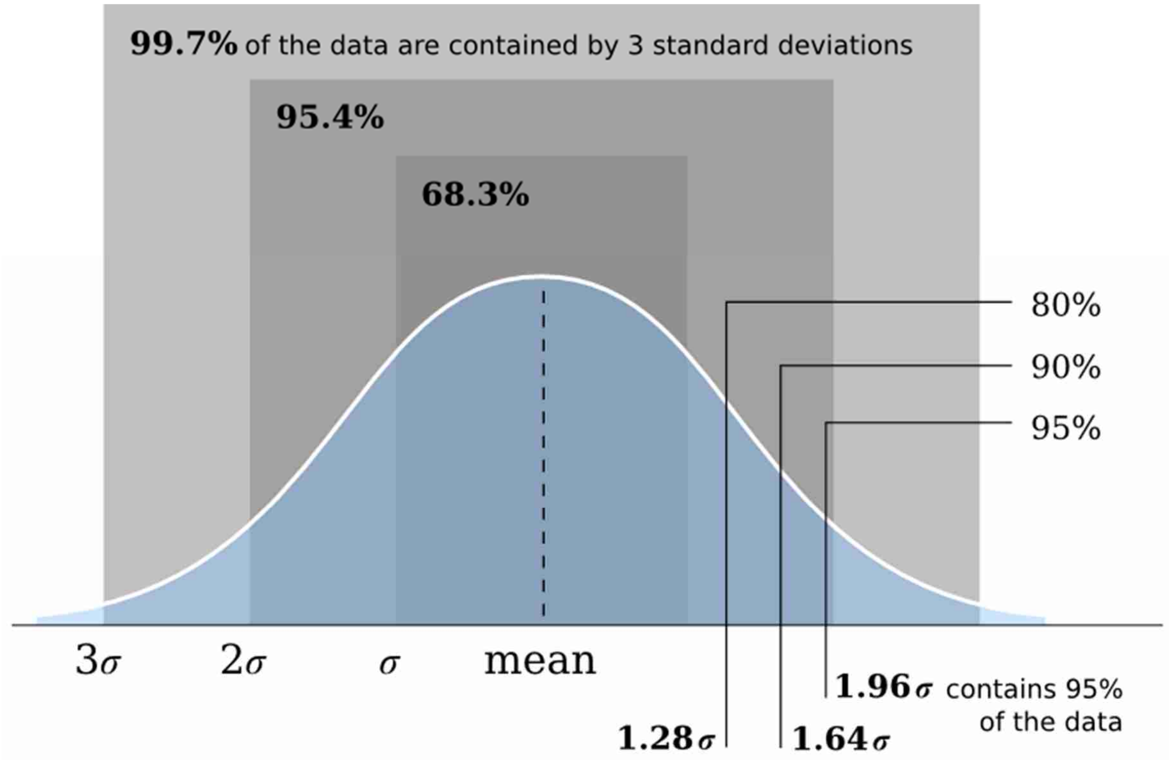


Figure 193: The Gaussian (normal) distribution



22.14 Standard Deviation

The standard deviation of the Gaussian distribution quantifies how close the data points described by the distribution lie together. Therefore, a large standard deviation implies that the data is spread over a large range, while a small standard deviation indicates that the data is compact and not very spread out. The standard deviation **σ** for a set of samples is calculated with the following formula:

$$\boldsymbol{\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n-1}}}$$

where n represents the number of data points in the data set and $\sum_{i=1}^{n}$ is the sum over all values ranging from 1 to n.

In Excel, the standard deviation of a data set A1, A2, …, An is calculated using STDEV(A2:An).

Box 71: Step-by-step computation of the standard deviation

Consider a group consisting of 7 children. Their height, in cm, is captured in the following data set: 90, 55, 70, 75, 65, 68, and 70. The task is to calculate the standard deviation.

First, one determines the mean value of this data set. Then, one subtracts the mean from each of the seven data values and squares the result. Then, one computes the sum of all the squares, and divides it by 6. Finally, one takes the square root, which yields the standard deviation. These steps are detailed in the table below.

Data point , x_i	Height (cm), x_i	Difference from mean, $x_i - \bar{x}$	Square of difference, $(x_i - \bar{x})^2$
x_1	**90**	**19.6**	**383.0**
x_2	**55**	**−15.4**	**238.0**
x_3	**70**	**−0.4**	**0.2**
x_4	**75**	**4.6**	**20.9**
x_5	**65**	**−5.4**	**29.5**
x_6	**68**	**−2.4**	**5.9**
x_7	**70**	**−0.4**	**0.2**

- **Mean** $\bar{x}$ **= 70.4**
- **Sum,** $\sum_{i=1}^{7}(x_i - \bar{x})^2$ **= 677.7**
- **Sum/6,** $\frac{\sum_{i=1}^{7}(x_i - \bar{x})^2}{6}$ **=113.0**
- **Square root** $\sqrt{\frac{\sum_{i=1}^{7}(x_i - \bar{x})^2}{6}}$ **σ = 10.6→11**

Note that the final value for the standard deviation, i.e. σ = 11, was rounded, to ensure that it has the same number of significant digits as the original data.

If this data set is normally distributed, some 68% of data (corresponding to 5 points) should fall within one standard deviation σ from the mean value μ. This implies that 5 of the 7 data points should lie within the range 70 + 11 = 81, and 70 – 11 = 59. Inspecting that data set 90, 55, 70, 75, 65, 68, and 70 shows that two values, i.e. 55 and 90, fall outside the range 59 < x < 81, and hence, as expected, the remainder, i.e. five data points, fall into this range.

22.15 Percentiles

Percentiles are a measure of inclusion, or confidence in a specific set of measurements. To illustrate: assume that one has determined the annual gamma exposure dose of a group of persons, having made ten separate measurements, in mSv/a:

3.0, 1.9, 1.0, 2.1, 3.1, 1.9, 1.7, 1.3, 1.5, 1.8.

The 90% *percentile* of this set includes the lowest 90% of these measurements, or conversely, excludes the highest 10% of the set. For the above data set, the 90% percentile is 3.0, noting that only one out of the ten data points was excluded, which implies that 3.1 was not included in the range.

In Excel, the percentile is computed using PERCENTILE.INC(A1:A10,k), where k is a value between 0 and 1, representing the desired percentile, such that, for example, k = 0.1 for the 10th percentile.

Excel does the calculation of percentiles based on a Gaussian distribution. For the above data set, it does not return the value 3.0 for the 90th percentile, but the value 3.01 instead, as it assumes that the distribution is a Gaussian distribution. The closer the distribution is to a true Gaussian, the better will the agreement be between the value calculated by Excel and the value calculated from first principles, as done in the above example.

22.16 Sampling

When one wishes to determine a physical characteristic of an object or phenomenon in nature, one takes several separate measurements to obtain a good estimate of the actual value. This is called *sampling*. The more samples one takes, the more likely it is that one is close or at least closer to the actual value one tries to determine. Often however, the relationship between the number of samples taken and the improvement of the value to be determined is not linear, and in some instances, taking a few sample measurements (say 6 or 10) is (almost) as good as taking a few hundred samples.

One essential criterion is that sampling is undertaken in a non-biased way. This means that one must undertake the measurements – i.e. take the samples – in such a way that any subset of the measurements taken is representative of all the measurements taken. If this is not the case, one says that the sampling has a bias, and that the approach taken resulting in the measurements was flawed.

The first rule in sampling is therefore to avoid – or at least minimise – any bias. The following examples illustrate how sampling can be biased, when monitoring the radiation doses of a group of persons:

- focus only on a handful of persons in a large group;
- include only those persons in the sampling run that are eager to participate;
- sample only persons who are working indoors, because the persons working outdoors are usually not present when undertaking the measurements;
- sample only those persons who work on day shifts, even though afternoon and evening shift-work takes place as well;
- take samples during a single week in the year, even though exposure conditions are known to change because of the seasons, or because of certain production schedules which change during a year;
- only take samples between 9 am and 3 pm, because of the convenience of taking samples in that specific timeslot.

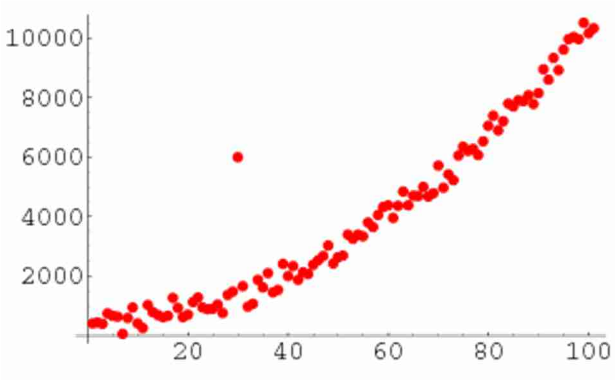
Sampling should be random, to exclude or at least minimise any possible selection bias. Random sampling can be achieved by – for example – randomly selecting the persons that are to participate in the sampling run, using a random number generator, or drawing the names of participants from a hat (or a list of participants). Actively selecting those participating in the sample, for example by choosing persons who have a surname starting with certain letters, introduces a bias in the sample, which in turn may affect the validity of the result.

Figure 194: Random sampling

22.17 Outliers

Outliers are data points that are different from the remainder of the data set. When a given data set is plotted, outliers are usually readily recognised. As illustrated in Figure 195, there is a single outlier, which is the dot that seems to sit all by itself, while the remainder of the data in the set follows a recognisable pattern.

