ABSTRACT

Biosphere Modelling of Radioactive Waste Disposal Systems in a Safety Assessment Framework

By

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Dissertation Submitted in Partial Fulfilment of the Requirements for the Degree of Masters in Science

(Applied Radiation Science and Technology)

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ABSTRACT

Radioactive waste is a major concern, not only in South Africa, but worldwide. South Africa produces radioactive waste through the full nuclear fuel cycle and the application of radioactive materials in industry, research and medicine. TE-NORM waste, due to a wide variety of mining and mineral processing facilities, is characterise by large volumes but low activity concentrations. The overall objective of radioactive waste management is to deal with radioactive waste in such a manner that human health and the environment are protected, now and in the future, without imposing an undue burden on future generations.

Radioactive waste does not have any economical value and must finally be disposed. According to the overall objective of radioactive waste management, the impact that the disposed radioactive waste will have on future generations needs to be assessed in such a manner that the safety of the public will be ensured. At present, the only tool available to do so is a safety assessment. The goal of safety assessment as a decision tool is to determine the conditions for which reasonable assurance of compliance with safety objectives can be provided. The implementation of a safety assessment, defined as a multi-disciplinary, iterative process focussed on regulatory compliance, is a highly technical exercise, but also contains vital social and political elements.

A radioactive waste disposal system can conveniently be divided into a near-field, geosphere and biosphere (internal components), and some external components that could influence the performance of the disposal system. The biosphere is defined, as that

portion of the environment normally inhabited by humans and other living organisms. The transport of radionuclides through the near-field, geosphere and biosphere result in a certain dose to man. In this dissertation, the different pathways through which radioactivity can reach a critical group are explained and demonstrated in a structured framework of a safety assessment, and in particular, the role that the biosphere plays in this assessment.

This structured framework was used to illustrate the biosphere part of a disposal system and all the factors that could have an influence on the biosphere. The application, *A radiological public hazard assessment at Foskor (Pty) Ltd.* was used to demonstrate that the associated activities do not pose a health hazard to humans. The objective was to conduct an integrated radiological public hazard assessment of doses to members of the public via the atmospheric, aquatic and secondary pathways as a result of the mining and mineral processing facilities at Foskor.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

All uses of radioactive material in the nuclear industry, agriculture, research and medicine generate waste, much in the same way as other human activities. The largest volume of radioactive waste is generated by activities related to the nuclear fuel cycle. In particular, radioactive waste is also generated from the operation of nuclear reactors, reprocessing of spent fuel and the decommissioning of nuclear facilities.

A wide variety of mining and mineral processing give rise to large volumes of residual material containing radioactivity at or somewhat above the levels found in the ore body. These waste, known as TE-NORM (Technically Enhanced Natural Occurring Radioactive Material) waste, is characterised by large volumes but low activity concentration.

Radioactive waste, like all other waste, does not have any economical value and must ultimately be disposed. Although radioactivity is a natural phenomenon that decreases with time, radioactive waste can pose considerable risks to the natural environment of the earth. Special precautions must therefore be taken with the radioactive waste, from its generation to its disposal, even to the time the activity has decayed to trivial or natural background levels, by public demand. This is clearly a management problem, hence the name *radioactive waste management*.

According to the overall objective of radioactive waste management (IAEA, 1995), these waste have to be dealt with in a manner that protects human health and the environment, now and in the future without imposing undue burden on future generations. It includes thus the activities of the waste generators, those responsible for the treatment of waste, the operators (managers) of waste disposal facilities and regulatory authorities if the waste is subject to regulatory control. If disposal is used as a long-term strategy for the management of radioactive waste, then one has to make sure that all disposal related actions and activities meet this objective. This means that the long-term safety of a proposed (or selected) disposal concept must be demonstrated convincingly prior to its implementation, a procedure generally referred to as a safety or performance assessment. According to Cho *et al.* (1990), the general objective of a safety assessment is to estimate the impact of radioactive waste disposal on humans and their surrounding environment as a function of time. To assess the impact, it is necessary to analyse how nuclides might escape from the disposal site and along which paths can it migrate and what effect it will ultimately have on human beings. The biosphere, conventionally used to describe that part of the environment inhabited by all living organisms (Van Blerk, 1999*a*), forms therefore an integral part in the safety assessment of a radioactive waste disposal site.

1.2 THE SITUATION IN SOUTH AFRICA

1.2.1 General

Radioactive waste in South Africa is generated mainly by the Atomic Energy Corporation of South Africa Ltd. (AEC) at Pelindaba, through its involvement in the full range of nuclear fuel cycle activities, and by the electricity utility ESKOM, through its operation of the Koeberg Nuclear Power Plant (NPP) near Cape Town in the Western Cape Province (See Figure 1-1). Radioactive wastes are also produced through the various uses of radioisotopes in industry, agriculture, medicine and research. TE-NORM waste in the form of tailings, waste rock, coal ash and plant residues is mainly generated by the various gold mines in South Africa, the mineral sands processing facilities on the east and west coast of South Africa, the phosphate industry and ESKOM coal power stations.

1.2.2 Radioactive Waste Disposal in South Africa

Two sites can currently be associated with the disposal of radioactive waste in South Africa. The first site, Thabana (previously known as Radiation Hill) is at Pelindaba near Pretoria in the North West Province (See Figure 1-1). This site has been in operation since 1969 and consists of a variety of near-surface earth trenches, used for the storage of uranium-contaminated waste and some plutonium, a stainless steel engineered borehole used for the storage of ^{60}Co sources, calcium fluoride bunkers, storage sheds, and a pipe storage facility for fuel elements from the AEC Safari reactor at Pelindaba. Some medical and industrial waste is also stored in the pipe storage facility. The second site is the National Radioactive Waste Disposal Facility at Vaalputs near Springbok in the Northern Cape Province (See Figure 1-1). This site came into operation in 1986 and is mainly being used for the disposal of low-and intermediate level waste from Koeberg in near-surface trenches.

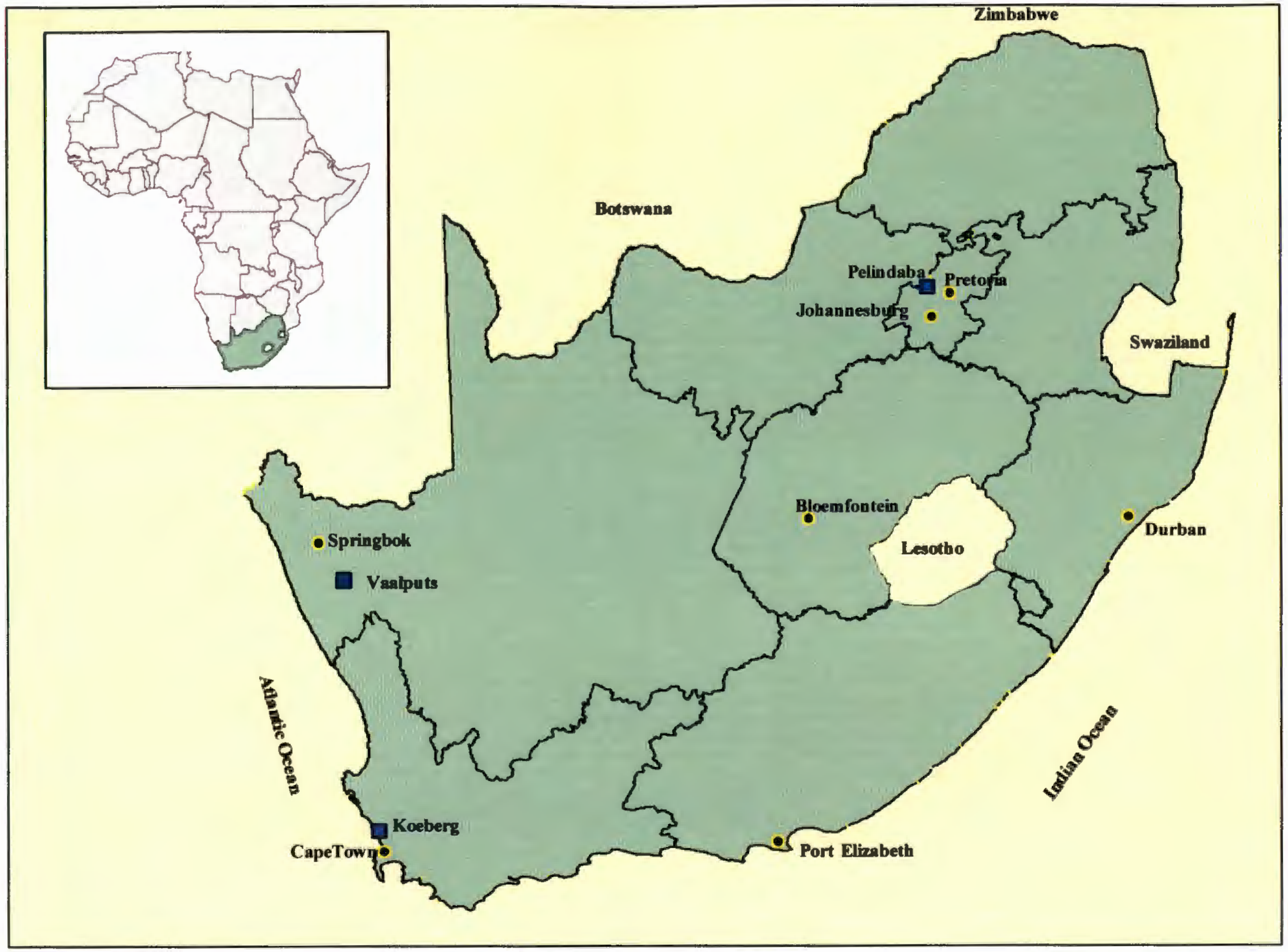


Figure 1-1: Locality map showing the radioactive waste disposal facilities at Vaalputs and Pelindaba as well as the Nuclear Power Plant at Koeberg.

Of the two sites, only Vaalputs went through a detailed screening, selection and characterisation process (Corner and Scott, 1980). The Council for Nuclear Safety (CNS), a statutory body established in the Nuclear Energy Act of 1993 as the national regulator, granted a nuclear license for the disposal of radioactive waste at Vaalputs in 1986 (Moore *et al.*, 1986). Very little is known about the criteria used to select Thabana as a waste disposal site. A license for the permanent storage of active solid waste at Thabana was obtained from the Safety Committee of the Atomic Energy Board (Niebuhr *et al.*, 1968). As yet, the AEC has not obtained a license from the CNS for the disposal of radioactive waste at Thabana. Key issues with regard to the Thabana facility are thus its present adequacy as a storage facility, the uncertainty regarding its total inventory and its future status, for example should it be upgraded to an approved disposal facility or rehabilitated and closed. In the mean time, Thabana has to be treated as a disposal facility, for which the long-term (post-closure) impact to future generations is largely unknown at this stage.

1.2.3 Current Status of Safety Assessment in South Africa

Safety assessments have been performed in many countries to evaluate the post-closure safety of disposed radioactive waste, and various approaches have been developed internationally to perform these assessments in a structured manner. In South Africa, however, safety assessment methodologies as applied internationally are largely unknown and have not been applied to the disposal sites mentioned in Section 1.2.2. In fact, the post-closure safety of the Vaalputs facility is not adequately addressed in the current license, something that has been confirmed by an International Atomic Energy Agency (IAEA) Expert Mission to Vaalputs (IAEA, 1998).

This has led Van Blerk (1999*a*) to develop a structured safety assessment methodology, which will be used to evaluate the long-term safety implications of radioactive waste disposal sites in South Africa to human beings and the environment.

1.2.4 Public Impact Assessment of Mining and Mineral Processing Facilities

Radioactive materials released to the environment from mining and mineral processing facilities create potential exposure of the public to radiation. The nuclear licence issued to all mining and mineral processing facilities, which generated radioactive contaminated materials, requires the licensee to perform a public impact assessment. The purpose of such a public impact assessment is to quantify the dose to members of the public arising from radioactive materials released from mining and mineral processing facilities.

Examples of these public impact assessments conducted by the A E C. are Palabora Mining Company (Van Blerk *et al.*, 1998) and Foskor Pty (Ltd.) (Vivier *et al.*, 1999). Although these assessments concentrated on the operational period of the mining activities, it was possible to use the safety assessment approach described in Van Blerk (1999*a*) to perform the assessments.

1.3 PURPOSE OF THE STUDY

A post-closure safety assessment of a radioactive site is an extensive exercise that requires input from various scientific, engineering, social and economic disciplines, which cannot be adequately covered by an individual. The safety assessment methodology presented in Van Blerk (1999*a*) concentrated exclusively on the broad principles of such a post-closure assessment. This document is an attempt to characterise the biosphere as one of the important components associated with the movement of radioactivity through the environment to human beings. This will be done within the safety assessment framework for a radioactive waste disposal site, but also related to the impact that mining and mineral-processing activities will have on the public.

1.4 SCOPE OF THE STUDY

Radioactive waste management is part of all activities related to the use of radioactive materials in the nuclear industry, agriculture, research and medicine. It is obvious that one must have a detailed knowledge of all the various factors that may have an influence on the use and disposal of radioactive materials, such as the nature and properties of radioactive materials, the origin and types of radioactive waste and the method that will be used to dispose the waste. The effects that waste have on humans and the natural environment will vary with the process that generates it and how it is treated before disposal. It is therefore useful to have a scheme, which can be used to classify the waste, and in Chapter 2 the classification scheme commonly used in the nuclear industry is discussed together with the nature and properties of radioactive materials and the origin and types of radioactive waste.

Radioactive waste management and disposal requires co-operation between scientists, politicians, licensing authorities, industry and the public. Some of the more important strategies developed over the years for the management of radioactive waste are discussed in Chapter 3. Disposal is the only suitable method for the long-term management of radioactive waste, although there are a number of strategies that can be followed. However, to use this approach one must ensure that the disposed waste will not affect humans and their environment. A number of waste disposal practices and the radiation protection objectives are also discussed.

A disposal strategy can only be implemented if it can be demonstrated that it satisfies the objectives of radioactive waste management. This can be achieved by performing an integrated safety assessment of the radioactive system. The term safety or performance assessment is defined in Chapter 4, together with a description of the framework in which it must be accomplished. A major contributor to the inexact nature of a safety assessment is the uncertainties that are inherently part of such an assessment. These uncertainties, which can be conveniently divided into uncertainties related to the future unknown state of the disposal system, data and parameter uncertainties, and model uncertainty, are also discussed.

This safety assessment can only be done if one has a solid knowledge of the components of the disposal system and how they are incorporated in a safety assessment, as described in Chapter 5. These components, which can be divided into internal and external components, provide the necessary information to characterise the movement of radionuclides through what is called the near field, geosphere and biosphere of the system. This movement of radionuclides is the result of the inability of the disposal system to isolate and contain the radionuclides and result in a certain dose to humans. In order for the radionuclides to reach the humans there must be certain receptors in the biosphere where radionuclide concentrations can be intercepted before it can impose a dose to humans. These receptors in the biosphere are also described in Chapter 5.

Biosphere models are used to simulate the movement of radionuclide concentrations through these receptors, to ultimately pose as a dose to humans, and are discussed in Chapter 6. However, these models can only be applied if one has a good knowledge and understanding of all the different transport processes in the biosphere. The major transport routes of radionuclides in the biosphere, through surface and ground water, soil, atmosphere, terrestrial ecosystems and food chain models are also discussed.

An application of the theoretical aspects, as discussed so far, will be applied in a case study, in Chapter 7. The Foskor (Pty) Ltd. site, situated at Phalaborwa, was used to demonstrate the theoretical aspects. The objective of the investigation at Foskor was to conduct an integrated public hazard assessment of doses to members of the public via the atmospheric, aquatic and secondary pathways as a result of the mining and mineral processing facilities at Foskor.

CHAPTER 2

PROPERTIES OF RADIOACTIVE MATERIAL

2.1 HISTORICAL OVERVIEW

The discovery of radioactivity dates back to 1896 when the French physicist Henri Becquerel tried to relate emanations from the fluorescent mineral called pitchblende to X-rays, discovered in 1895 by the German physicist W. C. Röntgen. Between 1896 and 1898, Becquerel and his students Pierre and Marie Curie discovered various naturally occurring radioactive elements such as uranium, radium and thorium, as indicated in Table 2-1 (Van Blerk, 1999*a*).

Despite the often tragic consequences of errors in handling and applying radioactive materials during the following decades, the general fascination with radioactivity did not diminish in any way. Even as late as the nineteen-thirties, charlatans were promoting radioactive toothpaste, radium hair-tonic, radium salve and clothe impregnated with radium. Mineral water with a high radon content was prescribed as being good for the health (IAEA, 1991). However, the recognition that radioactivity is a natural phenomenon in our environment, and advances in both theoretical and practical aspects of its application have since led to the introduction of radiation protection regulations that assure high levels of safety if applied correctly. As a result, the application of radioactive materials today range from modern medical, industrial and research techniques, to the generation of nuclear energy and the manufacturing of nuclear weapons.

The discussion on the properties of radioactive waste will start with a review of the nature and the effects of radioactive material in Section 2.2 as discussed by Chapman and McKinley (1988). This discussion will provide greater clarity on the principles and methodologies applied in the management of radioactive waste generated from nuclear related activities.

Radioactive waste is generated from a variety of sources and depending on the origin and type of radioactive waste, will exhibit different properties. Section 2.3 is therefore devoted to a discussion on the origin and types of radiation waste generated from various sources. The different properties of radioactive waste suggest that not all waste should be treated the same, but instead to define categories of waste with similar properties that can be managed accordingly. This led to different classification schemes for radioactive waste, which will be discussed in Section 2.4.

2.2 NATURE AND EFFECTS OF RADIOACTIVITY

To fully understand the principles and methodologies applied to the management of radioactive waste generated, it is necessary to review the nature and effects of radioactivity itself, as discussed by Chapman and McKinley (1988). The atomic nucleus itself is composed of positively charged protons and uncharged or neutral neutrons. The number of protons is balanced, in the neutral atom, by an identical number of electrons with an equal but negative charge, which surround the nucleus. These electrons are responsible for the chemical properties of the atom.

All atoms with the same number of protons are chemically identical and are called an *element*. The number of protons in a nucleus (atomic number) is consequently often represented by the chemical symbol for the element, e.g. U for uranium, or H for hydrogen. However, atoms of the same element sometimes contain different numbers of neutrons. These atoms are known as *isotopes* and denoted by the chemical symbol for the element superscripted to the left with the sum of its protons and neutrons (mass number), e.g. ^{238}U. In situations where it is necessary to describe a specific atom of an element, or nuclide, more precisely, the number of protons is added as a subscript to the left of the symbol and the number of neutrons as a subscript to the right of the symbol, e.g. $^{238}_{92}\mathrm{U}_{146}$.

The majority of the known nuclides is inherently unstable and is called radionuclides. Radionuclides will spontaneously transform by the emission of particles and/or electromagnetic radiation, or by splitting (fission) of the active nucleus. This transformation is called *radioactive decay*. Experiments have shown that the rate at which a radioactive material disintegrates, is directly proportional to the number of atoms, $N(t)$, in the sample at the time t, that is:

$$DN(t)/dt = -\lambda N(t)$$

where λ is known as the decay constant, which varies from isotope to isotope. Less stable nuclei, decays more rapidly and one can characterise this statistically by another constant, $t_{1/2}$, known as the *half-life* of the radionuclide.

Table 2-1: Chronicle of discovery and application of radioactivity between 1895 and 1992 (Issler, 1990; USDOE, 1998; IAEA, 1991).

1895	Wilhelm Röntgen discovers X-rays.
1896	Becquerel discovers radioactivity in association with uranium. He found that uranium salts affected photographic plates.
1898	Marie and Pierre Curie discover the radioactive element actinium, polonium, radium and thorium. They isolated radium from pitchblende, which was much more effective in darkening photographic plates than uranium.
1899	Rutherford distinguishes the three types of ionizing radiation, which are emitted from radioactive substances.
1901	Marie Curie provided a physician at a Paris hospital with a radium source to be used for medical treatment. The source was to be applied to a malignant surface tumour. Two years later the first successful treatment was reported.
1904	The first attempt to treat a tumour inside the body was made by inserting a glass capsule containing radium.
1911	Rutherfords model of the atom distinguishes between the atomic nucleus and the electron shell. Georg von Hevesy conceives the idea of using radioactive tracers. This idea is later applied to, among other things, medical diagnosis and the study of the transport of radioactivity in groundwater systems.
1927	Herman Blumgart, a Boston physician, first uses radioactive tracers to diagnose heart disease.
1938	Two German scientists, Otto Hahn and Fritz Strassmann discover that bombarding uranium atoms with neutrons produces barium atoms. Meitner explains this in terms of nuclear fission.
1939	Fermi and Scherrer discover the possibility of a chain reaction. Bethe identifies nuclear fusion as the energy of the sun.
1942	Fermi demonstrates the first self-sustaining nuclear chain reaction in the Chicago reactor.
1944	The first reactor begins operation in the USA.
1945	The USA explodes the first atomic device at a site near Alamogorda, New Mexico, and one month later drop the first atomic bomb on Hiroshima and Nagasaki.
1951	The first usable electricity from nuclear fission is produced.
1955	Arco, Idaho becomes the first U.S. town to be powered by nuclear energy.
1957	Radiation is released when the graphite core of the Windscale Nuclear Reactor in England catches fire. The International Atomic Energy Agency (IAEA) is formed to promote the peaceful uses of nuclear energy.
1963	The United States and Soviet Union sign the Limited Test Ban Treaty, which prohibits underwater, atmospheric and outer space nuclear tests.
1966	The large number of utility orders for nuclear power reactors makes nuclear power a commercial reality in the USA.
1968	The Nuclear Nonprolifiration Treaty – calling for halting the spread of nuclear weapons capabilities - is signed.
1972	Computer axial tomography, commonly known as CAT scanning, is introduced.
1977	United States president, Jimmy Carter, bans the recycling of used nuclear fuel from commercial reactors.
1979	Three Mile Island Nuclear Powerplant near Harrisburg, Pennsylvania suffers a partial core meltdown. Minimal radioactive material is released.
1986	Chernobyl Nuclear Reactor meltdown and fire occur in the Soviet Union. Massive quantities of radioactive material are released.
1987	Yucca Mountain, Nevada are designated for scientific investigation as candidate site for the United States first geological repository for high-level radioactive waste and spent fuel.
1992	One hundred and ten commercial reactors are operating in the United States.

The half-life is the time required for the number of atoms of a particular radionuclide to decrease by 50% due to radioactive decay, in other words, from their original number, N_0, at $t = 0$, to $N_0/2$. To prove this, one needs to integrate $DN(t) = -\lambda N(t)$ over time:

$$N(t) = N_0\exp(-\lambda t)$$

from which it follows that:

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

The half-life of a nuclide may vary from a fraction of a second to many millions of years. For example, the half-life of ^{219}Po is 5.3 x 10^{-8} s, while that of ^{128}Te is 8.0 x 10^{24} years. In real life, things are not always so simple and sometimes the nuclide produced by the decay process is itself unstable and decay again. This reaction results in a chain of many radioactive daughters for a certain nuclide. The nuclear transformation involved in the decay process is generally classified in terms of the radiation emitted and can be summarised as follows:

- α the emission of an alpha particle comprising a group of two protons and two neutrons which decrease the mass number of the decaying nucleus by four and its atomic number by two;
- β^- the emission of an electron (beta particle) from the nucleus resulting from the conversion of a neutron to a proton, in which case the mass number stays the same, but the atomic number decreases by one;
- β^+ the emission of a positron from the nucleus resulting from the conversion of a proton to a neutron; or where an orbiting electron is captured by the nucleus (known as *electron capture*), and
- γ the emission of high-energy electromagnetic radiation due to internal stabilisation of the nucleus following the transformation processes above.

In Figure 2-1 the different types of radioactive emissions are shown together with their ability to penetrate matter. The α-particles interact very strongly with matter and are easily stopped (e.g. by a thin sheet of paper). The β-particles interact less strongly with matter and a thin layer of metal can effectively stop them. The γ-radiation is very penetrating and requires large thicknesses of shielding materials, e.g. lead or concrete.

Mainly α, β and γ radiation are considered in radioactive waste disposal discussions, because these are the main types of radiation emitted by radioactive waste materials. The *activity* in any radioactive material is measured in terms of the number of individual nuclei, which decay or disintegrate each second. The unit of activity is the *becquerel* (Bq) where 1 Bq relates to a decay rate of 1 nucleus per second. Since the activity tells us nothing about the type of radiation emitted, its energy, or degree of interaction with matter, the quantity of *absorbed dose* was introduced with the *gray* (Gy) as unit. An absorbed dose of 1 Gy relates to an energy absorption of 1 $J.kg^{-1}$ of the exposed material. If human tissue is exposed, one is interested in the harmful effects of the radiation, which is more accurately presented by the *equivalent dose* as measured in *sievert* (Sv). The equivalent dose is obtained by multiplying the absorbed dose to the particular tissue or organ with suitable radiation weighting factors, which depend on the relative biological effects of various radiations.

Another very useful quantity used to describe radiation harm to human beings, is the *effective dose*, which is also expressed in *sievert* (Sv). This is the sum of the equivalent doses to various tissues or organs, each weighted with a suitable tissue weighting factor, taking account of the different susceptibilities to radiation-induced harm of the various tissues. Effective dose is particularly useful because it provides a measure of the total risk to an individual.

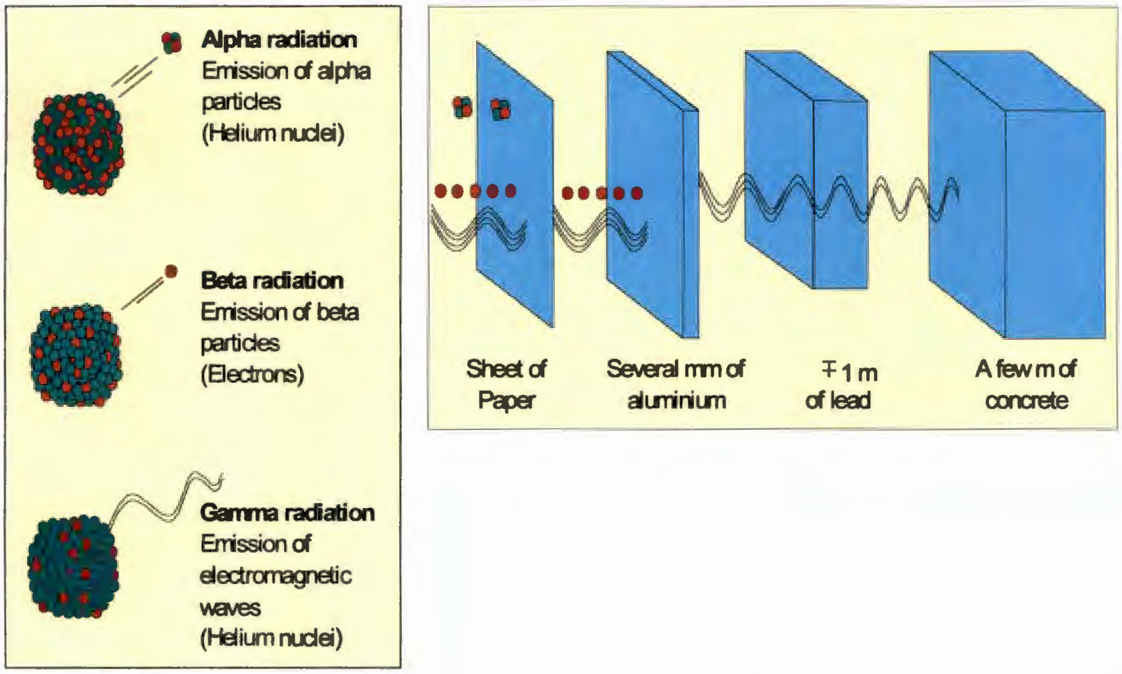


Figure 2-1: The three types of radiation emitted by radionuclides and the shielding required to stop them (After Issler, 1990).

Exposure to ionising radiation may occur as a result of the intake of radionuclides by inhalation if they are in the form of a gas or an airborne particle or by ingestion if they are present in food or drinking water. In these respects, they have the same intake and exposure routes as many other hazardous substances. However, the additional route of direct exposure of the body to external radiation, is unique to radionuclides.

The biologically harmful effects of radiation occur when absorbed radiation energy kills individual cells, prevents them from dividing and reproducing normally, or causes mutation of the genetic information carried in them, which can lead to cancers. Depending on the organ or tissue affected, radiation damage can manifest itself in many medical forms. Due to the short penetration distance of α-particles in particular, only the ingestion or inhalation of such particles can affect major organs. However, because of the very strong interaction with matter, the ingestion or inhalation of α-particles is most harmful.

2.3 TYPES OF RADIOACTIVE WASTE

2.3.1 General

Radioactive waste can be defined as material that contain or are contaminated with radionuclides at concentrations or activities greater than clearance levels as established by the regulatory body, and for which no use is foreseen (IAEA, 1993*a*). This definition is, however, purely for regulatory and legal purposes and it should be noted that material with activity concentrations equal to or less than clearance levels are radioactive from a physical viewpoint, although the associated radiological hazards are negligible.

As mentioned in Chapter 1, the nuclear industry, agriculture, research and medicine generate radioactive waste, with the largest volume of waste related to the nuclear fuel cycle. It was also mentioned that mining and mineral processing facilities (e.g., gold mines, mineral sand, phosphate and coal burning facilities) give rise to large volumes of residual material containing low levels of activity.

The generation of radioactive waste can be grouped into activities related to the nuclear fuel cycle and non-fuel cycle activities. The nuclide concentration of radioactive waste from the fuel cycle normally greatly exceeds those of non-fuel cycle activities. It can be in a solid, liquid or gaseous form and the different origins of radioactive waste can cause a variation in its physical state, activity and type.

Activity levels range from extremely high for spent fuel, to very low for radioisotope applications in laboratories, hospitals and universities. Equally broad is the spectrum of half-life's of radionuclides contained in the waste.

2.3.2 Nuclear Fuel Cycle Waste

The nuclear fuel cycle refers to activities associated with the supply of fuel, as well as the management of radioactive materials involved with the production of nuclear power. The major steps generating radioactive waste in the uranium fuel cycle are, for example (IAEA, 1994):

- *Fuel supply.* The waste results from purification, conversion and enrichment of uranium. In general, this waste contains uranium and, in the case of mixed oxide fuel, also plutonium.
- *Reactor operation / Power generation.* This waste results from treatment of cooling water and storage ponds, equipment decontamination and routine facility maintenance. It includes contaminated clothing, floor sweepings, paper and concrete. Radioactive waste from treatment of the primary coolant systems and off-gas systems includes spent resins and filters, as well as some contaminated equipment.
- *Management of spent fuel.* The radioactive waste generated from this activity contains uranium fission products and actinides. Spent fuel is considered as a waste, or waste is generated from reprocessing operations. Reprocessing generates solid and liquid radioactive waste.

2.3.3 Waste from the Decommissioning of Nuclear Facilities

Decommissioning wastes are those that result from decontamination (e.g. removal of radioactivity from the surfaces of facilities and site materials), from dismantling of a nuclear plant and its hardware, and from removal of soils and pavements from contaminated areas, and structural materials. Decommissioning wastes arise after the end of the operational phase and much of the solid debris is normally not radioactive and should be easy to dispose of, for example as landfill. A particular aspect of decommissioning waste, that may have an impact on disposal, is the large size of particular components, e.g. reactor vessels and heat exchangers. If size reduction is impractical, large size components may place constraints on disposal options.

2.3.4 Waste from Mining and Mineral Processing Facilities

A wide variety of mining and mineral processing give rise to large volumes of residual material containing radioactivity at levels found in the orebody. These wastes, known as TE-NORM (Technically Enhanced Natural Occurring Radioactive Material) waste, is characterised by large volumes but low activity concentrations. TE-NORM waste is generated mainly by the production of uranium with low concentrations and is contaminated principally by its daughter products, e.g. thorium, radium and radon. Other TE-NORM generators are gold, mineral sand, phosphate and coal mining facilities. These waste does not include materials associated with nuclear facilities that contains natural radionuclides, but include scrap recycling by mining and mineral processing activities (e.g., tailings, slag, ashes, resins, scales, liquids and gases and large soil areas).

2.3.5 Spent Sealed Sources

Another group of radioactive waste, which is small in volume but still may pose a considerable health risk to humans if not disposed properly, is that of spent sealed sources. The applications of sealed sources include industry, research and medicine. In industry it is used for belt, density, level and thickness gauges, industrial radiography, moisture detectors, sterilisation and food preservation, as well as roentgen fluorescence analysing. Research applications include calibration sources, electron capture detectors, tritium targets and eliminators for static electricity, while in medical fields sealed sources are used for bone densitometers, brachytheraphy, teletheraphy and clinical radiotherapy (IAEA, 1991). Since the physical dimensions of these sources are small, they are very susceptible to theft and misuse. Some of them may, however, contain highly active isotopes, with a corresponding potential radiation hazard to human beings.

2.4 CLASSIFICATION OF RADIOACTIVE WASTE

2.4.1 General

The proceeding discussion indicated that it would be wrong to treat the various types of waste on equal footing. The classification of radioactive waste is influenced by a variety of different aspects. Together with the origin of the radioactive waste, its physical, chemical, biological and radiological properties can be used as criteria to classify them into different categories.

Today, quite a number of alternatives for the safe management of radioactive waste exist, and to simplify its management, a number of schemes have evolved for classifying radioactive waste according to the physical, chemical, biological and radiological properties of significance to those facilities managing the waste (See Table 2-2). The classification schemes in use today can be divided into qualitative and quantitative schemes.

Table 2-2: Important properties used as criteria for classification of radioactive waste (IAEA, 1994*a*).