Figure 195: An example of a data outlier



To quantify how far off an outlier is from a data set, the so-called z-score is used, which is defined as

$$z_i = \frac{x_i - \bar{x}}{\sigma}.$$

Each data point’s z-score indicates how far away a given data point is from the data set’s mean.

A rule of thumb applied to data outliers is that one discards those values that have a z-score greater than 3. Here it is noted that small sample sets, for example those having only a few tens of data points, are often characterised by outliers with a z-score that is closer to 2, rather than greater than 3, which is often used for large data sets.

<u>HOWEVER:</u> it is critically important that one is aware that there may be some or even many reasons why particular data points are outliers. It is therefore essential that one does not to just discard data points simply because they happen to have a z-score that characterises them as outliers. Therefore, before a data set is ‘cleaned’, and outliers are removed, one first needs to understand the possible reason(s) why one or several data points may not fit into the general pattern displayed by the remainder of the data set. To this end, one should identify the reason(s) for any discrepancies before removing data from a data set, even though they may appear to be outliers.

Box 72: Using the z-score to identify data outliers

The results of a monitoring campaign which entailed the measurement of the ambient atmospheric radon concentration in a specific workplace yielded the following data, which is presented from the lowest to the highest value recorded, in Bq/m^3:

10, 20, 25, 27, 30, 35, 40, 42, 44, 1 050 Bq/m^3.

The data set's mean value $\bar{x}$ = 132 Bq/m^3, which is not a representative reflection of the data set. The data set's standard deviation σ = 323 Bq/m^3, and is larger than the mean, which is indicative of the fact that the data set's spread is large.

The z-score is calculated for each data point, and is summarised in the table below:

Value	z-score
10	-0.38
20	-0.35
25	-0.33
27	-0.33
30	-0.32
35	-0.30
40	-0.28
42	-0.28
44	-0.27
1 050	2.84

When using a z-score of 2 to identify those data points that are to be eliminated from the data set, then the 'cleaned' data set contains 9 values only, and its mean and standard deviation are 30 and 11 Bq/m^3 respectively, which are values that are much more representative of the above data set.

22.18 Errors Associated with Radioactivity Measurements

The laws of probability govern the phenomenon of radioactivity. The Gaussian/normal distribution is reliable for such data sets provided that

- the half-life of radionuclides exceeds the counting time for the measurement;
- the number of measured counts n is larger than 30; and
- the number of measured counts n is much smaller than the number of atoms contained in the material that is being measured (which is almost always the case).

The error E associated with single radioactivity measurement is a function of the confidence level k, and the measured quantity N, for example the counts per minute, i.e.

$$\boldsymbol{E = k \cdot \sqrt{N}}.$$

Table 56 provides the values of k and the associated confidence level.

Table 56: Confidence level k

k	confidence level
1.000	68%
1.645	90%
1.960	95%
2.576	99%

22.19 Limit of Detection and Limit of Quantitation

The limit of detection, which is abbreviated LOD, is the lowest value of a measurement that is still distinguishable. To illustrate: suppose one attempts to communicate in an environment with a noisy background, such as a workshop. If one is spoken to, and the communicator's voice is soft, one is unlikely to understand what is being said, as the person's voice is likely to be less than the LOD of one's ear. If the person's voice is a bit louder, one may hear them, but it may not be possible to hear exactly what is being said. In such a case, the voice level exceeds the LOD, but is still below the *limit of quantitation* (LOQ). If the person's voice is even louder, then one can understand what is being said, and their voice level exceeds both the LOD and the LOQ. Detection limits depend on both the signal intensity (for example the voice level), and the contribution of the background (for example the noise level generated in the workshop).

To measure a physical quantity, both the method of detection as well as the instrument used must be such that they allow the detection above the LOD and LOQ limits. This implies that one needs to be able to detect the signal and can distinguish it from the background (noise), which is attributable to the environment in which the measurement takes place. To illustrate: when determining the exposure dose because of the exposure to radiation, one needs to consider the natural background radiation that occurs in the place where the measurement takes place, which in some instances may be the only source of radiation present at a given location.

The standard rule applied in statistics stipulates that the signal to be measured must be at least three times greater than the standard deviation of the background noise to be above the LOD, as is further elaborated in Box 73.

Box 73: Illustrating the signal-to-noise ratio when quantifying the public radiation exposure dose

Assume that one wishes to quantify the radiation exposure dose contribution resulting from a specific mining operation to the total public exposure dose of persons living at the town of Arandis. This location has a natural background radiation field which results in an exposure dose of 3.2 ± 0.5 mSv/a. A previous theoretical public exposure dose assessment has determined that the incremental exposure dose contribution to the total dose of the critical group (i.e. the persons living at Arandis) because of the activities of the nearby mine amounts to 120 µSv/a when taking all relevant exposure pathways into account. Given the above information, can the contribution to the total exposure dose of the critical group be measured directly and reliably?

It is assumed that the standard deviation of the natural background radiation field is 0.5 mSv/a, as measurements are communicated in form of a mean value plus minus one standard deviation. Applying the standard rule of statistics, i.e. that the to-be-detected signal must be at least three times larger than the standard deviation of the background, one realises that a meaningful signal should at least be $3 \cdot 0.5 = 1.5$ mSv/a.

The expected 'signal' is of the order of 0.12 mSv/a, which implies that the signal is less than one-tenth of three times the standard deviation associated with the natural radiation background field at this location. This implies that it is unlikely that one can directly and reliably determine the contribution of the mining operation to the total public exposure dose of members of the critical group. As a result, one would have to infer the contribution made by the mining operation, from measurements at the mine's periphery, from which one would then determine the maximum contribution to the total exposure dose to members of the critical group. However, such a contribution is not likely to be uniquely measurable, as the noise significantly exceeds the signal.

22.20 Exercises

22.20.1 Scientific Notation

Work out the following:

1. $10^{-5} \cdot 10^{5}$
2. $10^{-8} / 10^{5}$
3. $10^{3} / 10^{-5}$
4. $10^{+5} + 10^{+5}$
5. $10^{+5} + 10^{+4} + 10^{+3}$
6. $10^{+5} - 10^{+4}$
7. $5 \cdot 10^{-5} + 5 \cdot 10^{-3}$
8. $5 \cdot 10^{-5} \div 10 \cdot 10^{2}$
9. $6 \cdot 10^{5} \div 2 \cdot 10^{12} \div 3 \cdot 10^{6}$
10. $25 \cdot 10^{6} + 2.5 \cdot 10^{7} + 0.25 \cdot 10^{8}$

22.20.2 Using Scientific Notation

Rewrite the following numbers using scientific notation:

1. 0.001004
2. 1 004
3. 1 004 000
4. 1.004000
5. 1 004 / 10^{-3}
6. 1 004 · 10^{3}
7. 1 004 / 10^{3}
8. 1 004 / (1 004 · 10^{5})
9. 1 004 · 10^{5} / 1 004
10. (1 004 · 10^{4}) / (1 004 · 10^{-4})

22.20.3 Using Prefixes

Rewrite the following numbers using scientific notation and the most suitable prefix:

1. 6 000 µSv
2. 0.005 GBq
3. 0.001 kBq
4. 10^{-8} GBq
5. 63 000 000 Bq
6. 0.000 000 1 Sv
7. 5 327 000 nSv
8. 1 / 1 000 Bq
9. 1 250 000 µSv
10. 0.52 · 10^{-3} Sv

22.20.4 Conversion to mSv

Convert the following to milli-Sievert (mSv):

1. 0.10 Sv
2. 1 000 000 nSv
3. 10^{5} µSv
4. 0.0004 Sv
5. 0.2 nSv
6. 10^{-4} Sv
7. 0.000 01 Sv
8. 10^{-2} µSv
9. 1.01 Sv
10. 2.5 · 10^{-3} Sv

22.20.5 Significant Digits

1. Rewrite the following using the correct number of significant digits:
    1. $25.6 - 21.1 + 2.43$
    2. $\frac{16}{4.001} \times 0.2$
    3. $\frac{1}{4} \cdot 6 \cdot 0.002$
    4. $0.007 + 0.07 + 0.7$
    5. $\frac{90}{0.030}$
    6. $450/0.5$

2. How many significant figures do the following numbers have: 5.00809, 0.0067, and 400?

3. Assume that it takes one second to switch off the alarm in the morning, five minutes to shower, 30 seconds to put on the shoes, 20 minutes to have breakfast, 10 minutes to brush the teeth, and one hour to drive to work, how long does the morning routine take before arriving at work?

22.20.6 Propagation of Errors

Assume that one has the following three values and their associated statistical errors:

$$A = 1.67 \pm 0.005,\ B = 5.23 \pm 0.009,\ C = 1.88 \pm 0.007.$$

a. Compute $A \times B \div C$
b. Compute $A + B$
c. Compute $A + B - C$
d. Compute $A \times B - C$
e. Compute $A + B \div C$

22.20.7 Solving for the Unknown Variable

Solve the following equation for x: $y \cdot x \cdot C \cdot \frac{R}{V} = C^2$

22.20.8 Averaging

Based on the following person's stated monthly salary, compute the representative salary of the following group of persons:

- Peter 10 000
- Mary 15 000
- Leanne 13 000
- David 25 000
- Mandy 20 000
- Chris 50 000

22.20.9 Mean and Median

The following data set is the result of gamma exposure dose monitoring, reflecting the annual exposure dose in mSv/a: 2.0, 1.0, 3.1, 0.2, 0.6, 0.8, 1.1, 1.6, and 1.4

Determine the mean, median and range of this data set and assess whether the mean or the median provides a better representation of the data.

22.20.10 Standard Deviation

1. Calculate the average and standard deviation for the data: 4, 20, 90, 3, 1.
2. Work out the standard deviation for this data set: 2.0, 1.0, 3.1, 0.2, 0.6, 0.8, 1.1, 1.6, 1.4

22.20.11 Weighted Average

Compute the weighted average exposure dose, in mSv/a, using the exposure groups and their respective exposure doses as provided in the table below:

Exposure group	Number of persons per group	Average exposure of a given group (mSv/a)
Field workers	100	2.3
Processing workers	10	5.5
Office workers	40	0.9

22.20.12 Sampling

To determine the radiation dose of select field workers, the radiation technician decides to sample everyone in the week starting June 6, during which the local weather was calm. As the responsible Radiation Safety Officer, what is your comment on the strengths and weaknesses of such a sampling method?

22.20.13 Outliers

The following table summarises the quarterly radiation doses of a group of persons in the processing plant. Based on the given data, determine if there are outliers in this data set, based on a z-score of 3.

Person #	Exposure dose (mSv/quarter)
1	5
2	0.5
3	0.3
4	0.4
5	0.13
6	0.15
7	0.4
8	0.6
9	0.8
10	1.4

22.20.14 Error of Measurement

The analysis of a filter sample containing radioactive sample material yields a result of 880 counts. For this empirical value, estimate the error at a confidence level of 68%.

23 Appendix B: Test your Knowledge!

1) How many nucleons does U-234 have?
   - a) 92
   - b) 146
   - c) 234
   - d) 142

2) On which subatomic particles does the electromagnetic force act?
   - a) Nucleons
   - b) Electrons
   - c) Protons and neutrons
   - d) Protons and electrons

3) The natural abundance of U-235 is
   - a) 12 400 Bq/g
   - b) 174 kBq/g
   - c) One needs to know the uranium concentration.
   - d) 0.7%

4) Complete the following sentence: Alpha decay
   - a) leads to progeny which has an atomic number of the parent minus 2
   - b) leads to progeny which has an atomic mass of the parent plus 2
   - c) leads to progeny which has an atomic mass of the parent minus 2
   - d) leads to progeny which has an atomic number of the parent plus 2

5) Gamma radiation, when compared to alpha and beta radiation, is
   - a) more ionising than alpha but less ionising than beta radiation
   - b) more ionising than alpha and more ionising than beta radiation
   - c) less ionising than alpha and more ionising than beta radiation
   - d) less ionising than alpha and less ionising than beta radiation

6) Alpha radiation, when compared to gamma and beta radiation, is
   - a) the most long-range form of all known ionising radiation
   - b) only of concern when acting directly on the outer skin
   - c) the least long-range form of ionising radiation
   - d) without any effect when inhaled in form of long-lived radioactive dust

7) Beta radiation, when compared to gamma and alpha radiation, is
   - a) the least ionising form of all known radiation
   - b) not affecting the internal organs when applied externally to the body
   - c) only of concern when inhaled and acting in the lung
   - d) the most long-range form of ionising radiation

8) You have determined that the dose rate next to an X-ray machine amounts to 1.2 µSv/h. What is the associated total exposure dose of a person spending 900 hours next to such a machine?
   - a) Approx. 1.2 µSv/a
   - b) Approx. 2.4 µSv/a
   - c) Approx. 1.1 mSv/a
   - d) Approx. 2.2 mSv/a

9) The annual exposure dose of occupationally exposed persons working in a plant where an X-ray machine is continuously in operation is approx. 1.8 mSv/a. What is the average dose rate next to the machine?
   - a) Approx. 0.2 µSv/a
   - b) Approx. 0.2 µSv/h
   - c) Approx. 0.9 µSv/a
   - d) Approx. 0.9 µSv/h

10) In an occupational setting, such as at a uranium mine, gamma radiation
    - a) is mostly of external origin and contributes significantly to the occupational exposure dose
    - b) does not have to be monitored because it is a long-range form of radiation

c) due to the natural background radiation is the most dominant contributor of occupational exposure doses
d) is always the smallest contributor to occupational exposure doses.

11) In an occupational setting, such as at a uranium mine, alpha radiation
a) can be safely ignored as there are no sources of alpha radiation
b) from long-lived radioactive dust may be a significant risk factor when such dust is inhaled
c) does not have to be monitored because it is a short-range form of radiation
d) is only contributed by radon and its decay products

12) In an occupational setting, such as at a uranium mine, radon progeny
a) is always the most significant risk factor for occupational exposures
b) can be safely ignored as radon gas is a noble gas and does not readily interact with lung tissue
c) may be a significant risk factor in poorly ventilated spaces and work areas
d) is readily mitigated by creating a dusty work environment, as radon progeny attach themselves onto the inhalable fraction of airborne dust

13) The activity of U-238 – when compared to all other decay chain members in the U-238 decay chain – is
a) the largest because U-238 has the longest half-life
b) is the lowest because its specific activity is the highest
c) is the lowest because it has the longest half-life
d) is the lowest because it is the most abundant uranium isotope in nature

14) The specific activity of uranium 238 – when compared to uranium 234 and uranium 235 – is
a) negligible because it has a half-life of 4.5 billion years
b) is the most important because it is in secular equilibrium with its decay chain members
c) is the lowest because it has the longest half-life of the 3 natural uranium isotopes
d) is 12 400 Bq/g when in secular equilibrium with its decay chain members

15) By only taking the contribution of the decay chain members of ^{238}U into account, the total activity of 1 kg of uranium-bearing ore having a uranium concentration of 450 parts per million is
a) 0.78 MBq
b) 78 kBq
c) 78 Bq
d) 0.78 Bq

16) By only taking the head-of-chain contribution of the ^{238}U decay chain into account, the total activity of 1 000 kg of uranium-bearing ore with a uranium concentration of 150 parts per million is
a) 1.86 GBq
b) 1.86 MBq
c) 1.86 kBq
d) 1.86 Bq

17) The waste rock dumps at your facility have an average uranium concentration of 70 parts per million. The specific activity of the material is
a) 0.86 kBq/kg, which is below the NRPA threshold for radiologically relevant uranium
b) 0.86 Bq/kg, which is below the NRPA threshold for radiologically relevant uranium
c) 0.86 kBq/kg, which is above the NRPA threshold for radiologically relevant uranium
d) 0.86 Bq/kg, which is above the NRPA threshold for radiologically relevant uranium

18) A given sample of natural uranium ore with a uranium concentration of 150 ppm has a total activity of 1 000 kBq (based on the complete ^{238}U decay chain). The mass of the sample, expressed in grams, is
    a) 0.057 grams
    b) 0.57 grams
    c) 5.7 grams
    d) 57 grams

19) How many grams of ^{238}U are in the same sample of 100 grams of natural uranium ore with a uranium concentration of 150 ppm:
    a) 99.3 grams
    b) 9.93 grams
    c) 0.993 grams
    d) More information is needed

20) A 100 kg sample of natural uranium ore with a uranium concentration of 400 ppm contains how many grams of ^{235}U:
    a) 0.028 grams
    b) 0.28 grams
    c) 2.8 grams
    d) 28 grams

21) A stash of concentrated uranium oxide, U_3O_8, that is found in the garage of an ex-employee of a uranium mine has a mass of 75 kg. Determine the mass of the uranium in the stash:
    a) 6.36 kg if one assumes that the product is 84.8% pure and contains 95% uranium
    b) 0.636 kg if one assumes that the product is 95% pure and contains 84.8% uranium
    c) 60.42 kg if one assumes that the product is 95% pure and contains 84.8% uranium
    d) 0.0636 kg if the product is 84.8% pure and contains 95% uranium

22) Determine the total activity of 75 kg of U_3O_8, if 84.8% of the product's content is in the form of uranium and ignoring the contribution of ^{235}U:
    a) 1.57 Bq
    b) 1.57 kBq
    c) 1.57 MBq
    d) 1.57 GBq

23) At your residence you measure a gamma dose rate of 0.9 µSv/h. The exposure dose of a person exposed to 8 760 hours per year to this gamma radiation is
    a) 78.84 µSv per hour
    b) 788.4 µSv per year
    c) 7.884 mSv per year
    d) 78.84 mSv per hour

24) The uranium concentration of ores at Rössing is about 0.035%. If you need 1 kg of ^{235}U, how many tons of uranium-bearing ore do you have to work through to extract this quantity, if you have no losses in the actual extraction process:
    a) 4.08 tons
    b) 40.8 tons
    c) 408 tons
    d) 4 080 tons

25) A drum of concentrated uranium oxide, U_3O_8, contains 375 kg of final product. Work out the total activity of the drum, if 84.8% of the drum's content is in the form of uranium at a purity of 90%:
    a) 7.1 Bq
    b) 7.1 kBq
    c) 7.1 MBq
    d) 7.1 GBq

26) The contribution of ^{235}U to the total activity of concentrated uranium oxide is
    a) the most important because it is in secular equilibrium with 11 other decay chain members
    b) the least important of the naturally occurring uranium isotopes as its abundance is low
    c) the most important because uranium 235 is the only naturally occurring element that is fissionable
    d) the least important because it is in secular equilibrium with U-238

27) The contribution of uranium 234 to the total activity of concentrated uranium oxide
   a) is important because it is in secular equilibrium with U-238
   b) is important because it is always in secular equilibrium with U-235
   c) is the least important of the three naturally occurring uranium isotopes because it has a natural abundance of only 0.005%
   d) is the least important because it only has a specific activity of 12 400 Bq/g when in secular equilibrium with U-238

28) The specific activity of calcined uranium oxide is about 10,500 Bq/g. The total activity of one drum of uranium oxide, containing some 300 kg of uranium oxide, is therefore
   a) 3 MBq
   b) 3 GBq
   c) 300 MBq
   d) 300 GBq

29) A sealed source was discovered to be leaking. The dose rate at 1m from the source is 10 µSv/h. Workers need to do work at a nearby plant, at least 4 m from the source but usually further away. What would you recommend?
   a) Dose at 4 m is 0.6 µSv/h, hence dose rate to workers is not a concern.
   b) Dose at 4 m is 2.5 µSv/h, hence dose rate to workers is a concern, need to relocate source.
   c) Leaking source is not ALARA, need to remove source immediately

30) The public dose limit is 1 mSv per annum. Hence a good approach for visitor control is
   a) not to exceed 0.5 µSv per day
   b) not to exceed 1 µSv per day
   c) record dose and report to visitor. Do not allow visitors in areas of higher rates.