General	Specific
Origin	
Criticality	
Radiological properties	Half Life Heat Generation Intensity of penetrating radiation Activity and concentration of radionuclides Surface contamination Dose factors of relevant radionuclides
Other physical properties	Physical state (solid, liquid or gaseous) Size and weight Compactability Dispensability Volatility Solubility, miscibility
Chemical properties	Potential chemical hazard Corrosion resistance/corrosiveness Organic content Combustibility Reactivity Gas generation Sorption of radionuclides
Biological properties	Potential biological hazards

2.4.2 Qualitative Classification

The most widely used qualitative classification system separates radioactive waste into three classes: low-level waste (LLW), intermediate-level waste (ILW) and high-level waste (HLW). *High-level waste* can be considered as the highly radioactive liquid, containing fission products, as well as some actinides, which is separated during chemical reprocessing. In addition to spent reactor fuel (if it is declared a waste), high-level waste also include any other waste with radioactivity levels intense enough to generate significant quantities of heat by the radioactive decay process (e.g.

2 kW·m^{-3}).

Intermediate-level waste is waste which, because of its radionuclide content, requires shielding, although little or no provision for heat dissipation is needed during its handling and transportation. *Low-level waste* is radioactive waste that, because of its low radionuclide content, does not require shielding during normal handling and transportation.

Within the ILW and LLW classification, the IAEA also differentiates between short- and long-lived waste, as well as alpha bearing waste (IAEA, 1994). Here the term *short-lived waste* refers to radioactive waste which will decay to an activity level which is considered to be acceptably low from a radiological viewpoint within a time period during which administrative controls are expected to last. *Long-lived* waste is radioactive waste that will not decay to an acceptable activity level during the time that administrative controls are expected to last. *Alpha bearing waste* is radioactive waste containing one or more α-emitting radionuclides, usually actinides, in quantities above the acceptable limits established by the national regulatory body.

2.4.3 Quantitative Classification

In many cases, the classification of radioactive waste is related to safety aspects of their management. In this context, it provides a link between the waste characteristics and safety objectives that have been set up by a regulatory body. Since safety objectives are formulated in terms of numerical values such as dose rate or activity levels, a quantitative classification system is often required (IAEA, 1994).

Radioactive waste classification at the AEC is based on a quantitative scheme (AEC, 1997). Three main categories of waste were identified, namely cleared waste (CW), low- and intermediate-level waste (LILW) and high-level waste (HLW). Cleared waste contains so little radioactive material that it cannot be considered as *radioactive*, and might be cleared from nuclear regulatory control. That is to say, although still radioactive from a physical point of view, this waste may be safely disposed of, applying conventional techniques and systems, without specifically considering its radioactive properties (IAEA, 1994).

Within this scheme, LILW is further subdivided into the subclasses indicated in Figure 2-2 and summarised below:

(a) Short-lived waste; sealed sources (LILW-SL(SS));

(b) Short-lived waste; low dose rate (LILW(L)-SL);

(c) Short-lived waste; intermediate dose rate (LILW(I)-SL);

(d) Long-lived waste; low dose rate (LILW(L)-LL);

(e) Long-lived waste; intermediate dose rate (LILW(I)-LL).

The high-level waste class retains the definition of the qualitative classification scheme.

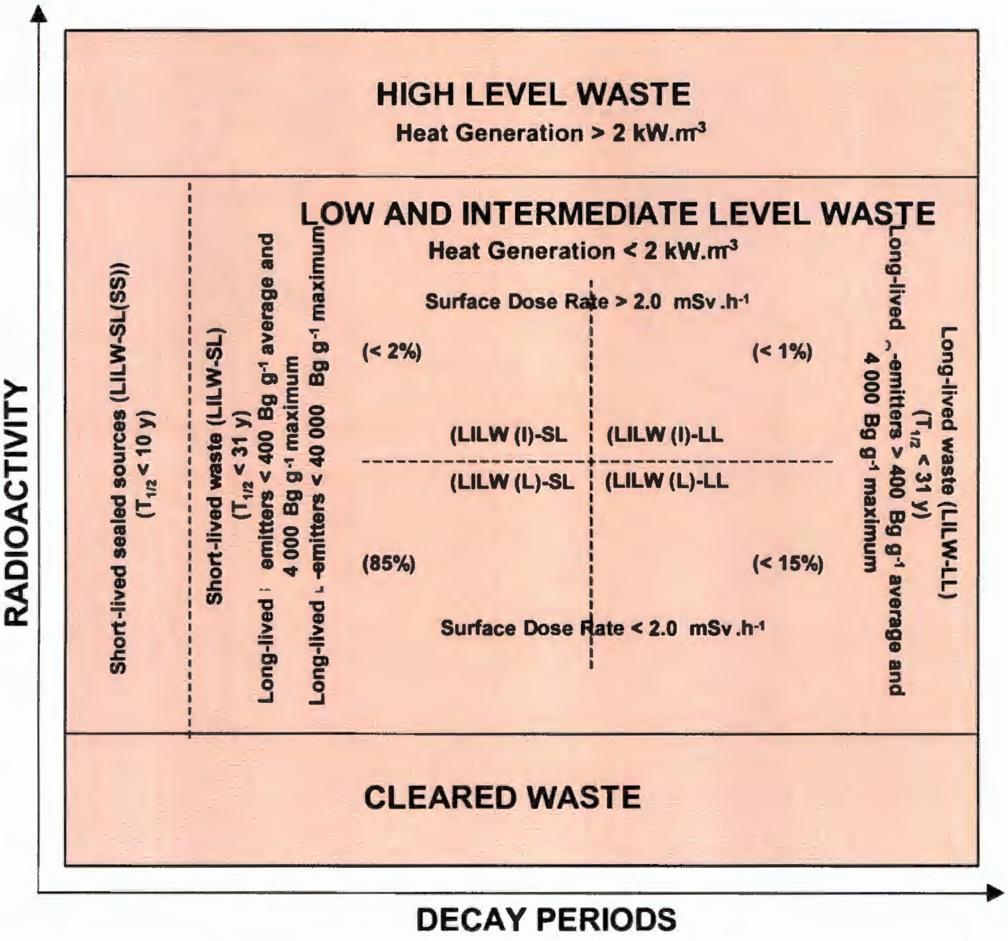


Figure 2-2: **The qualitative radioactive waste classification scheme proposed for the AEC. The figures in brackets represent the estimated percentage of AEC waste (AEC, 1997).**

CHAPTER 3

MANAGEMENT OF RADIOACTIVE WASTE

3.1 GENERAL

The generation of radioactive waste and the potential risks it pose to human beings and the environment calls for waste management strategies that guarantees the safety of humans and the environment now and in the future. During the first decade of the nuclear era, scientists and licensing authorities essentially handled the problem of radioactive waste management, since they were directly confronted with the necessity to develop reasonable and safe solutions. Today, after decades of research, study and testing, it can be confidently stated that technological solutions for safe radioactive waste management have been developed (IAEA, 1992). However, radioactive waste management and disposal, in particular, is no longer a matter for scientists alone, but requires co-operation between scientists and politicians, licensing authorities, industry and the public. The international community has consequently defined through the International Atomic Energy Agency (IAEA) an overall objective for radioactive waste management, namely (IAEA, 1995).

> *"to deal with radioactive waste in a manner that protects human health and the environment now and in the future without imposing undue burdens on future generations".*

According to this overall objective it is of the utmost importance that radioactive waste must be managed in an accurate and accepted manner. The internationally accepted fundamental principles for the management of radioactive waste can be use as a basis for the appropriate management of radioactive waste and are discussed in Section 3.2. This is followed by an overview of an integrated approach to radioactive waste management in Section 3.3, and some of the more important management strategies that have been advanced over the years for the management of radioactive wastes, in Section 3.4. Various waste disposal strategies have evolved over the years and in Section 3.5 an overview is provided of some of these practices for the disposal of LILW, high level waste and spent sources.

For all activities involving the use of radiation materials and due to the risk of radiation exposure to workers and members of the public from waste disposal, clear and consistent radiation protection goals are essential and in Section 3.6 the main objectives of radiation protection are discussed.

3.2 FUNDAMENTAL PRINCIPLES OF RADIOACTIVE WASTE MANAGEMENT

The objectives of safe and responsible radioactive waste management set by the international community, requires the implementation of measures that will afford protection of human health and the environment. Improperly managed radioactive waste could result in adverse effects to human health or the environment, now *and* in the future. The timely creation of an effective national legal framework, and an associated organisational infrastructure, provides the basis for appropriate management of radioactive waste (IAEA, 1995).

Observance of the fundamental principles of radioactive waste management, as agreed upon by the international community, will ensure that the above-mentioned considerations are addressed. Short descriptions of the principles are provided in Table 3-1.

Table 3-1: Fundamental principles agreed upon by the international community for the management of radioactive waste (IAEA, 1995).

Principle	Description
Protection of Human Health	Radioactive waste shall be managed in such a way as to secure an acceptable level of protection to human health.
Protection of the Environment	Radioactive waste shall be managed in such a way as to secure an acceptable level of protection to the environment.
Protection beyond National Borders	Radioactive waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be taken into account.
Protection of Future Generations	Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.
Burdens on Future Generations	Radioactive waste shall be managed in such a way that it will not impose undue burdens on future generations.
National Legal Framework	Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.
Control of Radioactive Waste Generation	Generation of radioactive waste shall be kept to the minimum practicable.
Radioactive Waste Generation and Management Interdependencies	Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account.
Safety of Facilities	The safety of the facilities for radioactive waste management shall be appropriately assured during their lifetime.

3.3 AN INTEGRATED APPROACH TO RADIOACTIVE WASTE MANAGEMENT

3.3.1 General

Radioactive waste management is the concluding part of all activities related to the production of nuclear power, research and development, and the many applications of radioisotopes. To take interdependencies that exist within waste management steps into consideration, an integrated approach to radioactive waste management is proposed. According to the IAEA glossary (IAEA, 1993*a*), the term integrated approach refers to

> *"a logical and preferably optimised strategy of a radioactive waste management programme as a whole, from waste generation to disposal, so that the interactions between the various stages of waste management are taken into account and that decisions made at one stage do not foreclose certain alternatives at a subsequent stage."*

It consists of all activities, administrative and operational, that are involved in the handling, pre-treatment, treatment, conditioning, transportation, storage and disposal of the waste generated by the facility (IAEA, 1993*a*). Clear and consistent radiation protection measures associated with limitation of the harmful effects of ionising radiation to human being and the environment forms part of all the steps associated with the radioactive waste management strategy.

3.3.2 Steps in Radioactive Waste Management

Waste pre-treatment comprises all technical and administrative operations to collect, characterise, classify, segregate, chemically adjust, decontaminate, package and document the radioactive waste. This is done according to the national waste classification procedures, taking the radiological content and characteristics of the waste into account.

Depending on the level of treatment done during the previous step, *waste treatment* encompasses the operations intended to try to change the characteristics of the waste in such a way that it can be handled more safely and economically in the future. This is done through volume reduction, removal or radionuclides from the waste and change in composition in order to achieve the preferred approach of concentration and containment, rather than dilution and dispersion in the environment.

After treatment, the waste is still not in a condition that it can be handled, transported, stored and/or disposed safely. To achieve this the waste is almost always immobilised first—a process known as *conditioning*. The simplest way to achieve this is to mix the waste with a solidifiable material, and place the mixture into a container that also serves as a mould during the infilling and solidification of the waste mixture, or waste form.

From the definition of a waste management procedure, it is clear that the previous steps should facilitate the *safe transport* of waste to the place of storage and/or disposal. This should include all operations and conditions associated with and involved in the movement of radioactive material by any mode.

The term *storage* of radioactive waste is commonly used to denote the emplacement of the waste in an approved, specified facility, with the intention of retrieving the waste in future, while *disposal* refers to the practice where there is no intention to retrieve the waste (IAEA, 1993*a*). The waste management procedure should include the intended storage and/or disposal options for the waste, including the impact of these options on human beings and the environment, now and in future.

3.4 MANAGEMENT STRATEGIES

3.4.1 General

Originally, radioactive waste residues resulting from radioisotope applications in medicine, industry and research, were stored for a interim period to allow for some decay, and then disposed of by dispersion and dilution in natural reservoirs (IAEA, 1993*b*). However, the anticipation of larger waste quantities, such as radioactive by-products from activities related to the nuclear fuel cycle, made it necessary to develop new management strategies to ensure that the objective and principles of radioactive waste management are being met. Consequently, the principles of concentration and confining of waste were introduced to ensure isolation of the radioactive material from humans and the environment.

Since those early days, numerous strategies for the management of radioactive waste have been formulated and are available for implementation. Which strategy to follow will to a great extent be determined by the classification of the radioactive waste, although, political, economical and social factors become more and more important.

3.4.2 Fuel Recycling

When spent fuel is discharged from a reactor, it contains substantial quantities of potentially valuable materials, notably plutonium and uranium, which could serve as an additional source of energy. The plutonium and uranium could be chemically separated from the rest of the fuel and used to make new fuel elements. This procedure is known as fuel recycling, while the chemical separation process to extract the plutonium and uranium from the spent fuel is known as fuel reprocessing. Fuel reprocessing is a costly process and produces highly radioactive liquid waste containing fission products and activation products. For this reason it is not often used.

3.4.3 Storage of Radioactive Waste

As mentioned in Section 3.3.2, storage of radioactive waste involves the placement of waste in a nuclear facility with the intent to retrieve the waste at a later stage. Storage is thus a temporary measure applied at any stage of the management process, which requires continuing surveillance. However, there are sound technical and economical reasons for storing radioactive waste. Spent fuel, for example, is usually stored in pools, taking advantage of water for both cooling and shielding. For longer-term storage of spent fuel, dry storage containers in concrete structures have also been developed, for example in Canada, Germany and USA (IAEA, 1992). For LLW containing short-lived radionuclides, storage allows for a considerable reduction in the quantity of volatile radionuclides. Economical, there may be a compromise between short-term and long-term costs.

Although storage has been proven feasible and safe, it remains a temporary solution and does not replace the need for the development and application of a longer-term solution, such as the disposal of radioactive waste (IAEA, 1992).

3.4.4 Disposal of Radioactive Waste

As mentioned in Section 3.3.2, the difference between disposal and storage, is the intent not to retrieve the waste in future. Disposal strategies of importance today are near-surface disposal and geological disposal. Per definition, near-surface disposal is the disposal of waste, with or without engineered barriers, on or below the ground surface where the final protective covering is of the order of a few meters thick (IAEA, 1993*a*). Typically, short-lived low-and intermediate level waste is disposed in this manner.

Special cases of near-surface disposal are borehole disposal. One example is the Greater Confinement Disposal Facility at the Nevada Test Site in Nevada, USA, which is used for the disposal of high specific-activity LLW (Price *et al.*, 1996). Another example is the Borehole Disposal Concept, which is currently under development and evaluation for the disposal of spent sources (Van Blerk *et al.*, 1999). Although these concepts are per definition still near-surface facilities with depths that range from 40 m to 100 m, it can be considered as intermediate depth disposal concepts.

Geological disposal involves the isolation of the waste, using a system of engineered and natural barriers at depths up to several hundred metres in a geologically stable formation. Geological disposal is used for high-level waste or any other waste containing long-lived radionuclides. Another disposal option that has been investigated extensively, but is not considered viable today is the disposal of radioactive waste in the sea. Here we can distinguish between disposal in the deep sea, in the seabed or in the sub-seabed.

Deep geological formations with a very low permeability have the greatest potential for long- term isolation of radioactive waste. All radioactive waste could be disposed of in this manner. However, alternatives that are more economical are available for radioactive waste that contains only short-lived radionuclides or low levels of long-lived radionuclides. The classification of radioactive waste will largely determine the disposal concept to be implemented for the long-term management of the waste. An important issue in the selection and design of a disposal concept is the establishment of waste acceptance criteria to ensure an acceptable low risk to humans and the environment. These criteria will not only take the waste characteristics into consideration, but also the site-specific characteristics in terms of the capability of the system to isolate radionuclides from humans and the environment.

Despite its advantages as a radioactive waste management strategy, disposal of radioactive waste is a controversial issue from a local to a national and international scale. It is of the utmost importance to have a legal framework and well-established procedures for decision-making. This will assist in evaluating alternatives and increase confidence that all relevant factors that could influence the decision-making process are being addressed. Society has the responsibility to create a clear legal framework, assign a proper mandate and responsibilities to authorities, as well as to provide the means by which the public can be involved in the evaluation and decision-making process (Forsström and Westerlind, 1997).

3.5 WASTE DISPOSAL PRACTICES

3.5.1 Low-and Intermediate Level Waste

Most LLW and ILW around the world are disposed of in near-surface disposal facilities, consisting of unlined trenches and pits or engineered concrete structures. These facilities are usually not more than 20 m deep. Currently, however, there is a tendency to dispose these wastes in deeper facilities. In the United Kingdom, for example, no further shallow land repositories will be constructed, except for the expansion of the Drigg facility (IAEA, 1993*b*).

Depending on factors such as the characteristics of the waste, the site, the sources, climatic conditions and legislative requirements, different repository designs have been adopted in different countries. The repository may, for example, as a whole or in part be located above the original ground level or totally below ground level. It may further be provided with engineered barriers, or the waste may be placed directly in contact with the geological material. The success of near-surface disposal depends on the capability of the system to prevent the mobilisation and migration of radionuclides. It is, therefore, essential to minimise contact time between waste and percolating water and/or groundwater. For this reason, there is trend to increase the engineered barriers in new repositories, for example, the use of concrete vaults (IAEA, 1993*b*). Depending on the site characteristics and possible exposure scenarios that are important to a site, special attention can also be given to the design of the engineered cap over the facility. One such an example is the Intrusion Resistant Underground Structure (IRUS) facility at Chalk River in Canada (Dolinar *et al.*, 1996).