31) How would you control worker exposures in an area where the dose rate is 20 µSv/h? Workers are needed in this area continuously, and your operation does not allow workers to exceed a daily dose of 80 µSv.
   a) Restrict time r to 2 hours
   b) Do not allow work in this area
   c) Restrict time to 4 hours
   d) Restrict time to 1 hour

32) You want to send tools from the processing plant for repairs in town. How would you do the clearance for the tools before they can leave the site?
   a) Measure alpha surface contamination and clear if less than 0.4 Bq/cm^2
   b) Measure beta surface contamination and clear if less than 0.4 Bq/cm^2
   c) Measure alpha and beta surface contamination and clear if less than 0.4 Bq/cm^2 for alpha and beta combined
   d) Measure alpha and beta surface contamination and clear if less than 4 Bq/cm^2 for alpha and beta combined

33) Someone measured radiation exposures in an area and took four different readings:
   10 µSv, 0.001 mSv, $2\cdot10^{-2}$ mSv, 0.0001 Sv. The average value measured is
   a) 10 µSv
   b) 33 mSv
   c) 33 µSv
   d) 257 µSv

34) Which exposure pathways are monitored personally for members of the public?
   a) External and radon
   b) External, radon, dust
   c) None as direct measurement is not possible
   d) Only those which affect the relevant critical group

35) The specific activity of U-238 is 12 400 Bq/g. Calcined uranium oxide has a specific activity of 85% of that of pure uranium. The total activity of one drum of uranium oxide, containing some 400 kg of uranium oxide, is therefore
    a) 8 MBq
    b) 8 GBq
    c) 4 MBq
    d) 4 GBq

36) Add the following numbers: $11 \cdot 10^4$, $2 \cdot 10^5$, $2 \cdot 10^1$, $20 \cdot 10^3$. The result – to the correct significant digit - is
    a) 330 000
    b) 330 020
    c) $3 \cdot 10^4$
    d) $3 \cdot 10^5$

37) Work out the following: $900 / 0.03 / 3 \cdot 0.02$
    a) $6 \cdot 10^2$
    b) $6 \cdot 10^{10}$
    c) 200
    d) 20
    e) 2

38) You have sampled three exposure groups, getting annual exposure doses in mSv

Group	**Dose (mSv/a)**	**Number of people in group**
Plant workers	6	10
Field workers	2	40
Office workers	1.2	100

The average exposure for the operation is, in mSv per annum,
    a) 2.3
    b) 3.1
    c) 2
    d) 1.7

39) A box of uranium-bearing ore samples needs to be sent to a lab in South Africa. The ore grade is 500 ppm, the ore was not and will not be processed, and the weight of the box is 5 kg. What do you do?
    a) Ore is not radioactive – send with a courier, no labelling needed
    b) Ore is exempt for transport but radioactive. Need export permit but not transport permit. Label UN 2910 and class 7 sticker
    c) Ore is exempt for transport but radioactive. Need export permit but not transport permit. Label UN 2910 but not class 7 sticker
    d) Ore is radioactive – need transport and export permit. Label UN 2912 and class 7

40) A box of leaching samples from your processing plant needs to be sent to a lab in Swakopmund. The average ore grade is 100 ppm, and the weight of the box is 5 kg. What would you recommend?
    a) Ore is radioactive - needs transport and export permit. Label UN2912 and class 7
    b) Ore is radioactive, but not for transport. Label UN2910, without class 7, no transport permit
    c) Ore is radioactive – needs transport permit. Label UN2912 and class 7
    d) Ore is not radioactive – send by car, no labelling, no permit required

41) The dose rate 1 m from a spherical sealed source is 40 µSv/h. How far do I have to move workers from the source so that the maximum exposure rate is 1 µSv/h?
    a) 6 m
    b) 40 m
    c) 2 m
    d) 4 m

42) The half-value layer for shielding Co-60 for lead is 12 mm. What thickness of lead is needed to reduce radiation from a Co-60 source to 3.1?
    a) 5 mm
    b) 60 mm
    c) 72 mm
    d) 600 mm

43) Calculate the effective half-life for a radionuclide in the body. If its biological half-life is 10 days, and the radiological half-life is 100 days.
    a) 100 days
    b) 10 days
    c) 9 days
    d) 110 days
    e) 5 days

44) Determine the effective half-life for U-238 in the human body if the radiological half-life is 4.5 billion years, while the biological half-life is approx. 6 days.
    a) 4.5 billion years
    b) 6 days
    c) 4.5 billion years *plus* 6 days
    d) 4.5 million years *minus* 6 days

45) The transport index (TI) for a container (20-foot) containing uranium drums needs to be determined. The following readings were taken: dose rate at 1 m from long side is 10 µSv/h, at 1m from container door is 5 µSv/h, on contact (long side) is 30 µSv/h, on contact of one drum is 40 µSv/h, and at 1 m from one drum is 0.5 µSv/h. The TI is
    a) 0.5
    b) 3
    c) 6
    d) 1

46) Your tailings area is also your contaminated waste site. Contaminated waste is covered with sand every day. Which of the following applies?
    a) On closure, the area is to be fenced for 10 years to ensure people do not dig up contaminated scrap.
    b) On closure, the area must be covered with sufficient material to ensure that digging up scrap is unviable.
    c) Upon closure, the area needs to be covered with sufficient material to ensure digging up scrap is unviable, and to ensure that the public dose from dust and radon to all groups is less than 1 mSv per year.
    d) Upon closure, the contaminated waste will have decayed sufficiently.

47) Work out the maximum activity of a lump of ore from Canada, with an ore grade of 40% and a weight of 2 kg. You may assume full secular equilibrium, and that the specific activity of U-238 is 12 400 Bq/g. Do not include the activity of U-235 and its decay products.
    a) About 14 MBq
    b) About 9 MBq
    c) About 140 GBq
    d) About 140 MBq

48) The transport of radioactive substances is
    a) undertaken in accordance with the provisions of the International Atomic Energy Agency (IAEA) if the source activity exceeds 1 Bq
    b) undertaken in accordance with the provisions of the International Atomic Energy Agency (IAEA) if the activity and specific activity of the source material exceeds relevant exemption thresholds
    c) undertaken in accordance with the provision of the International Atomic Energy Agency (IAEA) if a commercial transport entity is contracted for the conveyance of such materials
    d) undertaken in accordance with the provisions of the International Atomic Energy Agency (IAEA) if source material is moved across the borders of the state.

49) The concentration of uranium dust in an area is found to be 1 Bq/m^3. The dose conversion coefficient for pure uranium dust is 0.006 mSv/Bq. Assuming a working year of 2 000 hours and the standard breathing rate (1.2 m^3/h) for workers, calculate the annual dose from this concentration.

50) The ore grade of your mine is 300 ppm, and the extraction efficiency of your plant is 80%. What would you estimate the activity of your tailings to be?
    - a) 46 Bq/g
    - b) 52 Bq/g
    - c) 5 Bq/g
    - d) 46 Bq/g

24 Appendix C: List of Figures

25 Appendix D: List of Tables

26 Appendix E: List of Boxes

27 Acronyms and Abbreviations

Å	Ångstrom, i.e. 10^{-10} m
a	annum (year), i.e. 8 760 hours
/a	per annum (per year)
ALARA	as low as reasonably achievable
AMAD	activity median aerodynamic diameter
Bq	Becquerel, decays per second
Bq/cm^2	Bq per square centimetre
Bq/L	Bq per litre
Bq/m^3	Bq per cubic metre
BWR	boiling water reactor
cm	centimetre
cm^3	cubic centimetre, i.e. 10^{-6} m^3
DCF	dose conversion factor
DNA	deoxyribonucleic acid (hereditary material)
EPD	electronic personal dosimeter
eV	electron volt, $1.6 \cdot 10^{-19}$ Joule
EW	exempt waste
fm	Fermi, femtometre, 10^{-15} metres
FPR	Final Product Recovery
g/L	grams per litre
g/t	grams per ton
GBq	Giga-Becquerel, i.e. 10^9 Bq
GHz	Giga-Hertz, i.e. 10^9 Hz
Gy	Gray, unit for absorbed dose
h	hour
HLW	high-level waste
Hz	Hertz, oscillations per second
IAEA	International Atomic Energy Agency
ICRP	International Commission for Radiological Protection
ILW	intermediate level waste
J	Joule, energy unit
kHz	kilo-Hertz, i.e. 10^3 Hz
km	kilometre, 10^3 m
L, l	litre, i.e. 1 000 cm^3
LLRD	long-lived radioactive dust
LLW	low-level waste
LSA	low specific activity material
ly	lightyear, i.e. $9.4 \cdot 10^{15}$ m
M	mega, one million, 10^6
m	metre
m^3	cubic metre, i.e. 1 000 litres, or 10^6 cm^3
MeV	mega-electron Volt, i.e. 10^6 eV
mg/m^3	milligram per cubic metre
mGy	Milli-Gray, i.e. 10^{-3} Gy
MHz	mega-Hertz, i.e. 10^6 Hz
micron	micro-metre, i.e. 10^{-6} m

min	minute, i.e. 1/60th hour
ml	millilitre, i.e. 10^{-3} litre
MME	Ministry of Mines and Energy
MoHSS	Ministry of Health and Social Services
MSDS	Material Safety Data Sheet
mSv	milli-Sievert, i.e. 10^{-3} Sv
mSv/a	milli-Sievert per annum
MyRIAM	'My Radioactivity in Air Monitor', by SARAD
nm	nanometre, i.e. 10^{-9} m
ns	nanosecond, 10^{-9} s
NORM	naturally occurring radioactive material
NRPA	National Radiation Protection Authority
OEL	occupational exposure level
pCi/L	pico-Curie per litre, 10^{-15} Ci/L
PM10, PM$_{10}$	particulate matter < 10 µm in diameter
PM2.5, PM$_{2.5}$	particulate matter < 2.5 µm in diameter
PPE	personal protective equipment
ppm	parts per million
rad	unit for absorbed dose
rem	unit for equivalent and effective dose
RL	radiation level
RMP	Radiation Management Plan
RSO	Radiation Safety Officer
RSOs	Radiation Safety Officers
s	second
SA	specific activity
SCO	surface contaminated object
SEG	similar exposure group
SSR-6	IAEA Transport Regulations, refer to reference [96]
Sv	Sievert, Joule per kilogram of absorbing tissue
t	metric ton, i.e. 1 000 kg
TBq	tera-Becquerel, i.e. 10^{12} Bq
THz	tera-Hertz, i.e. 10^{12} Hz
TI	transport index
TLD	thermo-luminescent dosimeter
TSF	tailings storage facility
UOC	uranium oxide concentrate
VSLW	very short-lived waste
WHO	World Health Organisation
XRF	X-ray fluorescence
µg/L	micrograms per litre
µm	micrometres, i.e. 10^{-6} m
µSv	micro-Sievert, i.e. 10^{-6} Sv
µSv/a	micro-Sievert per annum
µSv/h	micro-Sievert per hour

28 References

[1] IAEA 2014, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, General Safety Requirements Part 3, No. GSR Part 3, Vienna 2014, http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1578_web-57265295.pdf

[2] Atomic Energy and Radiation Protection Act, 2005 (Act No. 5 of 2005), http://aebofnamibia.org/wp-content/uploads/pdf/2016/act.pdf

[3] Radiation Protection and Waste Disposal Regulations: Atomic Energy and Radiation Protection Act, 2005 (Act No. 5 of 2005), No. 211 of 2011, http://aebofnamibia.org/wp-content/uploads/pdf/2016/regulations.pdf

[4] IAEA Safety Glossary 2016, Terminology used in Nuclear Safety and Radiation Protection, 2016 Revision, Vienna, https://www-ns.iaea.org/downloads/standards/glossary/iaea-safety-glossary-draft-2016.pdf

[5] IAEA Safety Glossary 2007, Terminology Used in Nuclear Safety and Radiation Protection (2007 Edition), Vienna, http://www-ns.iaea.org/standards/safety-glossary.asp

[6] Properties of water, https://jungeuncho.weebly.com/water-properties.html

[7] Wikimedia Commons, https://commons.wikimedia.org/wiki/File:A-DNA,_B-DNA_and_Z-DNA.png

[8] VO Consulting, www.voconsulting.net

[9] Brilliant, https://brilliant.org/wiki/atomic-orbitals/

[10] Wikipedia, https://en.wikipedia.org/wiki/Transuranium_element

[11] Curve of binding energy, http://hyperphysics.phy-astr.gsu.edu and https://www.nuclear-power.net/nuclear-power/reactor-physics/atomic-nuclear-physics/binding-energy/nuclear-binding-curve/

[12] Nuclear stability curve, image credit John Wiley & Sons, 1996, http://slideplayer.com/slide/10298749/

[13] Wikipedia, https://en.wikipedia.org/wiki/Wilhelm_R%C3%B6ntgen

[14] Wikipedia, https://en.wikipedia.org/wiki/Henri_Becquerel

[15] Wikipedia, https://en.wikipedia.org/wiki/Marie_Curie

[16] ExplainThatStuff, http://www.explainthatstuff.com/electromagnetic-spectrum.html

[17] World Health Organization, http://www.who.int/mediacentre/factsheets/fs193/en/

[18] Emblem by Rolf Scheffer, for VO Consulting, www.voconsulting.net

[19] Tuli JK, Nuclear Wallet Cards, 8th Edition, October 2011, National Nuclear Data Center, Brookhaven National Laboratory, United States of America, http://rehs.rutgers.edu/pdf_files/RU-ORSS-Nuclear%20Wallet%20Cards%208th%20Edition.pdf

[20] Von Oertzen G, 2015, Using Alpha Recoil as a Tool for Contamination Control in the Khan River Aquifer, Rössing Uranium Limited, http://www.rossing.com/files/reports-research/Report%20technical%20-%20Using%20Alpha%20Recoil%20as%20a%20Tool%20for%20Contamination%20Control%20in%20the%20Khan%20River%20Aquifer%202015.pdf

[21] United States Department of Energy, Office of Environmental Management, http://web.archive.org/web/20050829231403/http:/web.em.doe.gov/takstock/phochp3a.html

[22] Wikimedia Commons, https://commons.wikimedia.org/w/index.php?curid=10476288

[23] Wikipedia, https://en.wikipedia.org/wiki/Boiling_water_reactor

[24] Picture by https://www.eco27.co.za/wp-content/uploads/2016/08/Eskom.jpg

[25] Sime R, 1997, *Lise Meitner: A Life in Physics*, University of California Press

[26] Photo by André Terblanche, courtesy of Rössing Uranium Limited, www.rossing.com

[27] Woods P, Seminar on Governance of Uranium Production Activities, Background to Mining and Concentrating Uranium Ore, Copenhagen, Denmark, 27-28 May 2014, Slide 22 showing calcined U_3O_8 (courtesy of Cameco), http://slideplayer.com/slide/6155227/

[28] Uranium Chem110 blog, 2016, https://rampages.us/chem110spring2016ss/

[29] Paladin Energy, http://www.paladinenergy.com.au

[30] Photo courtesy of Klaus-Peter Knupp, www.earthmapsconsulting.com

[31] Photo courtesy of Swakop Uranium, www.swakopuranium.com

[32] Photo courtesy of Bannerman Resources Namibia, www.bannermanresources.com.au

[33] Ministry of Mines and Energy, 2010, Strategic Environmental Assessment for the Central Namib Uranium Rush. Southern African Institute for Environmental Assessment, Namibia, http://www.the-eis.com/data/literature/Strategic%20Environmental%20Assessment%20for%20the%20central%20Namib%20Uranium%20Rush_Final_Merged.pdf

[34] Rössing Uranium Limited, www.rossing.com

[35] World Nuclear Association, http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/namibia.aspx

[36] Chamber of Mines of Namibia, http://chamberofmines.org.na/index.php/home-menu/

[37] Namibian Uranium Association, http://www.namibianuranium.org/

[38] Wikipedia, https://en.wikipedia.org/wiki/Ionizing_radiation

[39] Bianconi E et al, An estimation of the number of cells in the human body, Annals of Human Biology, 40 (6), 2013, https://www.ncbi.nlm.nih.gov/pubmed/23829164

[40] Reactor Concepts Manual, Biological Effects of Radiation, USNRC Technical Training Center, https://www.nrc.gov/reading-rm/basic-ref/students/for-educators/09.pdf

[41] ICRP, 2005, Low-dose Extrapolation of Radiation-related Cancer Risk, ICRP Publication 99, Ann. ICRP 35 (4), 2005, http://www.icrp.org/publication.asp?id=ICRP%20Publication%2099

[42] Wikipedia, https://en.wikipedia.org/wiki/Radiation_burn

[43] http://www.baeyesite.com/why-eye-exams-matter/cataract-awareness/

[44] http://www.bbc.com/news/health-29014838

[45] ICRP, 2007, The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2-4), http://www.icrp.org/publication.asp?id=ICRP%20Publication%20103

[46] ICRP, 2000, Pregnancy and medical radiation, ICRP Publication 84, Ann. ICRP 30 (1), http://www.icrp.org/publication.asp?id=icrp%20publication%2084

[47] UNSCEAR, 2006, United Nations Scientific Committee on the effects of atomic radiation 2006 report to the General Assembly. Sources and effects of ionizing radiation. Volume II. Annex E: sources-to-effects assessment for radon in homes and workplaces. New York: United Nations, http://www.unscear.org/docs/reports/2006/07-82087_Report_2006_Web.pdf