Deep disposal facilities for LLW and ILW have been or are being constructed and operated in some countries. In this case, disposal is performed in low permeability geological formations, at depths of tens to hundreds of metres. Waste acceptance criteria for these facilities can be quite different from near-surface disposal, since the desired isolation capabilities of the system are much greater.

An alternative waste disposal concept is deep-sea disposal. This concept is technically feasible with negligible environmental impact, in part because of the enormous dilution potential of the sea. Since 1983, there has been an international non-binding moratorium on sea disposal of radioactive waste while certain issues raised by the London Dumping Convention are being resolved (IAEA, 1993*b*).

3.5.2 High-Level Waste

There is no urgency to dispose of HLW and spent fuel, since vitrified HLW and spent fuel can be stored safely for many years (IAEA, 1993*b*), but a concept for the disposal of HLW is under development. Researchers have considered three types of disposal internationally, investigating alternatives for the disposal of spent fuel (AECL, 1994):

(a) Removal of the waste from the earth by transporting it into space;

(b) Transmutation, which would entail changing some of the elements in the waste to different elements, by nuclear methods, in order to reduce the long-term radiotoxicity of the waste; and

(c) Geological disposal, which would entail isolating the waste in a geological medium (e.g. an ice sheet, sediments or rock beneath the seabed, sediments or rock on land) in such a way that maintenance and administrative control would not be required in the long-term.

Transport of an entire spent fuel bundle (or reprocessed waste for that matter) into space would be prohibitively expensive. This, together with the probability of a launch failure, suggests that radiological risk would be higher than geological disposal. Although transmutation may not, strictly speaking, be a type of disposal, it is included in this discussion because it has the potential to eliminate some of the radioactive elements in the waste. In future, when the technology for transmutation is more advanced, then there might be merit in using it, especially if reprocessing is considered.

Disposal either in an ice sheet or under the deep seabed is potentially feasible. In this concept, high-level waste is to dispose of in suitable geological media (natural barriers) beneath the ocean floor at a depth of at least 4000m. Engineered barriers similar to geological disposal would ensure the safety of the system. In addition, the sea provides a supplementary factor of high dilution (IAEA, 1993*b*). The only option left for the disposal of high-level waste is geological disposal. As yet, there is no repository for HLW or spent fuel in operation. However, many countries are investigating potential host rocks (IAEA, 1993*b*). Some have developed underground research laboratories while others have developed conceptual repositories (AECL, 1994). All these efforts consider deep geological repositories, using a system of multiple barriers to give greater assurance of isolation and ensuring that any release of radioactivity to the environment will occur at an acceptably low rate.

3.5.3 Spent Sealed Sources

The disposal of spent sealed sources that originate from research, hospitals and industry, for which no further use are foreseen, are causing problems as to what is the best disposal strategy to follow. In South Africa, small amounts is stored in near-surface trenches at Thabana, while spent ^{60}Co sources are stored in stainless steel tubes in the ground. To find a suitable disposal solution for ^{226}Ra is in particular a concern because of its small volume and long half-life.

One possible solution to the disposal of all spent sources is the Borehole Disposal Concept that is currently under development and evaluation by the AEC (Van Blerk *et al*., 1999). The concept, for which an initial safety assessment with promising results are available, consists of a water borehole (165 mm to 185 mm) drilled to a depth of 100 m and then filled with specially designed waste packages containing the sources, up to a depth of 50 m from the top. The top 50 m of the borehole is then filled with concrete.

3.6 RADIATION PROTECTION OBJECTIVES

For all activities involving the use of radiation materials and the risk of radiation exposure to a workforce or a member of the public from waste disposal, clear and consistent radiation protection goals are essential. The current set of protection goals that constitute a *framework for radiological protection* is based on recommendations of the International Commission on Radiological Protection (ICRP, 1977). The framework provides the basis for protection of the workers in nuclear installations that generate and treat the waste, and for protection of the public potentially at risk from radioactive effluent releases from disposal of radioactive waste.

The protection of human health has always been a fundamental objective in the operation of nuclear reactors and the management of radioactive waste. The basic ICRP recommendations for radiological protection form the basis for regulations in most countries and for the safety standards of the IAEA (IAEA, 1989, OECD/NEA, 1977).

The basic components of the ICRP system of protection for practices have been set out in Paragraph 112 of Publication 60. They can be summarised as follows (ICPR, 1997):

(a) no practice involving exposures to radiation should be adopted unless it produces at least sufficient benefit to the exposed individual or to society to offset the radiation detriment it causes *(Called the justification of a practice)*;

(b) in relation to any particular source of radiation within a practice, all reasonable steps should be taken to adjust the protection so as to maximize the net benefit, economic and social factors being taken into account (*Called the optimization of protection*); and

(c) a limit should be applied to the dose (other than from medical exposures) received by an individual as the result of all the practices to which he is exposed (*Called the application of individual dose limit*).

To apply the framework of radiological protection to waste disposal practices, ICRP (1997) state the following:

(a) The control of public exposure from waste disposal should be exercised by the use of the constrained optimization of protection. To allow for exposures to multiple sources, the maximum value of the constraint used in the optimization of protection for a single source should be less than 1 mSv in a year. A value of no more than 0.3 mSv in a year would be appropriate.

(b) In situations in which environmental monitoring is required to supplement the limitation of releases, derived restrictions should be developed for application to the monitoring results. Since environmental monitoring is often used to assess the combined implications of all the relevant practices, these restrictions should be based on a dose to the critical group approaching 1 mSv in a year.

In 1977, the IAEA initiated an integrated program on the geological disposal of radioactive waste. As part of this program, basic requirements for protection of human health and the natural environment were recommended, as were criteria for underground disposal of solid radioactive waste (IAEA, 1983). The IAEA (1989) has set out the following two objectives for disposal of high-level waste:

(a) to ensure the long-term radiological protection of humans and the environment in accordance with current internationally agreed radiation protection principles (*Radiological Safety*); and

(b) to isolate high level waste from the human environment over long time-scales without relying on future generations to maintain the integrity of the disposal system, or imposing upon them significant constraints due to the existence of the repository (*Responsibility To Future Generations*).

The *radiological safety objective* is relevant to nuclear fuel waste disposal in two ways (AECL, 1994*a*):

(a) the reason for disposal is to protect human health and the natural environment from the potential harmful effects of the waste far into the future; and

(b) human health and the natural environment have to be protected while the disposal concept is being implemented.

In terms of the *responsibility to future generations*, the AECB (1987) requires that the burden on future generations shall be minimised by:

(a) selecting disposal options for radioactive waste which, to the extent reasonably achievable, do not rely on long-term institutional controls as a necessity to ensure safety in the future;

(b) implementing these disposal options at an appropriate time, technical, social and economical factors being taken into account; and

(c) ensuring that there are no predictive future risk to human health and the environment that would not be currently accepted.

All radiological protection objectives for the disposal of radioactive waste have two aspects in common: *protection of future generations* and *protection of the environment*. The protection of future generations relates to two principles:

(a) Future generations should be afforded at least the same degree of radiation protection as given to the public today; and

(b) The safety of radioactive waste should not depend on active maintenance of the disposal system by future generations beyond a period of active surveillance.

Both principles are derived from the idea that significant risks, burdens and constraints should not be imposed on future generations after the time when institutional control of a waste site is relinquished. Although rarely stated, the basic principles of the protection of the environment are clear (IAEA, 1992):

(a) The ecological balance of areas should not be unnecessarily disturbed;

(b) Pressures on rare and endangered species should not be increased;

(c) Known toxic materials should not be released into the environment without careful assessment of their potential for re-concentration or accumulation.

Sensitivity to radiation increases as the development and the DNA content increases.

It can thus be argued that humans appeared to be the category most sensitive to radiation exposure. Radiation protection measures for humans will thus also satisfy general environmental protection principles.

CHAPTER 4

SAFETY ASSESSMENT OF RADIOACTIVE WASTE DISPOSAL SYSTEMS

4.1 GENERAL

In Chapter 1 it was mentioned that the general objective of a safety assessment is to estimate the impact of radioactive waste disposal on the human and surrounding environment as a function of time. However, to achieve this, one must have a framework, also known as a *disposal system*, that describe the disposal method and site in detail (Van Blerk, 1999*a*). The safety assessment then becomes an investigation, quantification and explanation of the effects that a proposed (or selected) radioactive waste disposal system will have on its surroundings. In Section 4.2, a definition will be provided of what the disposal system consists of.

Various definitions exist of what is meant with the term safety or performance assessment. The IAEA formally defines performance assessment as (IAEA, 1993*a*):

> *"...an analysis to predict the performance of a disposal system or sub-system, followed by comparison of the results of such analysis with appropriate standards or criteria."*

A performance assessment becomes a *safety assessment* when:

> *"...the system under consideration is the overall waste disposal system and the performance measure is the radiological impact or some other global measure of impact on safety."*

This definition fails to answer specific questions about the meaning of such an assessment, what one tries to achieve through the assessment (its purpose) and what it consists of. The basic principles of a post-closure safety assessment were discussed in great detail in Van Blerk (1999*a*) and therefore summarised information will be provided as background in Section 4.3, followed by a few characteristics that are unique to a post-closure safety assessment in Section 4.4.

The goal of a safety assessment is not to predict the actual outcome of the radioactive system, but to determine the conditions for which reasonable assurance of compliance with safety objectives can be provided. To do this a structured scientific based method must be followed. In Section 4.5 a framework for such an approach is discussed. As in any study concerning the physical processes in the environment, uncertainties exist in safety assessments. In particular, safety assessments must extrapolate over large spans of time and space and therefore the level of uncertainty increases. These uncertainties need to be addressed to a satisfactory level before the outcome of the assessment can be accepted with confidence. This chapter is concluded with the uncertainties associated with a safety assessment as well as the treatment of it, in Section 4.6.

4.2 DEFINITION OF A DISPOSAL SYSTEM

As mentioned in Section 4.1, the disposal system serves as a framework that describes the disposal method and site in detail. This include the potentially affected geology and the accessible environment (e.g., air, land water people, plant and animal life) surrounding the site (AECL, 1994). More specifically, the disposal system domain is defined as the spatial and temporal domain that consists of:

(a) The waste,

(b) The engineered and natural barriers expected to contain the waste,

(c) The potentially contaminated geology and surface environment,

(d) The geology, surface environment and human behaviour necessary to provide an estimate of the movement and the exposure of man to the radionuclides, following the closure of the repository.

Within this framework, it is possible to determine how radioactive materials may escape from the disposal site and along which paths can it migrate and what effect it will ultimately have on human beings. A more structured representation of the components of the disposal system, as well as the flow of information between these components, will be discussed in Chapter 5.

4.3 DEFINITION OF A SAFETY ASSESSMENT

Scientific Committee 87-3 established by the National Council on Radiation Protection (NRCP) recently conduct a study concerned with providing a review of current guidelines, acceptable approaches, and concepts for conducting safety assessments for near-surface low-level radioactive waste disposal facilities. In their findings (Kennedy, 1997), the committee portrayed safety assessment as a multi-disciplinary, iterative process focussed on regulatory compliance rather than an analysis of a disposal system for the purpose of predicting actual outcomes. With this in mind, they defined safety assessment as: *'the iterative process involving site-specific, prospective evaluations of the post-closure phase of the system'* with three primary objectives:

(a) to determine whether *reasonable assurance* of compliance with quantitative performance objectives can be demonstrated;

(b) to identify data, design and model development needs for *reaching defensible decisions about regulatory compliance;* and

(c) to identify waste acceptance criteria – i.e. a list of the waste types for which the repository is intended – relate to the quantities of wastes that need to be disposed.

This definition contains carefully selected phrases that have specific implications for safety assessments, especially if it is compared to any other scientific or technical problems.

Iterative process in the definition means that safety assessments should be conducted with the expectation that two or more sequential sets of calculations will be necessary. An iterative approach helps reduces the tendency of a safety assessment to become focussed on detailed modelling considerations, without questioning the relative importance of each of the components. This term also emphasises that modelling must be conducted in parallel with data collection and engineering design activities. An iterative process serves to increase the credibility of the final product in identified stages. When efficiently applied, safety assessment is a powerful decision-making tool, providing input regarding additional design and data collection activities.

Site-specific in the definition underlines the need to include data from the site, waste and facility being considered.

Prospective evaluations in the definition emphasises that the results are not intended as predictions of actual behaviour. The analyst is tasked with projecting consequences many generations into the future, for which some data are non-existent. Although some aspects of safety assessments are based on a stronger scientific basis than others, much of the analysis depends on the judgement and experience of the analyst. Modelling in a safety assessment is thus directed towards building a sufficient understanding of the system behaviour for the purpose of the analysis. This is done by following multiple lines of reasoning and developing a suite of potential outcomes that reflect the importance of specific aspects of the system with respect to the compliance decision.

Post-closure in the definition highlights the need to only address future performance following closure of the facility.

Reasonable assurance in the definition emphasises the inexact nature of safety assessment calculations, the role of judgement in the process, and the inability to absolutely ensure safety, and thus, regulatory compliance. In this regard, reasonable assurance is limited to the context of *reaching defensible decisions about regulatory compliance.*

The goal of safety assessment as a decision tool is thus not to predict the actual outcome, but to determine the conditions for which *reasonable assurance* of compliance with safety objectives can be provided. This goal should drive the entire assessment process, especially when models are defined and used to predict the behaviour of radionuclides through the near field, geosphere and biosphere. The results are largely a function of the data, design and assumptions considered in the analysis. Changes in any one of these conditions can result in changes to the conclusions resulting from the assessment (Kennedy, 1997).

4.4 UNIQUE CHARACTERISTICS OF SAFETY ASSESSMENT

The disposal system defined in Section 4.2 is used to protect future generations (our children and their children) and the environment they are living in beyond the time scales over which we have control today. It is therefore necessary to qualitatively and quantitatively link how the concrete reality of the disposal facility, which is something that was designed, constructed and implemented today, will affect things important to us, like risks and doses to future generations. To qualitatively describe the relationship between what has been disposed of in the ground and it's potential influence on future generations and the environment, safety analyses need to be done into the extreme distant future. The demographic features of future generations are unknown and, therefore, safety assessment analysis has to calculate doses to hypothetical persons from a hypothetical source.

Assessment calculations are normally done using dubious models and questionable data. In addition, because of our inherent lack of knowledge about the future, these calculations have to assume that the past is an accurate reflection of the future. This is a sound approximation for geological analysis, because geological environments, for example, are more stable than human activities.

The long-term implication of the objective of radioactive waste management seems to require the application of radiological protection to future generations. The radiological protection criteria established by the ICRP, however [e.g. acceptable effective dose limit of 1 mSv·year^{-1} (ICRP, 1990)], introduce some problems if applied to radioactive waste disposal. The ICRP criteria were established for *real* doses to *real* people coming from *real* practices. That is not the case in waste disposal, because people will not be exposed to doses until some time in the future. Depending on the classification of the waste and the concept implemented, this point in time can be anything from 10^1 to 10^6 years. One does not know what the disposal facility would look like in a 1000 years, for example, or what the demographical features of the population will be? Where does the dose calculated today apply to in future? A well today used for water supply will not exits in a 1000 years time.

Despite the difference of safety assessment analysis when compared with other scientific activities, many people come to this point and try to force it to be a scientific problem. They ignore the limiting factors and concentrate on the science by doing good science, in the interest of science. This has resulted in enormous expenditure and many resources being allocated to the problem, especially for high-level waste disposal. Alternatively one can use the unique characteristics of safety assessment and do a *compliance calculation* instead of a *predictive calculation* (Kozak, 1997). The goal of safety assessment is to make good management decisions and to do this, it is not necessary to predict the future, or the *exact* future doses to humans. The safety assessment definition stated that the decision is about reasonable assurance of regulatory compliance of safety and for that predictive calculations are unnecessary. Mathematically, this approach is equivalent to try and solve an inequality (dose < x) rather than an equality (dose = x).

The mechanistic approaches used in safety assessment to reach these goals are different from what would be used in predictive analysis. What one tries to do is to illustrate what might happen under different circumstances rather than predict what will happen under real conditions. This requires data to *bound* the problem and not to predict the problem. The models that are used in the analysis need not be scientifically rigorous in terms of the three dimensional properties of the domain under consideration. Instead, it should be useful for achieving the objectives of the safety assessment.

4.5 FRAMEWORK FOR A SAFETY ASSESSMENT

4.5.1 General

The worldwide interest in safety assessment from both the regulators and operators has led to numerous variations in the structural framework of safety assessment. The framework that served as a guideline for the development of a structured methodology in Van Blerk (1999*a*), corresponds to the approach proposed in the IAEA Coordinated Research Programme (CRP) on the "*Improvement of Safety Assessment Methodologies for Near-Surface Radioactive Waste Disposal Facilities*" (ISAM) (IAEA, 1997). The safety assessment approach, of which the elements will be discussed briefly, is presented Figure 4-1.