[48] UNSCEAR, 2016, United Nations Scientific Committee on the effects of atomic radiation 2016 report to the General Assembly. Sources, Effects and Risks of Ionizing Radiation. New York: United Nations, 2016, http://www.unscear.org/unscear/en/publications/2016.html

[49] Biological Effects of Exposure to Ionizing Radiation: Health Effects of Exposure to Radon: BEIR VI, National Academy Press, Washington. 1999, an executive summary can be viewed at http://fixradon.com/wp-content/uploads/2016/08/BIERVIExecutiveSummary.pdf

[50] Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII – Phase 2, NATIONAL ACADEMY PRESS, Washington, 2006, http://www.philrutherford.com/Radiation_Risk/BEIR/BEIR_VII.pdf

[51] ICRP, 1993, Protection Against Radon-222 at Home and at Work, ICRP Publication 65, Ann. ICRP 23 (2), http://radon-and-life.narod.ru/pub/ICRP_65.pdf

[52] Natural Exposure to Gamma Rays in Background Radiation Linked to Childhood Leukaemia, ScienceDaily June 18, 2012, https://www.sciencedaily.com/releases/2012/06/120618150045.htm

[53] Kendall GM, Little MP, Wakeford R, Bunch KJ, Miles JC, Vincent TJ, Meara JR, Murphy MF, A record-based case-control study of natural background radiation and the incidence of childhood leukaemia and other cancers in Great Britain during 1980-2006, Leukaemia. 2013 Jan;27(1):3-9. doi: 10.1038/leu.2012.151, https://www.ncbi.nlm.nih.gov/pubmed/22766784

[54] Kojo K, Occupational cosmic radiation exposure and cancer in airline cabin crew, STUK-A257/March 2013, http://www.julkari.fi/bitstream/handle/10024/124951/stuk-a257.pdf;sequence=1

[55] Strahlentelex Nr 362-363/2002, http://www.strahlentelex.homepage.t-online.de/Stx_02_362_S02-03.pdf

[56] Strahlentelex Nr 382-383/2002, http://www.strahlentelex.de/Stx_02_382_S08.pdf

[57] Strahlentelex Nr 490-491/2007, http://www.strahlentelex.de/Stx_07_490_S06-08.pdf

[58] Strahlentelex Nr 494-495/2007, http://www.strahlentelex.de/Stx_07_494_S01-07.pdf

[59] Grosche B, Kreuzer M, Kreisheimer M, Schnelzer M & Tschense A, 2006, Ling cancer risk among German male uranium miners: a cohort study, 1946-1998, British Journal of Cancer 95, 1280-1287, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2360564/

[60] Strahlentelex 506-507/2008, http://www.strahlentelex.de/Stx_08_506_S07-08.pdf

[61] Eigenwillig GG, Fehlerhafte Ermittlung und Zuordnung von Expositionswerten an der WISMUT in den Jahren 1946 bis 1976, Zbl Arbeitsmed 57 (2007), 375-390, https://link.springer.com/article/10.1007/BF03349139

[62] Strahlentelex 582-583/2011, http://www.strahlentelex.de/Stx_11_582_S01-02.pdf

[63] Wismut und die Folgen des Uranbergbaus: Tagung der Friedrich-Ebert-Stiftung, 19. Juni 1992, Gera, Verfasser des Tagungsberichts: Joachim Kahlert, Bonn, 1992, Electronic Edition: Bonn, FES Library, 2001, http://library.fes.de/fulltext/fo-wirtschaft/00311toc.htm

[64] Brugge D, Buchner V, Health effects of uranium: new research findings, Rev Environ Health 2001; 26(4): 231-249, https://www.ncbi.nlm.nih.gov/pubmed/22435323

[65] Vacquier B, Caer S, Rogel A, Fuerprier M, Tirmarche M, et al, Mortality risk in the French cohort of uranium miners: extended follow-up 1946-1999, Occup Environ Med 2008; 65:597-604

[66] Tomasek L, Rogel A, Tirmarche M, Mitton N, Laurier D, Lung cancer in French and Czech uranium miners: radon-associated risk at low exposure rates and modifying effects of time since exposure and age at exposure, Occup Environ Med 2008; 65:597-604

[67] Schubauer-Berigan MK, Daniels RD, Pinkerton LE, Radon exposure and mortality among white and American Indian uranium miners: an update of the Colorado Plateau cohort, Am J Epidemiol 2009; 15: 718-30

[68] Boice JD Jr, Mumma M, Schweitzer S, Blot WJ, Cancer mortality in a Texas county with prior uranium mining and milling activities, 1950-2001, J Radiol Prot 2003; 23: 247-62

[69] Boice JD Jr, Mumma M, Blot WJ, Cancer and noncancer mortality in populations living near uranium and vanadium mining and milling operations in Montrose County, Colorado, 1950-2000, Radiat Res 2007; 167: 711-26

[70] Boice JD Jr, Cohen SS, Mumma M, Chadda B, Blot WJ, Mortality among residents of Uravan, Colorado who lived near a uranium mill, 1936-86, Radiol Prot 2007; 27:299-319

[71] Boice JD Jr, Mumma Magado T, Blot WJ, Cancer incidence and mortality in populations living near uranium mining and milling operations in Grants, New Mexico, 1950-2004, Radiat Res 2010; 174: 624-36

[72] Shuey C, Uranium legacy impacts on health in Eastern Navajo Agency, Dineh Network for Environmental Health, Sep 2010

[73] Lewis J, Uranium legacy: impacts in health of residents, Dineh project update, Sep 2010.

[74] Canu IG, Jacob S, Cardis E, Wild P et al., Reprocessed uranium exposure and lung cancer risk. Health Phys 2010;99:308 – 13.

[75] Craft ES, Abu Quare A, Flaherty MM, Garofolo MC, Rincavage HL, et al. Depleted and natural uranium: chemistry and toxicological effects. J Toxicol Environ Health Part B 2004; 7: 297 – 317.

[76] Tatz C, Cass A, Condon J, Tippett G, Aborigines and uranium: monitoring the health hazards. AIATSIS Research Discussion Paper Number 20, 2006, http://www.aiatsis. gov.au/research/discussion.html

[77] Brugge D and Buchner V, Health effects of uranium: new research findings, Rev Environ Health 2011;26(4):231–249, https://www.degruyter.com/view/j/reveh.2011.26.issue-4/reveh.2011.032/reveh.2011.032.xml

[78] World Health Organisation, www.who.int/ionizing_radiation/pub_meet/en/Depluranium4.pdf

[79] Canu IG, Ellis ED, Tirmarche M, Cancer risk in nuclear workers occupationally exposed to uranium – emphasis on internal exposure, Health Physics 94(1):1-7, 2008, https://www.ncbi.nlm.nih.gov/pubmed/18091147

[80] Zablotska LB, Lane RS, Frost SE, Mortality (1950-1999) and cancer incidence (1969-1999) of workers in the Port Hope cohort study exposed to a unique combination of radium, uranium and γ-ray doses, BMJ Open 2013; 3, https://www.ncbi.nlm.nih.gov/pubmed/23449746

[81] Lane RS, Frost SE, Howe GR, Zablotska LB, Mortality (1950-1999) and cancer incidence (1969-1999) in the cohort of Eldorado uranium workers, Radiat Res 2010; 174:773-85, https://www.ncbi.nlm.nih.gov/pubmed/21128801

[82] Vacquire B, Caer S, Rogel, A, Feurprier M, Tirmarche M, Luccioni C, Quesne B, Acker A, Laurier D, Mortality risk in the French cohort of uranium miners: extended follow-up 1946-1999

[83] Kreuzer M, Walsh L, Schnelzer M, Tschense A, Grosche B, Radon and risk of extrapulmonary cancers: results of the German uranium miners' cohort study, 1960-2003, British Journal of Cancer (2008) 99, 1946-1953, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2600695/

[84] Pinkerton LE, Bloom TF, Ward EM, Mortality among a cohort of uranium mill workers: an update, https://www.ncbi.nlm.nih.gov/pubmed/14691274

[85] Hnizdo E, Loss of lung function associated with exposure to silica dust and with smoking and its relation to disability and mortality in South African gold miners, British Journal of Industrial Medicine 1992; 49, 472-479, https://www.ncbi.nlm.nih.gov/pubmed/1322158

[86] Suppan H.D. 2016, Marking Time: The Radium Girls of Ottawa, Outskirts Press

[87] Wikipedia, https://commons.wikimedia.org/wiki/File:International_policy_system_radiological_protection.png

[88] Von Oertzen G and von Oertzen D, 2011, Guide to Radiation in Namibia's Uranium Mining and Exploration Sectors, Chamber of Mines Uranium Institute, Namibia, https://www.voconsulting.net/pdf/radiation/Guide%20to%20Radiation.pdf

[89] Von Oertzen G and von Oertzen D, 2012, Questions Answered About Uranium and Radiation, Chamber of Mines Uranium Institute, Namibia, https://www.voconsulting.net/pdf/radiation/Questions%20Answered.pdf

[90] Namibia Uranium Institute, http://namibiauraniuminstitute.com

[91] Rio Tinto, www.riotinto.com

[92] Renn O, and Rohrmann B, 2000, Cross-cultural risk perception. A survey of empirical studies, Kluwer Academic Publishers, Dordrecht/Boston/London, http://www.springer.com/gp/book/9780792377474