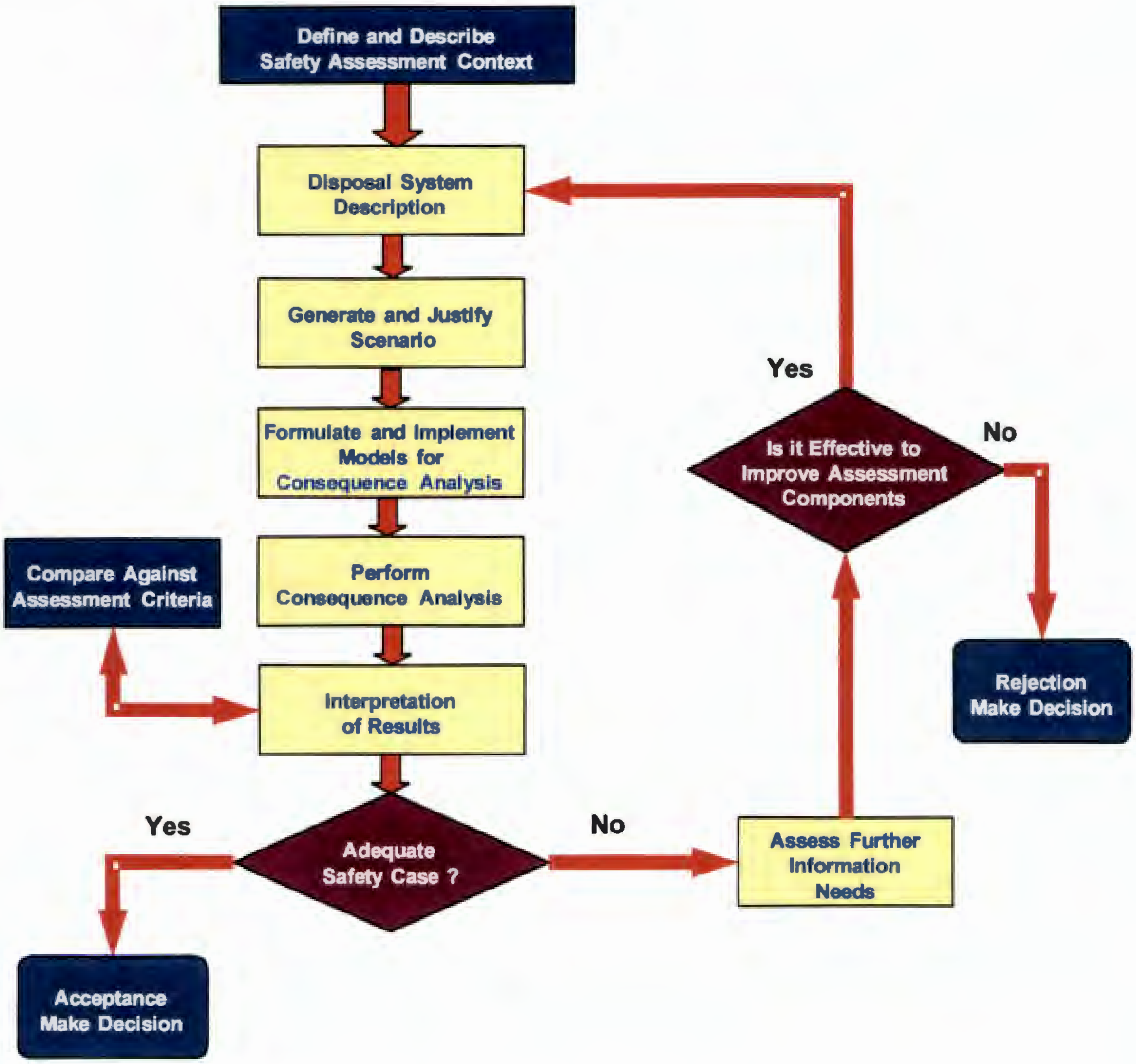


Figure 4-1: A framework for the ISAM approach for the safety assessment of near-surface radioactive waste disposal systems.

4.5.2 The Assessment Context

The scope and content of the safety assessment that will be performed are defined in the assessment context. Generally, it contains a set of high-level assumptions and constraints that reflect the regulatory framework, purpose and focus of the safety assessment, what to include or exclude from the assessment and the justification for the choices. Essentially, it can be considered as the bounding conditions for the safety assessment. Examples of issues to address in the safety assessment context include:

(a) Assessment purpose,

(b) Regulatory requirements and exclusions,

(c) Assessment endpoints, and

(d) Stakeholders.

The assessment purpose relates to various aspect of radioactive waste management, such as site selection, site characterisation, derivation of waste acceptance criteria, concept selection, development and engineering design of a new disposal concept, data accumulation programmes, remedial actions, system optimisation and public confidence.

The regulatory requirements may include the fundamental principles as well as additional principles in terms of radiological protection standards. The *radiological protection standards* define the safety criteria used by regulators and management to make decisions concerning the acceptability of the site concept or facility. Other regulatory requirements may concern the institutional control and the time scales of analysis.

The assessment endpoints (safety indicators) define which indicators will be used in the assessment. In most safety assessments the dose or risk impact on humans will be the assessment endpoint.

The stakeholders as part of the assessment context define the target audience for the assessment. In other words, all parties that will have an interest in the results of the assessment or which could be affected by the presence of the disposal facility. An example of a detail safety assessment context for a radioactive waste disposal facility can be found in Van Blerk, (1999*b*).

4.5.3 Disposal System Description

The assessment context, together with the characteristics of the disposal system, provides the necessary basis for the safety assessment. For this reason it is worthwhile to provide a detailed description of currently available information on the disposal system and its various components. This description can be updated as the safety assessment process iterates.

4.5.4 Generation and Justification of Scenarios

As mentioned in Section 4.4, one of the major sources of uncertainty in post-closure safety assessments, is our inherent lack of knowledge about future conditions at the site. An approach commonly used to circumvent this problem is to collate and screen all currently available information on the characteristics of the disposal system and any other natural or human induced conditions. Personal judgement is then used to develop a number of scientifically sound descriptions, commonly referred to as scenarios, of the future conditions of the site (Van Blerk, 1999*a*). The procedure of doing so is referred to as scenario generation and justification.

4.5.5 Formulation and Implementation of Models

Once the scenarios have been developed, their consequences in terms of the assessment context must be analysed. To quantitatively assess the consequences of each scenario (a qualitative assessment approach would be sufficient for some), the scenario must be organised into a form that is amenable to mathematical representation. The equations of the mathematical model may be empirically and/or physically based, depending upon the level of understanding and information concerning the processes represented. A mathematical model on its own could not be used for analysing the behaviour of a certain phenomenon. It requires a set of model-level assumptions (concerning the dimensionality, modelling domain, initial conditions, boundary conditions, etc.) to solve the mathematical model. These assumptions comprise the *conceptual model.*

4.5.6 Consequence Analysis

Once the computer model is prepared with the necessary input data, the consequences of all the scenarios implemented in specific mathematical and conceptual models can be assessed. The consequence analysis phase is very important and an integral part of a safety assessment. It comprises of compliance calculations to assess the contribution of the near-field, geosphere and biosphere contribution to a total dose.

4.5.7 Interpretation of Results

Interpretation of results box in Figure 4-1 represents the first opportunity for the analyst to examine quantitative results from the modelling of scenarios. The results should be compared with applicable criteria as defined in the assessment context. The assessment context will include regulatory criteria and may include other indicators against which results can be compared. The results interpretation represents the way the modelling outputs are eliminated screened or conditioned to facilitate comparison with the assessment context.

4.5.8 Confidence Building

The purpose of assembling a safety assessment is to provide a level of confidence to all stakeholders that it is reasonable for waste disposal to proceed and most importantly, that reasonable assurance of regulatory compliance can be demonstrated. In other words, the proposed disposal system complies with the overall objective of radioactive waste management.

Confidence building is involved in all aspects of assembling a safety assessment. Application of a quality assurance programme is another confidence building measure. Activities associated with the use of good science and good engineering practice can add an additional level of confidence. Consideration of sensitivity and uncertainty as part of the consequence analysis may also be helpful, as may simple scoping calculations. In Figure 4-1, many of these activities are associated with the elements "*Compare against assessment criteria*", "*Adequate safety case?*" and "*Is it effective to improve assessment components*".

4.6 UNCERTAINTIES IN SAFETY ASSESSMENT

4.6.1 General

As in any study concerning the physical processes in the environment, uncertainties exist and must be addressed before anyone will accept the assessment with confidence. In particular, safety assessments must extrapolate over large spans of time and space, into conditions that cannot be empirically observed. Conditions currently prevailing at the site are usually so complex, even the small subset of conditions that are empirically available at the field scale, confound attempts to *predict the actual behaviour* of the system accurately. It therefore increases the level of complexity of the assessment. However, this does not change the fact that uncertainties exist and need to be addressed. In fact, the treatment of uncertainties is central to the establishment of a defendable post-closure safety case.

Uncertainties associated with safety assessment analysis can be grouped into the following general categories, namely:

(a) Uncertainty in the future state of the disposal system;
(b) Data and parameter uncertainty; and
(c) Model uncertainty.

4.6.2 Uncertainty in the Future State of the Disposal System

Radioactive waste has the advantage above chemical and toxic waste in that its activity decreases with time. However, the long half-life of many isotopes (tens to millions of years) makes it virtually indestructible as far as human life is concerned. For this reason, safety assessments must extrapolate system behaviour far into the future, and consequently, assumptions about future conditions of the system are entered into the analysis. These uncertainties are the result of our inherent lack of knowledge about how the system will evolve in time, e.g.:

(a) potential differences between the intended design of the repository and the eventual real facility;
(b) potential differences between the intended waste emplacement schedule and configuration, and as it is implemented;
(c) the numerous natural, human induced or disruptive events and processes, which will act on the disposal system after its closure; and
(d) the difficulty in anticipating future human habits and behaviour.

As mentioned in Section 4.5.4, scenario generation and justification is aimed at this issue and for this reason uncertainty in the future state of the system is sometimes termed scenario uncertainty (Van Blerk, 1999*a*). The main purpose of scenario generation in the post-closure safety assessment of a radioactive system is to use scientifically informed expert judgement to guide the development of descriptions of the system and its future behaviour. Basically, it consist of four steps, namely:

(a) identifying a comprehensive list of Features, Events and Processes (FEPs);
(b) screening the comprehensive list to a practical number that can be analysed

with available resources;

(c) describing the relationship between the FEPs; and

(d) arranging them into scenarios for consideration in the safety assessment.

The first step in the generation of scenarios for a radioactive system is to identify a comprehensive list of Features, Events and Processes (FEP) associated with the components of the system. Since not all the FEPs in the list will be important to a specific site, this comprehensive list is systematically screened and only those that are significant for the underlying assessment context and system description are retained.

A RES (Rock Engineering System) matrix is used to describe the relationship between FEPs. In this matrix the main variables or parameters are identified and listed along the leading diagonal of a square matrix, and the interactions between the parameters occur in the off-diagonal terms. The RES matrix is used as an auditing tool to order the FEPs in a structured and traceable manner and finally, to generate scenarios and the conceptual model.

4.6.3 Data and Parameter Uncertainty

Uncertainties in data can arise from measurement errors for which there are essentially two sources, namely: instrumental and human errors. It is usually not too difficult for an observer to limit the influence of instrument errors, which are mainly caused by the imprecision and malfunctioning of the available measuring devices. Human errors, on the other hand, are often difficult to detect. A few of the major human error sources include, for example, incorrect or misapplied measuring techniques, systematic errors and blunders.

Parameter uncertainty incorporates data uncertainty and, in addition, can be caused by measurement errors. However, there are additional sources of parameter uncertainties, such as the large spatial and temporal variation in many of the data sets and lack of representativeness, e.g. scale and geometric effects.

The influence of data and parameter uncertainty can be studied by two methods, namely: deterministic methods and probabilistic methods. In deterministic methods a set of estimated values of a parameter is used to evaluate the impact that the specific parameter might have on the final result, particularly the regulatory decision. In probabilistic methods, such as the Monte Carlo method, a parameter is represented through a probability density function (pdf), or the mean and variance of such a distribution. These values are then used in a series of analyses to arrive at a probability that the regulatory decision will be achieved or not. From a classical statistical approach, this means that a lot of parameter values must be available, and this is not always the case. If a Bayesian statistical approach is followed, then whatever data is available at a specific time will be used and whenever additional data becomes available the probability density function must be updated.

4.6.4 Model Uncertainty

Data and parameter uncertainty will certainly affect model uncertainty, but there are a number of additional uncertainties that are particular important for the development of models in the analysis of scenarios. These uncertainties arise in all the models used, namely:

(a) uncertainty in the mathematical model describing the behaviour of some phenomena in the disposal system,

(b) uncertainty in the formulation of the conceptual model to solve the mathematical equations, and

(c) uncertainty in the analytical or numerical models used to denote the solution of the conceptual model.

It is not always possible to proof that the computer codes implemented in the conceptual model are correct and does not contain programming errors. This adds an additional source of uncertainty referred to as computer code uncertainty.

There do not exist specific guidelines to study model uncertainty, except for the verification and validation. Otherwise one has mainly to rely on strict quality control over the calculations and the applications of various assurance procedures to limit the level of uncertainty. One model uncertainty that may arise is to what extent does the mathematical model represent the physical processes responsible for the phenomenon. In safety assessments the mathematical models used are tested thoroughly, so one can safely neglect mathematical model uncertainties if compared with other uncertainties. The main contribution to model uncertainty comes from the ability of the chosen conceptual model, which is based on the mathematical model, to represent the phenomenon. Model verification means the model must be able to reproduce observations of the phenomenon for which it was developed and model validation is a process to show that the model is able to describe observations of the phenomenon not used in its verification.

CHAPTER 5

BIOSPHERE COMPONENT OF THE DISPOSAL SYSTEM

5.1 GENERAL

In Chapter 1 it was mentioned that the biosphere is one of the important components associated with the movement of radioactivity through the environment to human beings. It can be defined as that portion of the environment normally inhabited by humans and other living organisms and comprises those parts of the atmosphere, the hydrosphere (ocean, seas, inland waters and subsurface waters) and the lithosphere normally related to human habitats or the environment (IAEA, 1993*b*).

In the context of a safety assessment, it is a description of the biotic and abiotic components of the surface environment, and their relationships to the movement of radionuclides through the disposal system. This suggests that the biosphere form an important part of the disposal system. It would therefore make sense to discuss the components of the disposal system in more detail, which will be done in Section 5.2. There are various ways in which radionuclides can move through the disposal system and in Section 5.3 the transport of radionuclides through the disposal system will be discussed

5.2 COMPONENTS OF THE DISPOSAL SYSTEM

5.2.1 General

The components of a disposal system can be conveniently divided into two classes, namely the internal and external components. The internal components are those components that are situated within the spatial and temporal boundaries of the system, while the external components are situated outside these boundaries (Van Blerk, 1999*a*). These components can be further divided into a number of subsystems or components, that are linked to one another through various elements more commonly known as features, events and processes (FEPs), as presented in Figure 5-1.

5.2.2 The External Components

The external components in Figure 5-1 are usually the components over which people has the least control. The external factors include natural and human induced issues that originate from outside the spatial and temporal boundaries of the disposal system. In other words it referred to processes taking place on a regional scale (e.g., geological and climatic processes and events) and much larger time scales as the operation of a disposal facility. Although these issues are not necessarily part of the disposal system, they have the potential to influence the long-term performance of the disposal system. It is therefore important to include these factors in the characterisation of the disposal system.

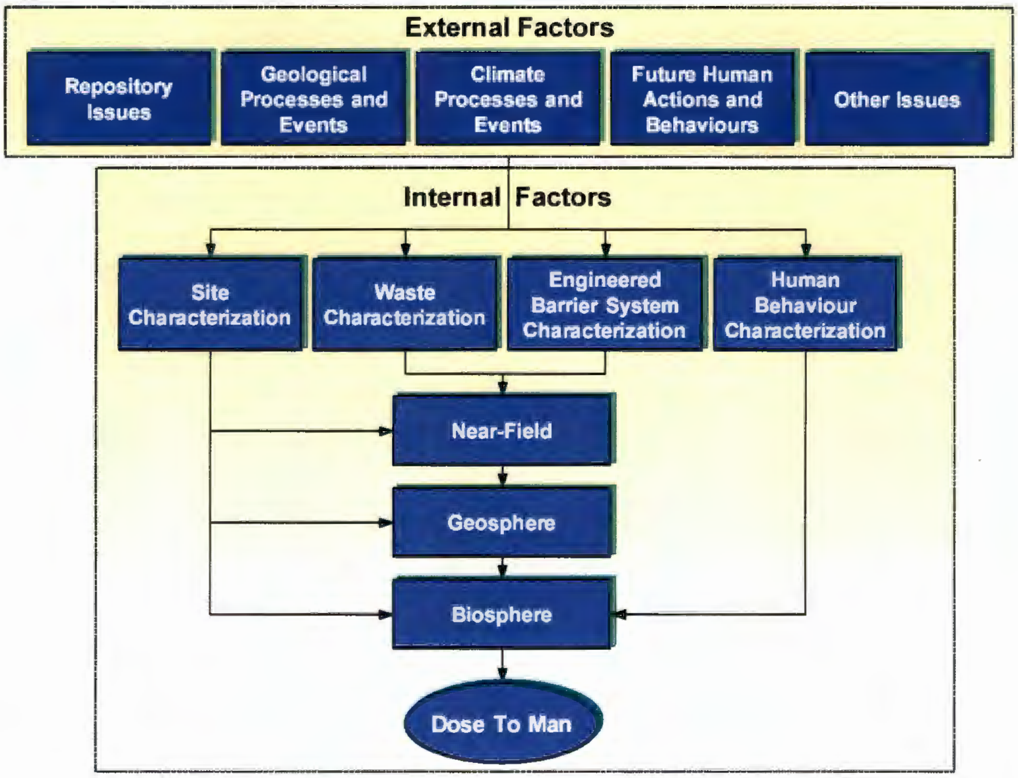


Figure 5-1: Conceptual representation of the different components of a disposal system and the flow of information between them. (Van Blerk, 1999*a*)

One factor that is frequently ignored in the design of a disposal system, but may have a major influence on its long-term performance, is the time span and degree of reliance that can be placed on institutional control of the facility. Closely related to this factor are future human actions and regional practices that can change the engineered barrier system and geological barriers, and thereby affecting the performance of the disposal system adversely. These actions may either be inadvertent or deliberate and may occur during the institutional control period or thereafter (Van Blerk, 1999*a*). A few examples of future human actions that can affect the safety assessment are:

(a) mining and other underground activities,
(b) changes in the social and institutional structures,
(c) non-intrusive site investigations, e.g. for human resources,
(d) future drilling activities in the repository or its surroundings,
(e) surface activities, e.g. excavations, site development and archaeology,
(f) future actions needed to remedy problems with waste repository,
(g) knowledge of the location of the repository (inadvertent or deliberate intrusion),
(h) humankind's influence on the climate, e.g. emission of greenhouse gasses, deforestation, and
(i) groundwater and surface water management activities, e.g. groundwater withdrawal, dam construction, irrigation schemes.

From the definition of the biosphere in Section 1.1 and Section 5.1, it is clear that these future human actions could influence the performance of the biosphere in a post-closure safety assessment and should therefore be included in the study of the biosphere.

5.2.3 The Internal Components

As mentioned above, the internal components are those components that are situated within the spatial and temporal boundaries of the disposal system. From Figure 5-1 it is clear that site information, physical, chemical, biological and radiological properties of the waste, engineered barrier system information and human behaviour characteristics that could influence the performance of the disposal system, are all used in combination with the external factors to define the migration of dissolved waste through what is known as the near-field, geosphere and biosphere.

The *near-field* can be defined as the excavated area (disposal domain) of the disposal system, including the repository, the EBS, as well as that part of the surrounding geology whose characteristics have been or could be altered by the presence of the repository or its content (IAEA, 1993*a*). Generally, the term *geosphere* includes the host medium surrounding a repository, the soil and bedrock from the repository down to the water table, any sediments overlying the host medium below the water table, as well as the groundwater in the host medium and sediments. The extent of the geosphere will be influenced by whether a near surface or a geological disposal system is considered. Using this configuration, the radionuclides that escape the near-field, will move through the geosphere to reach the biosphere.

Site characterisation as part of a safety assessment includes a detailed surface and subsurface investigation at a candidate disposal site. During this process, information to evaluate the suitability and the possible long-term performance of a waste disposal facility at the site is obtained (IAEA, 1993*b*). Information to be acquired during site characterisation depends on the purpose of the safety assessment. Site characterisation is an important part of the assessment and provides input to the near-field, geosphere and biosphere.

Waste characterisation as part of a safety assessment includes a description of the physical, chemical, biological and radiological properties of the waste that need to be disposed of. During the waste characterisation phase the need for further adjustment, treatment or conditioning of the waste, and its suitability for further handling, processing, storage or disposal, will be established (IAEA, 1993*a*).

Characterisation of the engineered barrier system (EBS) consists of a detailed description of each component of the EBS to be used in the concept. This includes a description of the materials to be used, their physical and chemical characteristics, or any other characteristic (e.g. biological, mechanical, thermal) that might affect other components of the EBS or the surrounding geology.

Waste characterisation and the engineered barrier system characteristics are used as input into the near-field.

Characterisation of human behaviour in the context of a safety assessment entails the identification of the human community (known as the critical group) that could potentially be affected by the waste disposal system. This includes human behaviour characteristics that might influence the performance of the disposal system in terms of the regulatory requirements, like future human actions. From the definition of the biosphere in Section 1.1 and Section 5.1, it is clear that these characteristics could influence the way in which one treats the biosphere in a safety assessment. It therefore makes sense to define these characteristics as part of the description of the biosphere. Factors that may serve as a guideline as to the type of information that should be gathered in this regard, include:

(a) time spent in the environment,

(b) community and social characteristics,

(c) normal activities of the group and their use of materials,

(d) dietary patterns of the group and their variation with age,

(e) leisure and other activities associated with the environment,

(f) rural, urban, agricultural and industrial use of land and water,

(g) information about the dwellings or other structures of the target group,

(h) anatomical and physiological characteristics and their variability with age, and activities associated with the processing and preparation of food and water.

These human behaviours and actions are an important part of the assessment and provide fundamental input to the biosphere.

5.3 TRANSPORT OF RADIONUCLIDES THROUGH THE DISPOSAL SYSTEM

There are different ways through which radionuclides may migrate through the disposal system. Depending on the site-specific characteristics of the system, some of these processes may be more relevant than other and some of the processes may be more applicable to either the near-field, geosphere or biosphere.

Six different transport mechanism can be identified through which radionuclides may migrated through the disposal system, namely

(a) Water mediated transport;

(b) Solid mediated transport;

(c) Gas-mediated transport;

(d) Atmospheric mediated transport;

(e) Animal, plant and microbe mediated transport; and

(f) Human action mediated transport.

Water-mediated transport processes represent all processes leading to transport of radionuclides in water. Radionuclides may travel in water as aqueous solutes associated with colloids in surface and groundwater or, if flow conditions permits it, with larger particulates/sediments in surface water bodies. Examples include advection, molecular diffusion, matrix diffusion, dispersion, transport by surface run-off and transport in rivers and streams.

Solid-mediated transport processes represent all processes leading to transport of radionuclides in solid phase. Examples include large-scale movement of sediments, landslides, solifluction, volcanic activities, rock falls, resuspension and deposition.

Gas-mediated transport processes represent all processes leading to transport of radionuclides in gas or vapor phase or as fine particles or aerosol in gas or vapor. Examples include radioactive gases generated from the waste (e.g. ^{14}C-labeled carbon dioxide or methane).

Atmospheric-mediated transport processes represent all processes leading to transport of radionuclides in air as gas, vapor, and fine particulates or aerosol. Radionuclides may enter the atmosphere from the surface environment because of a variety of processes including transpiration suspension of radioactive dust and particulates or as aerosols.

Animal, plant and microbe mediated transport processes represent all processes leading to transport of radionuclides because of animal-, plant- and microbe activity. Of particular importance in this category is all burrowing animals (animal intrusion) through the process of bioturbation, deep rooting plant species (plant intrusion) through uptake and desorption, as well as movement of contaminated microbes.

Human-action-mediated transport processes represent all processes leading to transport of radionuclides as a direct result of human actions. Examples include processes such as drilling into or excavation of the repository, the dredging of contaminated sediments from lakes, rivers and estuaries and placing them on land. Earthworks and dam construction may result in the significant movement of solid material from one part of the biosphere to another. Ploughing results in the mixing of the top layer of agricultural soil, usually on an annual basis.

5.4 RECEPTORS IN THE BIOSPHERE

5.4.1 General

The inability of the disposal system to isolate and contain radionuclides for long periods of time or failure of the disposal system to perform as originally anticipated, results in the transport of radionuclides through the near-field, geosphere and biosphere to expose man to a certain *dose*. The site, waste, EBS and human behaviour characteristics are used to accumulate the information necessary to characterise the potential flow and transport of radionuclides through the system. The dose (or its equivalent risk factor) is then compared with the appropriate regulatory criteria set for the disposal system under consideration and a decision is made. In the remainder of this document, the emphasis will be on the contribution of the biosphere in the performance of the disposal system.

Figure 5-2 shows the biosphere represented as subsystems connected to each other through discrete boundaries, with homogeneous conditions inside. Within these subsystems, generally referred to as compartments, radionuclides are assumed to be instantaneously distributed, with different transport processes taking place between the different compartments. Human behaviour and characteristics of the potentially affected group of people are of particular importance in analysing the biosphere as part of the total disposal system. The biosphere is normally not considered as being part of the natural barrier system. However, several processes within the biosphere can contribute to the retardation and dilution of radionuclides.

In Figure 5-2, the different receptors within the physical and living compartments of the biosphere are identified. In order to calculate the movement of radionuclides through the biosphere, it is necessary to describe the different receptors of radioactivity in the biosphere. As in the geosphere, water movement is the dominant process for radionuclide transport. It therefore makes sense to consider the hydrological cycle (Freeze and Cherry, 1979) in terms of precipitation, run-off, infiltration, plant-uptake, transpiration, evaporation, recharge to an aquifer, discharge to a surface water body and the influence it will have on the biospheric compartments, and will be discussed in Section 6.3.2.2. Water bodies are important and include wells, small watercourses, lakes and the sea.

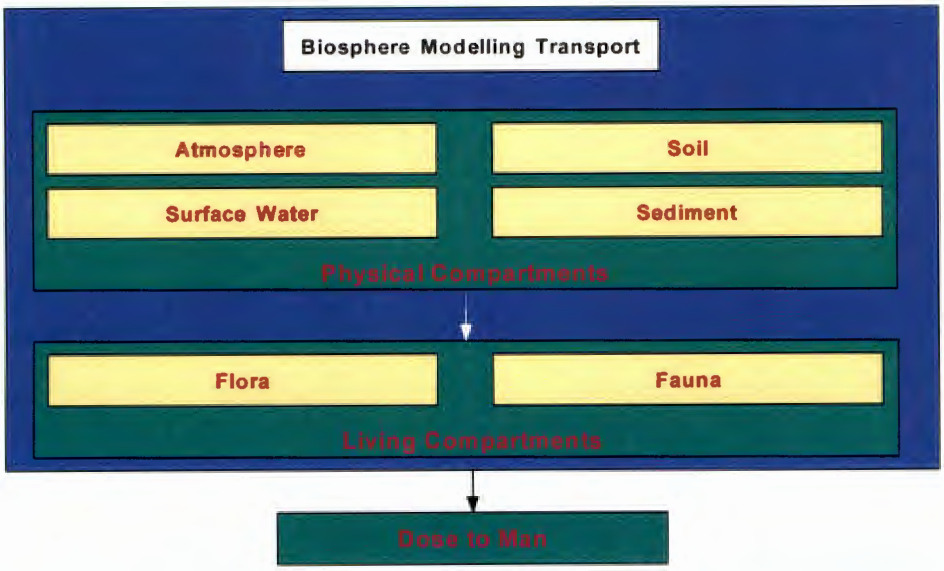


Figure 5-2: The composition of the biosphere in terms of the receptors and the relationship between the different compartments (Torres and Simon, 1997).

5.4.2 Wells

Although small, wells are very important for the biosphere analysis. They constitute a short circuit between the geosphere and the biosphere. The groundwater travel time can be shortened considerably in the geosphere, and the dilution will be much less than in large water volumes such as lakes, watercourses or superficial groundwater reservoirs. Water usage from wells will not only differ from country to country, but also from region to region. Abstraction from contaminated wells could lead to contamination of irrigation-, livestock-, household and drinking water, and consequently result in internal exposure through crop, animal product and water consumption.

5.4.3 Watercourses

In watercourses such as ditches, creeks, brooks and rivers, groundwater seepage will be mixed with a large quantity of surface water. This means that any radionuclides present in the groundwater will be greatly diluted. The important exposure pathways are largely the same as for a well, with the added internal pathway of fish and shellfish consumption and external exposure of swimming and bathing.

5.4.4 Lakes

Dilution is even greater in lakes. Fish and shellfish consumption and bathing are of greater importance than in the case of watercourses. External exposure from water and sediments on beaches is another exposure pathway. Studies on the exposed bottom sediments of dried-up lakes after land uplift, showed that crop cultivation on these soils lead to a 10 times higher dosage compared to an undrained lake.

5.4.5 Sea

If radionuclides reach the biosphere via the oceans, dilution is extensive and the dosage to the critical groups is only a few tenths of a percent of the dosage from inland releases. The highest dose contributions are obtained from fish consumption.

5.4.6 Sedimentation

Closely related to water bodies, is the process of *sedimentation* within a water body. The suspension-sedimentation-resuspension cycle provides opportunity for intimate contact between suspended particulate matter and radioactivity in solution in the water, as well as between the water and the bed of the system.

5.4.7 Soil

Nuclides may reach the *soil* directly through contaminated groundwater that discharge to a terrestrial zone, or indirectly through irrigation water or deposition from the atmosphere. Regardless of the source, nuclides may gradually accumulate in the soil over time, and enter crops and natural vegetation.

5.4.8 Atmosphere

Nuclides reach the *atmosphere* through suspension processes and are lost through deposition processes. In reality, atmospheric dispersion acts as a "*sink*" for contaminants, as mass is redirected away from the source. The processes of suspension and dispersion of contaminants result in a radionuclide concentration in the air. Examples of physical processes that should be considered as part of atmospheric transport are:

(a) dispersion by turbulent diffusion and downwind transport;
(b) dry deposition onto the ground due to effects at the air/ground interface;
(c) wet deposition due to washout; and
(d) radioactive decay.

5.4.9 Living Compartment

Nuclides in the physical compartments of the biosphere may be taken up by living organisms, such as plants and animals. These nuclides may affect the organisms, move along the food chain and eventually be ingested by humans. Ingestion of radionuclides in food or contaminated water can be an important contributor to the total dose received by an individual or critical group. The information obtained during the human behaviour characterisation will be of particular importance in analysing the physical compartment of the biosphere. Of particular importance is the terrestrial ecosystem. Not only is man part of this system, but a significant portion of his food also comes from terrestrial sources. Radioactive materials can enter the terrestrial ecosystem in a variety of ways:

(a) from the atmosphere through deposition;
(b) from water used for irrigation; or
(c) from soil contaminated by groundwater or deposited radionuclides.

Examples of physical processes that should be considered as part of a terrestrial food chain are (Torres and Simon, 1997):

(a) deposition by dry or wet processes;
(b) interception and retention by vegetation;
(c) translocation from sites of deposition to the edible tissues of vegetation;
(d) post-deposition retention by vegetables and soil surfaces;
(e) uptake by plant roots;
(f) direct ingestion of surface soil by grazing animals;
(g) transfer of contamination from soil, air, water and vegetation into milk and meat of grazing animals;
(h) transfer of contamination from surface water to the terrestrial system via spray;

(i) transfer of contamination from surface water to sediments and aquatic biota; and

(j) transfer of contaminants from groundwater to the terrestrial system.

Another ecosystem of importance is the aquatic ecosystem, which refers to freshwater, saltwater (marine) and brackish water (estuarine) environments. The estuarine ecosystem usually acts as a bridge between the fresh- and saltwater environments, where rivers and streams flow into bays and other arms of the sea. Although different species may occupy the same niche in different systems, the components of the systems are similar and can be modelled and discussed together (Van Blerk, 1999*a*).

CHAPTER 6

BIOSPHERE MODELS, TRANSPORT AND DOSE MODELLING

6.1 GENERAL

As mentioned in Chapter 5, the near field and the geosphere act as barriers to toxic concentrations of radionuclides. However, the possibility that radionuclides may be released to the biosphere does exist because of the long timescale, although the design and siting of the repository can minimise potential impacts to future generations. The purpose with models of the biosphere, as discussed in Section 6.2, is to estimate this potential radiological impact of the system.

From the discussion in Chapter 5, it is clear that transport of radionuclides occurs not only in the near-field and geosphere, but also in the biosphere, e.g., in surface waters, soil, atmosphere and transport through terrestrial ecosystems. It is important to fully understand the transport of radionuclides through these different mediums and the processes involved, before the actual dose to humans can be calculated. In Section 6.3 the transport of radionuclides through the various media important to the biosphere are discussed.

The radiological impact of a disposal system is calculated in the form of doses that people will receive when exposed to the environment. This dose received by a person is calculated with transfer coefficients, which represent the transport of radionuclides between different mediums, concentration ratios and dose conversion factors as discussed in Section 6.4.

6.2 BIOSPHERE MODELS

6.2.1 General

In Chapter 5 the biosphere component, as part of the disposal system, was discussed together with the receptors and transport of radionuclides through the disposal system. The discharge of radionuclides can be either directly to the receptors, or through the groundwater flow, and the living organism (fauna and flora).

6.2.2 Type of Models

The output from the geosphere flow and transport simulations, together with the characteristics of human behaviour, will be used as input into the biospheric processes, normally considered as the secondary pathways (See Figure 5-1). The output from the geosphere will be in the form of concentration values at the interface between the geosphere and the biosphere, while the behaviour will define the context of the biosphere analysis. Either mechanistic or transfer coefficient models can be used to simulate the movement of these radionuclide concentrations through the physical and living compartments of the biosphere. These models range in complexity from simple expressions to highly complex mathematical algorithms.