[93] Pope, Alexander, An Essay on Criticism, 1709, https://www.poetryfoundation.org/articles/69379/an-essay-on-criticism

[94] Atomic Energy Board of Namibia, http://aebofnamibia.org/regulatory-requirements-guides/

[95] Atomic Energy Board of Namibia, 2011, Advisory material to license holders relating to the appropriateness and competency of a person who is appointed as a radiation safety officer issued pursuant to sections 8(c) and 30(1) of the Atomic Energy and Radiation Protection Act, Act no 5 of 2005, http://aebofnamibia.org/national-radiation-protection-authority/

[96] IAEA, 2012, Regulations for the Safe Transport of Radioactive Material, 2012 Edition, Specific Safety Requirements No. SSR-6, Vienna, http://www-pub.iaea.org/books/IAEABooks/8851/Regulations-for-the-Safe-Transport-of-Radioactive-Material-2012-Edition

[97] IAEA, 2014, Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2012 Edition), Safety Guide No. SSG-26, Vienna, http://www-pub.iaea.org/books/IAEABooks/8952/Advisory-Material-for-the-IAEA-Regulations-for-the-Safe-Transport-of-Radioactive-Material-2012-Edition

[98] Wikipedia, https://en.wikipedia.org/wiki/Paracelsus

[99] National Research Council, 2006, Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation. Health risks from low levels of ionizing radiation: BEIR VII, Phase 2. Washington, DC: The National Academies Press,

https://www.nap.edu/catalog/11340/health-risks-from-exposure-to-low-levels-of-ionizing-radiation

[100] Munich A, A brief history of the X-ray, http://adammunich.com/a-brief-history-of-the-x-ray/

[101] UNSCEAR, 2000, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly. Vol. 1: Sources and effects of ionizing radiation, http://www.unscear.org/docs/publications/2000/UNSCEAR_2000_Report_Vol.I.pdf

[102] Symmetry Magazine, http://www.symmetrymagazine.org/article/november-2014/auger-reveals-subtlety-in-cosmic-rays

[103] National Centres for Environmental Information, Data provided by National Geophysical Data Centre are for June 2006, www.ngdc.noaa.gov

[104] Wackerle R, Cosmic Radiation Map of Namibia, Geointrepid Consulting Services Namibia, October 2009

[105] Brodsky A, 1978, CRC Handbook of Radiation Measurement and Protection, CRC Press, https://catalog.hathitrust.org/Record/000266874

[106] Eisenbud M and Gesell T, 1997, Environmental Radioactivity from Natural, Industrial and Military Sources, Academic Press, Inc, https://www.elsevier.com/books/environmental-radioactivity-from-natural-industrial-and-military-sources/eisenbud/978-0-12-235154-9

[107] World Health Organisation, Fact Sheet No. 313, *Ambient (outdoor) air quality and health*, www.who.int/mediacentre/factsheets

[108] World Health Organisation, 2010, *WHO guidelines for indoor air quality: selected pollutants,* *http://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf*

[109] South African Weather and Disaster Information Service, http://saweatherobserver.blogspot.com/2010/06/oosweer-takel-namibiese-kus.html

[110] http://www.bfs.de/SharedDocs/Bilder/BfS/DE/bfs/forschung/ion-wismut-1.jpg;jsessionid=C67EBBE6CC45579651AB6C332EB929B9.1_cid349?__blob=poster&v=3

[111] Ludwig P and Lorenser E, 1924, Untersuchung der Grubenluft in der Schneeberger Gruben auf den Gehalt an Radiumemanation, Zeitschrift für Physik 22 178 (1924)

[112] National Resources Canada, www.nrcan.gc.ca

[113] Northwest Radiography, http://nwrad.com/imagery/panoramic/

[114] Chest X-ray, http://www.chestx-ray.com/index.php/education/normal-cxr-module-train-your-eye#!1

[115] Radiopaedia, Case courtesy of A. Prof Frank Gaillard, Radiopaedia.org, rID: 2715, https://radiopaedia.org/cases/pelvic-x-ray-normal-different-ages-1

[116] RadiologyInfo.org, https://www.radiologyinfo.org/

[117] Radiopaedia, https://images.radiopaedia.org/images/4170261/c5d7c3ed6c7fe53e59c2dd902e44b9_big_gallery.jpg

[118] ANZSVS, http://www.anzsvs.org.au/patient-information/angiograms-and-angioplasty/

[119] National Cancer Institute (US), https://imaging.cancer.gov/imaging_basics/cancer_imaging/nuclear_imaging.htm

[120] National Council on Radiation Protection and Measurements, 1987, Report No. 095 - Radiation Exposure of the U.S. Population from Consumer Products and Miscellaneous Sources (Supersedes NCRP Report No. 56) (1987), https://www.ncrppublications.org/Reports/095

[121] Godwin WS, Subha VR and Feroz KM, 2010, Po-210 radiation dose due to cigarette smoking, Current Science, Vol. 98, NO. 5, 10 March 2010, http://environmentportal.in/files/smoking.pdf

[122] Rössing Uranium, 2016, Report to Stakeholders 2015, Namibia, http://www.rossing.com/files/Rossing%20Uranium%20Report%20to%20stakeholders%202015.pdf

[123] Quarkology.com, http://www.quarkology.com/11-physics/82-world-communicates/82D-em-waves.html

[124] NDT Resource Center, https://www.nde-ed.org/EducationResources/CommunityCollege/Radiography/Physics/HalfValueLayer.htm

[125] IAEA, 2004, Occupational Radiation Protection in the Mining and Processing of Raw Materials, IAEA Safety Guide No. RS-G-1.6, Vienna, https://www-pub.iaea.org/MTCD/publications/PDF/Pub1183_web.pdf

[126] Lane SD et al, 2010, Mortality (1950–1999) and Cancer Incidence (1969–1999) in the Cohort of Eldorado Uranium Workers, Radiation Research 174, 773–785, http://www.rrjournal.org/doi/full/10.1667/RR2237.1?code=rrs-site

[127] Von Oertzen G and Schneeweiss R, 2013, Baseline and Mining-related Radon Concentrations in the Rössing Mining Area, Rössing Uranium, http://www.rossing.com/files/reports-research/Report%20-%20Baseline%20and%20Mining-related%20Radon%20Concentrations%20in%20the%20Rossing%20Mining%20Area.pdf

[128] Wikipedia, https://en.wikipedia.org/wiki/Health_effects_of_radon

[129] ICRP, 2012, Lung cancer risk from radon and radon progeny and statement on radon, ICRP Publication 115, Ann. ICRP 40(1), http://www.icrp.org/publication.asp?id=ICRP%20Publication%20115

[130] ICRP, 2012, Occupational Intakes of Radionuclides, Draft report for consultation, Part 3 (consultation period now closed), http://www.icrp.org/page.asp?id=169

[131] ICRP, 1994, Human Respiratory Tract Model for Radiological Protection. ICRP Publication 66. Ann. ICRP 24 (1-3), http://www.icrp.org/publication.asp?id=icrp%20publication%2066

[132] ICRP, 1979, Limits for Intakes of Radionuclides by Workers: Part 1, Publication 30, Pergamon Press, Oxford and New York, http://www.icrp.org/publication.asp?id=ICRP%20Publication%2030%20(Part%201)

[133] European Nuclear Society,

http://www.euronuclear.org/info/encyclopedia/h/half-life-effective.htm

[134] IAEA, 2004, Methods for assessing occupational radiation doses due to uptakes of radionuclides, IAEA Safety Reports Series No 37, Vienna,

https://www-pub.iaea.org/MTCD/publications/PDF/Pub1190/Pub1190_web.pdf

[135] Wikipedia, https://en.wikipedia.org/wiki/Scintillation_counter

[136] Borehole Wireline, http://borehole-wireline.com.au/2017/03/spectral-gamma-logging-overview/

[137] ALGADE, http://www.algade.com/

[138] Sensidyne, http://www.sensidyne.com/air-sampling-equipment/gilian-air-sampling-pumps/gilair-plus/

[139] United States of America, Office of Environmental Management, https://content.govdelivery.com/accounts/USDOEOEM/bulletins/1a572fc

[140] See for example https://www.thermofisher.com/na/en/home/industrial/spectroscopy-elemental-isotope-analysis/portable-analysis-material-id/portable-xrf-analyzer-selection-guide.html

[141] See for example https://www.thermofisher.com/na/en/home/industrial/spectroscopy-elemental-isotope-analysis/oes-xrd-xrf-analysis/x-ray-fluorescence-xrf.html

[142] See for example http://www.ndttester.com/

[143] See for example https://cehs.mit.edu/core-facilities/bioanalytical-facilities-core/major-equipment

[144] See for example http://www.p-n-f.com/en/products/analytical-scientific-instrument/molecular-spectroscopy/ultraviolet-visible-spectroscopy-uv-vis/

[145] ICRP, 1985, Principles of Monitoring for the Radiation Protection of the Population, ICRP Publication 43 (1985), http://www.icrp.org/publication.asp?id=ICRP%20Publication%2043

[146] ICRP, 2007, Assessing Dose of the Representative Person for the Purpose of Radiation Protection of the Public and The Optimization of Radiological Protection: Broadening the Process, ICRP Publication 101 (2007), http://www.icrp.org/publication.asp?id=ICRP%20Publication%20101a