Mechanistic models describe processes in a physical realistic manner and are normally specific to a given process (e.g. wind erosion of landfill surface or of soil). *Transfer coefficient models* do not describe the physical processes in a mechanistic way, but instead quantitatively describe the transfer of radionuclide concentrations at release points to humans, through different compartments in the biosphere. Although the transfer coefficient approach is often not scientifically rigorous, it considers many other parts of the process implicitly, is simple and is based on real data (Torres and Simon, 1997).

There are several factors that affect the type and complexity of the models. Biosphere modelling is strongly influenced by the context in which the assessment is carried out. In particular, the approach taken should be consistent with the objectives of the assessment, the end points that need to be calculated, and the types of release to the biosphere.

It is preferable to divide the biosphere system into subsystems, which are connected to each other through discrete boundaries and assuming homogeneity inside. In Figure 5-2 these *"compartments"* are illustrated together with the transport processes that take place between one compartment and the others.

6.3 TRANSPORT MODELLING

6.3.1 General

As the radionuclides reach the biosphere through different pathways, it can be transported further to ultimately reach human beings. The major transport routes, namely: in surface water, groundwater, soil, the atmosphere, transport of radionuclides through terrestrial ecosystems, and food-chain models will be discussed in more detail.

6.3.2 Transport Modelling in Surface Water and Groundwater

6.3.2.1 General

It is a matter of observation that virtually all rivers discharge water into the sea. As the level of the sea remains more or less constant, and as the rivers show no apparent sign of ceasing to flow, there must be some mechanism by which water is returned from the sea to the land, at the same rate at which it flows via the rivers to the sea. This mechanism is known as the water cycle, and is also referred to as the hydrological cycle. Hydrology is *"the science that treats of water of the Earth, their occurrence, circulation, distribution, their chemical and physical properties, and their reaction with their environment, including their relation with living things"* (Torres and Simon, 1997). It is necessary to understand the hydrological cycle before one can actually model the movement of radionuclides in surface waters.

6.3.2.2 The Hydrological Cycle

The energy of the sun's rays caused water to evaporate from the surface of the oceans and the water vapour produced is a normal part of the earth's atmosphere. It remains in the atmosphere, completely invisible, unless cooled sufficiently to cause it to condense and form water droplets. The cooling occurs as a result of the vapour-laden air rising into higher and colder regions of the atmosphere. This may result from the air being forced upwards over a physical barrier, such as a mountain range, or over a meteorological barrier, such as a mass of colder, denser air; or it may result from convection. Whatever the cause, the chilled vapour condenses as droplets, which form around suitable nuclei (tiny dust and other particles) which are nearly always present in the atmosphere. When the droplets are present in sufficient quantity, they can be seen as clouds. These water droplets are much smaller than raindrops, and are light enough to remain suspended in the atmosphere. A graphical demonstration of the hydrological cycle can be seen in Figure 6-1.

A large amount of precipitation occurs over the oceans, and thereby short-circuiting the hydrological cycle. Water precipitation over land areas may take several routes through the remainder of the cycle. Some of it will never reach the ground surface. It will be *intercepted* by foliage, and held on the leaves of trees and plants until it evaporates. Some of the water reaching the ground will fall on bare impermeable rock or on artificial, paved surfaces. Apart from that which collects in depressions and remains there until it evaporates, this water will *run off* these surfaces into natural or artificial drainage channels. The remainder of the water will fall on soil, and it is largely the condition of that soil which will determine what happens to the water thereafter.

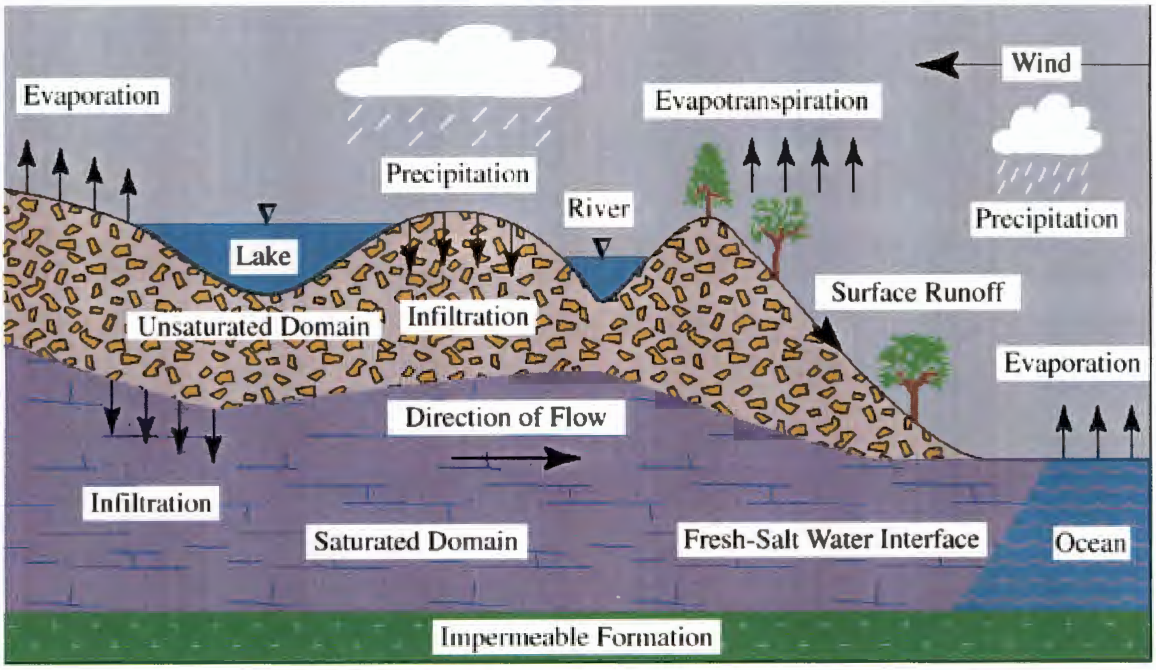


Figure 6-1: The hydrological cycle (Botha, 1994)

Broadly speaking, the water falling on soil may be disposed of in three ways:

(a) It may be *evaporated*, either directly or by transpiration from vegetation after being drawn up by plant roots;

(b) It may *run off* (run over) the surface of the soil or travel in the near-surface soil layers until it reaches a ditch or stream; and

(c) It may *soak* into deeper layers of the soil and so perhaps into the underlying rock (Torres and Simon, 1997)

When rain begins to fall on relatively dry soil, we know from experience that it is readily absorbed. In everyday terms we say that the rain *soaks* into the ground, and in scientific terms we speak of *infiltration*, which is the process whereby water enters the ground at the surface. If the soil is dry and the rainfall is light, all the water reaching the ground will infiltrate into the soil and be held there as films of moisture which surrounds the individual soil particles. This water is held in the soil until it is either evaporated directly from the soil surface or taken up by the roots of plants. A small fraction of the water, which the roots take up, is retained in the plants as part of their growth process, but the majority is evaporated from openings in the leaves and stems in the process known as *transpiration*. The combined effects of evaporation and transpiration in returning water to the atmosphere are frequently grouped together and termed *evapotranspiration*.

As each successive layer of the soil absorbs water, infiltration moves on downward through the soil and subsoil to the underlying rock. If this rock is permeable, the infiltration process will continue downwards, through the unsaturated zone, until the infiltrating water arrives at the water table and joins the groundwater in the saturated zone. Precipitation reaching the water table is called *recharge*, because it is helping to replenish the store of groundwater.

The maximum rate at which water can enter the soil is called the *infiltration capacity* of the soil. If the rainfall is exceptionally heavy, a situation may arise where water is arriving at the surface of the soil more quickly than it can enter the soil, and in this case, the infiltration capacity has been exceeded by the rate of rainfall. In these circumstances, the soil will behave like an impermeable surface, and depressions will fill and then *overland flow* (water flowing across the ground surface, usually as small trickles and rivulets) will occur. *Surface runoff* is that part of total runoff (the river flow leaving the area) which results from overland flow.

Water reaching the water table is called groundwater. It percolates slowly through the aquifers, at rates, which under natural conditions may vary from more than a metre in a day to only a few millimetres in a year. The groundwater moves towards an outlet from the aquifer, which is usually a point where the water table intersects the ground surface. Where this occurs, water will seep or flow from the aquifer, and in doing so, it will cease to be groundwater and will revert to being surface water, usually finding its way into a river channel.

6.3.2.3 Modelling Water Bodies (Aquatic Ecosystem)

The aquatic environment can be divided into four categories for the purpose of modelling the dispersion of radioactive elements released into it:

(a) Rivers;

(b) Lakes;

(c) Estuaries; and

(d) Coastal seas.

The basic characteristics of a river are unidirectional axial flow, which is at its simplest like an open pipe. Rivers flow into lakes and into estuaries. At the confluence with a lake, a river merges with a body of water in which recalculation is possible. The basic characteristics of a lake are that of a body of water with tank-like configuration, perhaps with stratification, having river input and output. The interface between a river and the estuary into which it flows may be defined by the transition of salinity, an estuary becoming progressively more saline until it merges into the sea. Alternatively, a more specific characteristic of an estuary, which merges into tidal seas, is the tidal influence; the boundary between river and estuary is then defined as the highest point to which tides flow. Probably the most difficult interface to recognise is that between estuaries and the sea, generally decided by geographical characteristics rather than particular physical properties, although the sea is easily recognised where salinity is high and tidal forces strong.

Radionuclide releases to surface waters are subject to a series of physical and chemical processes, which affect their transport from the source point. These processes include flow processes, sediment processes, and other processes (e.g. radionuclide decay, and other mechanisms that will reduce concentrations in water such as radionuclide volatilisation), and are, in general, three-dimensional and transient in nature. However, for simplicity reasons, these processes will be assumed to be at a steady state, with mining considered to be either complete or to change in one or two dimensions (Torres and Simon, 1997).

6.3.3 Transport Modelling in Soil

6.3.3.1 General

Nuclides may reach the soil directly with contaminated groundwater that discharges to a terrestrial zone, or indirectly via irrigation water or deposition from the atmosphere. Regardless of the source, nuclides may accumulate gradually in the soil over time, and enter crops and natural vegetation. Because the soil interacts directly with the atmosphere and geosphere, and is pivotal in the primary production of agricultural and natural ecosystems, it is not surprising that it is an important determinant of radiological consequences.

6.3.3.2 Transport Processes in Soil

Radionuclides in unsaturated soil are subject to a number of transport mechanisms such as:

(a) The mass flow of dissolved nuclides with the movement of soil water,
(b) Vapour diffusion of gaseous nuclides through both the vapour and liquid phases of the soil,
(c) Molecular diffusion along a concentration gradient,
(d) Diffusion along potential gradients induced by temperature differences in the soil,
(e) Movement in association with fine particles,
(f) Microbes or colloids, and
(g) Mechanical mixing through processes such as ploughing and bio-turbation.

Since water flow controls nuclide transport, nuclides can move upward or downward through the soil profile. For nuclides deposited on the soil surface from the air or with irrigation water, primarily downward leaching and sorption determine root-zone concentrations. For nuclides reaching the bottom of the soil profile with groundwater, capillary rise also plays a role. These nuclides move upward through the profile during dry periods, and to some extent to the soil solids. A portion is leached back down following the next rainfall, but the remainder continues to rise to the surface in subsequent dry periods. In this way it is possible for nuclides to reach the root zone from the water table, even in areas where the net flow of water through the soil is downwards.

The transport of radionuclides depends on the interactions of the deposited materials with various soil compounds. The association of trace substances in soils can be summarised broadly as:

(a) precipitation with soil components to form a new solid phase,

(b) occlusion during formation of a new solid phase,

(c) incorporation into organic matter and micro-organisms,

(d) absorption onto changed surfaces of clays, precipitates and organic matter,

(e) inclusion in soil materials (e.g. during mineralisation or later via solid state diffusion).

These associations will affect the mobility and transport of elements within and from a soil and hence the supply to plants via root uptake (Torres and Simon, 1997). A number of processes, see Figure 6-2, act to deplete nuclide concentrations in soil.

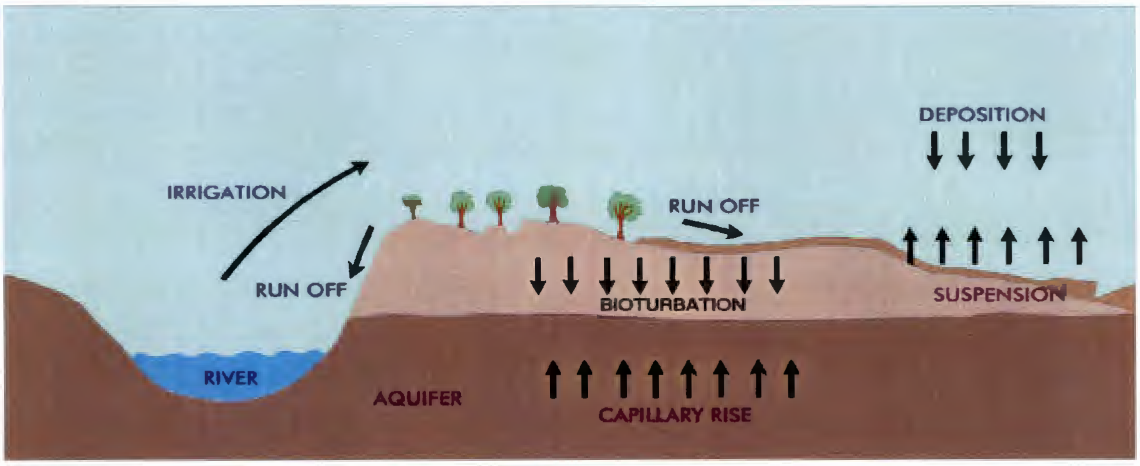


Figure 6-2: Transport processes in soil (Torres and Simon, 1997)

Radionuclides may flow out of the bottom of the profile with drainage water and be lost to the regional groundwater system. During wet weather, some may escape the soil with surface runoff. Nuclides may be lost to the atmosphere through suspension of contaminated particulate matter, or through gaseous evasion. Finally, plants may take up nuclides through their roots, although a portion of these may return to the soil when the plant dies and decays.

6.3.4 Transport Modelling in the Atmosphere

6.3.4.1 General

Radionuclides reach the atmosphere through suspension processes, and are lost through deposition processes. In reality, atmospheric dispersion acts as a *"sink"* for contaminants, as mass is redirected away from the source. The processes of suspension and dispersion of contaminants, resulting in a concentration in air, can be modelled through either a detailed mechanistic treatment or a simple transfer coefficient (Torres and Simon, 1997).

6.3.4.2 Transport Processes in the Atmosphere

When the source term to the atmosphere is known, the results must be coupled to a dispersion model to calculate an atmospheric concentration. There are many dispersion models in the literature, and many have been developed to evaluate elevated point sources, such as smokestacks. The problem of a ground level area source has also been studied, and several meteorological models have been applied to this type of problem (Culkowski, 1984). Most of these models are based on Gaussian Plume model, where inputs of wind speed and atmospheric stability are used to estimate statistical parameters to predict the distribution of air concentrations. One of the main criticisms of this approach is that it was developed for, and is usually based on, fluid motions that occur above the surface boundary layer, and does not adequately describe a ground area source. It is recommended by Torres and Simon (1997) to use the Gaussian model for screening and with some reservations for assessment purposes.

The physical processes, which are to be considered in the analysis of transport in the atmosphere area, which are demonstrated in Figure 6-3, are:

(a) Dispersion by turbulent diffusion and downwind transport,

(b) Dry deposition onto the ground due to effects at the air/ground interface,

(c) Wet deposition due to washout and rainout, and

(d) Radioactive decay

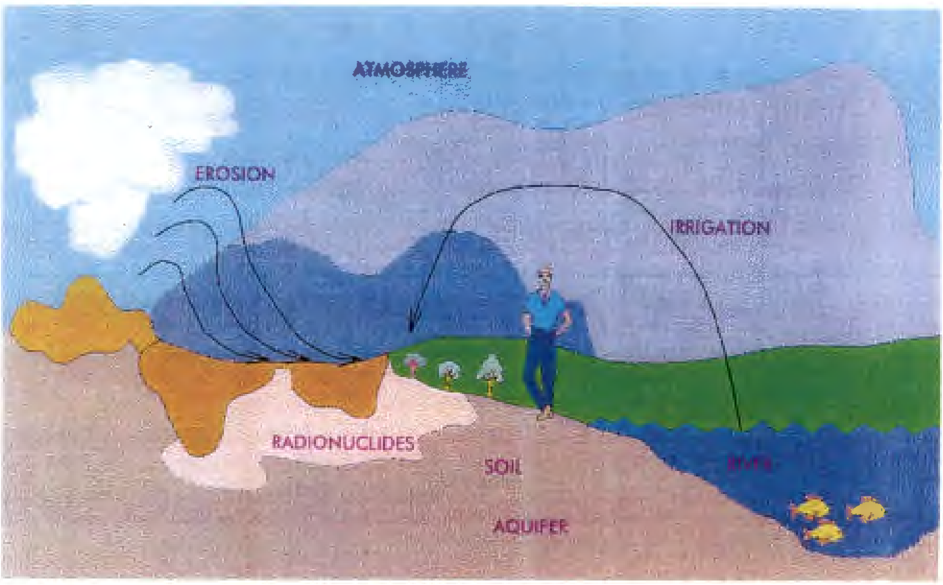


Figure 6-3: Transport in the atmosphere

6.3.5 Transport of Radionuclides through Terrestrial Ecosystems and Food-chain Models

6.3.5.1 General

Living organisms, both plant and animal (as seen in Figure 5-2) may take up nuclides in the physical compartments of the biosphere (surface water, sediment, soil and the atmosphere). These nuclides may affect the organisms and may move along the foodchain and eventually be ingested by humans. Ingestion of radionuclides in foods can be an important contributor to the total dose received by an individual or population group.