[147] Von Oertzen G, Rössing Uranium Limited, 2016, Report on the Implementation of the Radiation Management Plan to the NRPA, www.rossing.com

[148] Kringel R, Wagner F and Klinge H, 2010, Groundwater quality assessment in the Khan- and Swakop-River catchment with respect to geogenic background concentrations of dissolved uranium, Bundesanstalt für Geowissensschaften und Rohstoffe, Hannover, https://www.bgr.bund.de/EN/Themen/Wasser/Projekte/abgeschlossen/TZ/Namibia/nausea_fb_en_pdf.pdf?__blob=publicationFile&v=1

[149] Von Oertzen G, Rössing Uranium Limited, 2015, Report on the Implementation of the Radiation Management Plan to the NRPA, www.rossing.com

[150] Martin JMR, Department of Technical Cooperation, International Atomic Energy Agency, 2015, https://www.iaea.org/technicalcooperation/Mulitmedia/Photo-Essays/BOTSWANA.html

[151] https://marshield.com

[152] IAEA, 1998, Agreement Between the Republic of Namibia and the International Atomic Energy Agency for the Application of Safeguards in connection with the Treaty on the Non-Proliferation of Nuclear Weapons, https://www.iaea.org/sites/default/files/publications/documents/infcircs/1998/infcirc551.pdf

[153] Protocol Additional to the Agreement between the Republic of Namibia and the International Atomic Energy Agency for the Application of Safeguards in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons, https://www.iaea.org/sites/default/files/publications/documents/infcircs/1998/infcirc551a1.pdf

[154] IAEA, Republic of Namibia country page, https://ola.iaea.org/ola/FactSheets/CountryDetails.asp?country=NA

[155] Pelindaba Treaty, http://www.nti.org/media/pdfs/aptanwfz.pdf?_=1316624116

[156] Nuclear Threat Initiative, http://www.nti.org/learn/treaties-and-regimes/african-nuclear-weapon-free-zone-anwfz-treaty-pelindaba-treaty/

[157] IAEA Safety Standards, Categorization of Radioactive Sources, Safety Guide, No. RS-G-1.9, International Atomic Energy Agency, Vienna, 2005, https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1227_web.pdf

[158] Levi M, On Nuclear Terrorism, Viva Books, 2010

[159] Mueller J, Atomic Obsession – Nuclear Alarmism from Hiroshima to Al-Qaeda, Oxford University Press, 2010

[160] Ackerman G and Halverson J, War on the Rocks, Not Secure Enough: The Threat of Terrorists Acquiring Nuclear Materials Is Still Serious, https://warontherocks.com/2016/04/not-secure-enough-the-threat-of-terrorists-acquiring-nuclear-materials-is-still-serious/

[161] Mowatt-Larssen R, Al Qaeda WMD Threat: Hype or Reality?, Belfer Center for Science and International Affairs, Harvard Kennedy School, Cambridge, USA, January 2010, http://belfercenter.ksg.harvard.edu/files/al-qaeda-wmd-threat.pdf

[162] Ferguson CD, Kazi T and Perera J, Commercial Radioactive Sources: Surveying the Security Risks. Occasional Paper No 11, Centre for Non-Proliferation Studies, Monterey Institute of International Studies, 2003, http://hps.org/documents/MontereyReport.pdf

[163] United Nations Economic Commission for Europe (UNECE), United Nations Recommendations on the Transport of Dangerous Goods - Model Regulations, http://www.unece.org/trans/danger/publi/unrec/rev13/13nature_e.html

[164] United Nations Economic Commission for Europe (UNECE), 2017. Recommendations on the Transport of Dangerous Goods – Model Regulations, Revision 20, June 2017, http://www.unece.org/index.php?id=46066

[165] United Nations, 2015, UN Recommendations on the Transport of Dangerous Goods - Model Regulations (Rev. 19), https://www.unece.org/trans/danger/publi/unrec/rev19/19files_e.html

[166] US Compliance Centre, https://www.thecompliancecenter.com/labels/ship_handling/quantity.htm

[167] IAEA, 2004, Application of the Concepts of Exclusion, Exemption and Clearance, IAEA Safety Standards Series No. RS-G-1.7, Vienna, https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1202_web.pdf

[168] Low-level Radioactive Waste Test Site at Nevada, United States of America, http://nuclear.energy-business-review.com/news/major-types-nuclear-waste-that-produce-radioactivity-6027468, courtesy Federal Government of the United States of America and Wikipedia

[169] YouTube video, refer to www.youtube.com/watch?v=0fKBhvDjuy0

[170] Photo courtesy of Dr Gabi Schneider, Namibian Uranium Institute

29 Index

30 The Authors

Dr Gunhild von Oertzen is a radiation safety professional at Rio Tinto Rössing Uranium Limited, where she is the Principal Advisor: Radiation Safety and Product Stewardship, and overall responsible for radiation protection and the company's radiation safety program.

Born in Swakopmund in 1963, Gunhild holds a PhD in nuclear physics from the University of Cape Town.

In her 30+ years career, she worked as a lecturer in physics and radiation physics at the University of Pretoria and the University of Namibia respectively, as a senior researcher at VO Consulting, and in computational physics at Flinders University, Australia, and the University of South Australia, before joining Rössing as radiation physicist.

Gunhild is also an experienced auditor in health, safety and environment certification and compliance, and is the lead author of a major epidemiological study on the impacts of occupational radiation exposure.

Dr Detlof von Oertzen is the director of VO Consulting, which is an independent specialist consulting firm active in the energy, environ-ment and radiation sectors.

Detlof was born in Windhoek in 1962, holds a PhD in high-energy nuclear physics from the University of Cape Town, and an MBA in finance from the Adelaide Graduate School of Business in Australia.

Detlof has worked in numerous multi-disciplinary teams, and as member of international expert groups. His clients include international bodies including the World Bank, GEF, IAEA, UNDP, UNFCCC, as well as government institutions and various ministries, statutory bodies and regulators, and development agencies. He also provides services to the mineral exploration and mining industry, and his clients include AREVA, B2Gold, Bannerman Resources, CGNPC, Reptile, Rio Tinto, Swakop Uranium and others. In the electricity industry, he has worked as consultant for companies including NamPower, the Electricity Control Board, and Rural Electrification Agencies in the region, for whom he has led or participated in specialist assessments and studies, technical and techno-economic assessments, and audits in his fields of expertise. Detlof can be contacted at Detlof@voconsulting.net.

31 Acknowledgements

This book was commissioned by the **Namibian Uranium Institute**, which is most gratefully acknowledged by the authors.

Special words of thank you go to

- **the Executive Director of the Namibian Uranium Institute, Dr Gabi Schneider**, for her steadfast support in realising the compilation of this book, and for availing the Institute's facilities for training, capacity development and public awareness raising, which is critically important to create and foster a culture of radiation safety in Namibia;
- **the Namibian Chamber of Environment,** for their co-funding contribution to enable the creation of this Handbook;
- **the founding Executive Director of the Namibian Uranium Institute, Dr Wotan Swiegers,** for initiating and actively supporting the development of the training courses on radiation protection, including those for Radiation Safety Officers, which have laid the foundation of the materials presented in this book. Without this support, the many radiation safety courses offered through the Namibian Uranium Institute, and this very book, would not have been realised. The authors also wish to thank Dr Swiegers for his most insightful and considered guidance over the years, which has fundamentally shaped the development of radiation protection and radiation safety in Namibia;
- **staff members of the Namibian Uranium Institute, specifically Monika Ruppel and Ailly Namupala,** for many years of close collaboration, dedication, and support, especially in the authors' offerings of countless courses on all aspects of radiation protection and the training of Radiation Safety Officers and other radiation professionals at the Namibian Uranium Institute in Swakopmund;
- **Rio Tinto Rössing Uranium Limited**, for supporting Gunhild and readily availing her capacity to all matters relating to radiation protection and radiation safety, training and awareness raising. The authors also gratefully acknowledge the information and pictures provided by Rössing, which are used throughout this book;
- **the many Radiation Safety Officers** who have – through the past seven years - contributed in one or the other way to the refinement of the RSO course materials as are summarised in this book, and the authors are especially thankful to **Sandra Müller (AREVA), Mervyn Titus, Werner Ewald (Bannerman), Kaarina Nkandi (AREVA), Dr Bertram Schleicher (Rössing), and Nelao Endjala (Rössing);**
- **the Director-General of the National Radiation Protection Authority, Mr Axel Tibinyane, as well as the staff of the regulatory Authority**, for their excellent support in the past years, and their efforts in establishing the operational and regulatory conditions on which radiation protection practices are now developed and advanced in Namibia;
- **Sandra le Roux,** for creating the book cover;
- **Rolf Scheffer**, for inspirational design ideas and the cover emblem; and
- **VO Consulting**, for liberally sponsoring many an hour of pro bono work, cognisant that person-hours are a finite and non-renewable resource, to enable Detlof to advance radiation protection, improve radiation safety practices and contribute to raising public awareness of energy- and radiation-related topics.

One does not need to be in favour of smoking, airline travel, uranium mining, nuclear power, or the use of radioactive material or X-rays in medicine to be interested in radiation safety practices when dealing with sources emitting ionising radiation.

This book provides Radiation Safety Officers and others active in radiation-related work environments with the necessary perspective and tools to competently and confidently fulfil their roles while striving to keep exposures as low as reasonably achievable.

Namibian
Uranium
Association