6.3.5.2 The Terrestrial Ecosystem

The terrestrial ecosystem is more important than the aquatic ecosystem, because not only man resides within this ecosystem, but a significant portion of human food also comes from terrestrial sources. Radioactive materials can enter the terrestrial ecosystem in a variety of ways, namely: from the atmosphere through wet and dry deposition, from water used for irrigation which contains suspended particles, or from soil contaminated by ground water or deposited radionuclides.

In Figure 6-4, some exposure pathways in a terrestrial ecosystem can be seen. The terrestrial foodchain models consider a variety of processes, either explicitly or implicitly, such as:

(a) deposition by dry or wet processes,

(b) interception and retention by vegetation surfaces,

(c) translocation from sites of deposition to the edible tissues of vegetation,

(d) post-deposition retention by vegetation and soil surfaces,

(e) uptake by roots,

(f) direct ingestion of surface soil by grazing animals,

(g) transfer of contamination from soil, air, water and vegetation into milk and meat of grazing animals,

(h) transfer of contamination from surface water to the terrestrial system via spray,

(i) transfer of contamination from surface water to sediment and aquatic biota, and

(j) transfer of contamination from groundwater to the terrestrial system.

The terrestrial foodchain models are designed to accept an input of radionuclides from either the atmosphere or the hydrosphere (Torres and Simon, 1997).

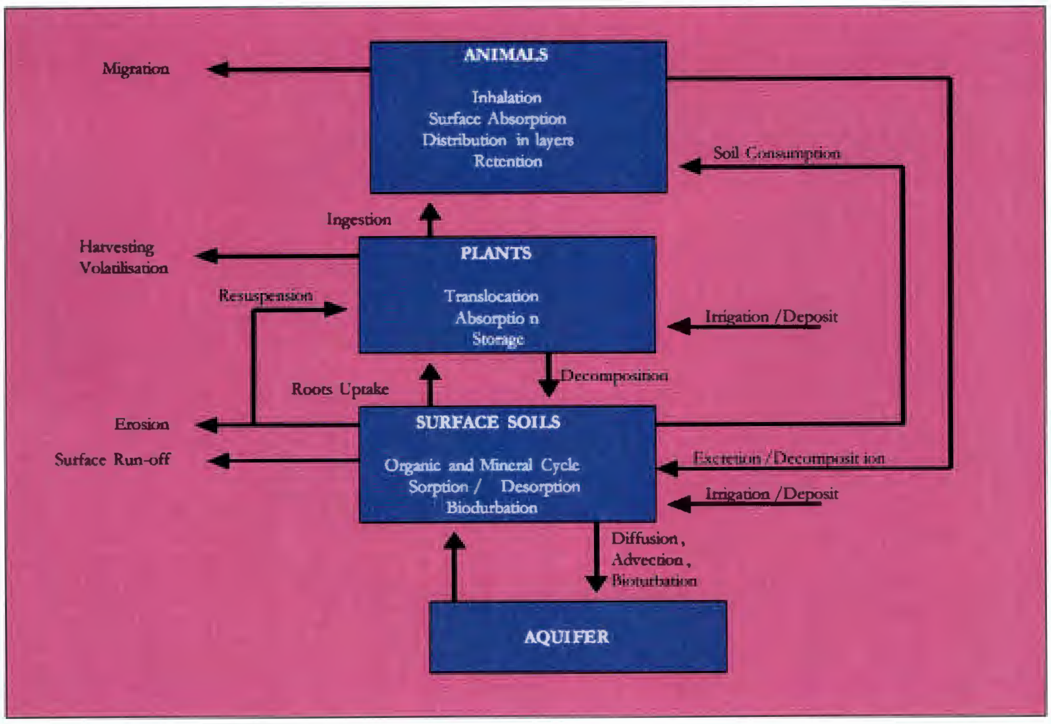


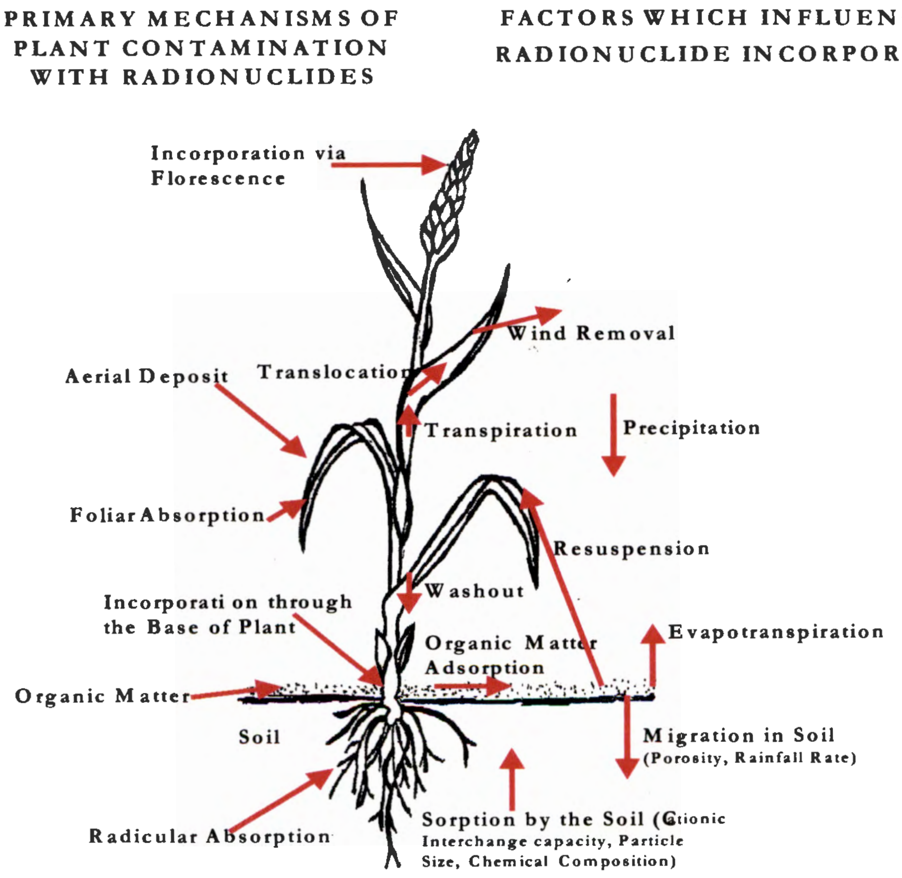
Figure 6-4: Exposure pathways in a terrestrial ecosystem

6.3.5.3 Concentration in Vegetation

Contamination of vegetation may result from the interception of radionuclides either from atmospheric or hydrospheric origin. Radionuclides retained on vegetation may come from fallout, washout, rainout, irrigation from contaminated water, and from resuspended matter. External deposits can be taken up by foliar absorption into plants.

Another source of plant contamination is the uptake of radionuclides from soil via roots and internal redistribution of the various parts of the plants. Processes in addition to radioactive decay can lead to the reduction of radionuclide concentrations in vegetation. These processes include rainfall and soil fixations. The processes in crops can be seen schematically in Figure 6-5. Further removal of radioactive material from vegetation can occur due to grazing and harvesting.

Figure 6-5: Processes in crops (Torres and Simon, 1997)



It is often difficult to separate the losses, which are attributable to leaching during rainfall, from those due to abscission, mortality and resuspension. It is emphasised that all processes of uptake and loss from plants can be expected to be related not only to the maturity of the plant, but also to the temperature, surface wetting, humidity, chemical form of the substance concerned and general nutritional status (Torres and Simon, 1997). A simplified approach for modelling the radionuclide concentration in the plant is usually used, by assuming a concentration factor between soil and crop.

6.3.5.4 Concentration in Terrestrial Animals and Consumption Products

Animals take in radionuclides via ingestion of contaminated feed, soil or water. The relationship between concentration in animal products, e.g. meat, milk and eggs, and the daily intake of contaminated feed can be determined experimentally, or via the use of compartment models representing the distribution of radioactivity in the body and animal products after ingestion. Natural variation, as is the case for all biological systems, is inevitable. The relationship between activity in animal products and feed is uncertain, because the uptake and the retention in the body is dependent among others on age and condition of the animal, morphological characteristics of the plant, chemical form of elements in plants, the difficulty in representing short term fluctuations in activity content of food and uncertainties in the value of gastro-intestinal transfer.

The transfer of radionuclides from animal feed to a food product depends upon the metabolism of the animal. The simplest model of this process is shown in Figure 6-6.

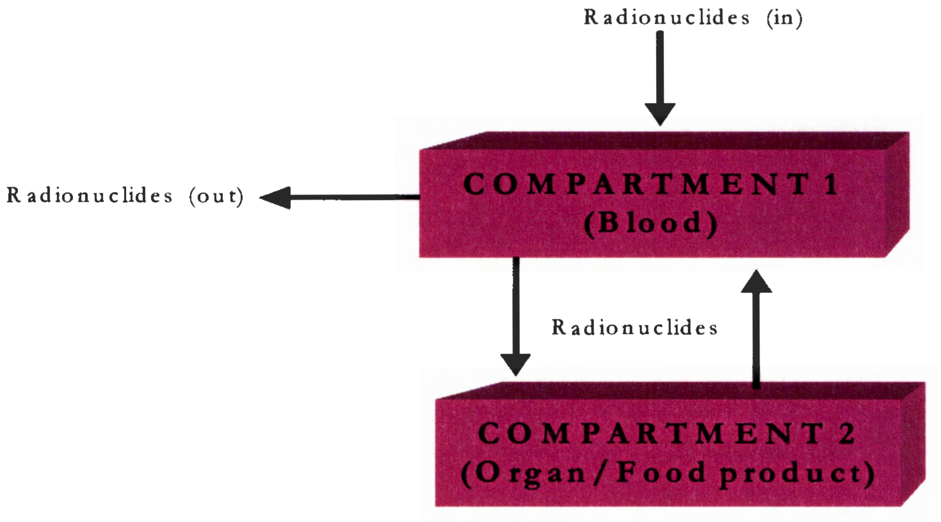


Figure 6-6: Two-compartment transfer model (Torres and Simon, 1997)

This model consists of two compartments; the first compartment typically represents the blood and the second compartment the organ or the food product of interest. Radionuclides enter through the blood and pass in and out of the second compartment, but may leave the system only through the blood compartment. Losses due to radioactive decay occur in both compartments. The difference in the input and excretion rates from the compartment representing the food product will determine the radionuclide content in the food product.

This simple two-compartment model has been successfully used for some applications, but three- or four-compartment models (or more) are more typically used to describe radionuclide metabolism (Torres and Simon, 1997).

6.4 DOSE TO HUMANS

6.4.1 General

Potential routes, through which people may be exposed to radionuclides or radiation, are commonly known as *exposure pathways*, which can be divided into internal exposure and external exposure. The exposure pathways for a critical group are illustrated in Figure 6-7. Internal doses are caused by radionuclides taken into the body through ingestion and inhalation. Ingestion doses arise from the daily intake of contaminated plants, animal products, fish, water and soil. The water source may either be a well drilled into the contaminated groundwater plume, or the lake or river in the discharge zone. Inhalation doses arise from breathing contaminated air, both indoor and outdoor. External doses arise from radiation field originating from contaminated parts of the environment. They involve no dose commitment; rather the magnitude of the dose depends on the duration of the exposure. Humans may receive an external dose from exposure to contaminated ground or by living in houses built of contaminated materials. External doses may also arise from immersion e.g. while swimming or bathing in water contaminated with radionuclides.

6.4.2 Modelling of Doses to Humans

Biosphere models attempt to estimate radiation doses by evaluating the dilution in surface and groundwater bodies and possible radionuclide concentration in biosphere "compartments". The radionuclide transport rate from a compartment is proportional to its concentration in that compartment and a factor called the *transfer coefficient*.

Once a food chain for a specific application is constructed for each compartment, the change in radionuclide concentration along them is calculated by the use of *concentration ratios* (CR) between various links (e.g. water to grass, grass to cow, cow to milk or beef, milk or beef to man).

Finally, doses are calculated using the activity concentrations in water and in the individual foodstuffs, the assumed food quantities, and *dose conversion factors*. In calculating these factors, the variations of dose per unit intake with the age of the individual and with the chemical form of the radionuclide must be taken into account (Van Blerk, 1999*a*).

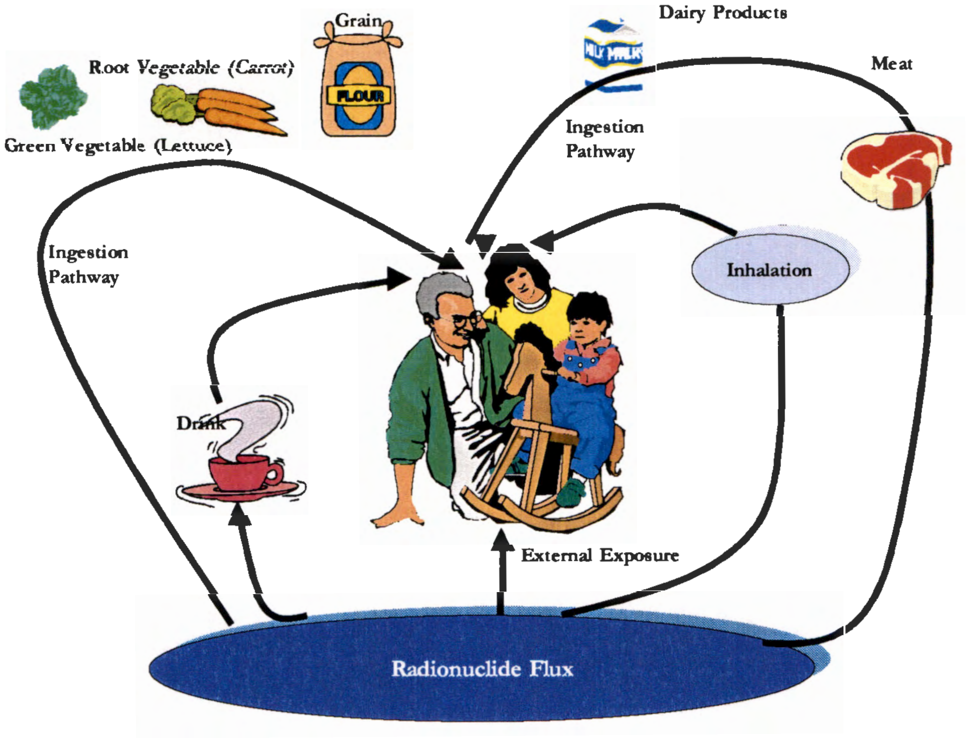


Figure 6-7: Exposure pathways for a community

The concentration in plants and animal products do not take into account the alterations during food processing by humans. Cooking may drive off volatile nuclides, but can also concentrate others. In general, it may be assumed that preparation neither dilutes nor concentrates radionuclides (Torres and Simon, 1997)

For inhalation, doses can be calculated using the similar compartment specifications, standard intakes derived from inhalation rates, and specific dose conversion factors, and parameters are presented in Table A-1 to A-5 of Appendix A.

Mathematical expressions that can be used to calculate the dose through some of the exposure pathways are presented in Table 6-1. The total dose to members of the critical group is found by summing the doses over all exposure pathways, nuclides and, where appropriate food types.

6.4.3 Doses Inside the Human Body

The major pathways through which radiation can enter the human body are inhalation and/or ingestion. Internal parts of the human body can be pictured and treated in the case of cancer patients with ionising radiation. Ionising radiation includes electromagnetic radiation (x- and γ-rays), neutrons as well as charged particles either from radioactive decay (α- and β-particles) or those produced in accelerators. They are called ionising radiation because they transfer sufficient energy to the matter with which they interact to directly or indirectly ionise the atoms and molecules (Van der Woude, 1989). Despite the beneficial applications of ionising radiation there do exist risks and these risks must be analysed and quantified in order to protect people from the detrimental effects of ionising radiation.

The ICRP (International Commission on Radiation Protection) distinguishes between stochastic- and deterministic (non-stochastic) effects of radiation on cells and the organs they constitute (ICRP Publication 26). In the case of stochastic effects, like changes in the DNA of cells which can lead to cancerous progeny, the probability that the effect will occur is assumed to be directly proportional to the radiation dose received by all the cells involved. Dose limits are set by the ICRP to reduce the overall risk from these effects to values similar with other non-radiation risks. To further encourage the minimisation of stochastic effects the ICRP proposed the ALARA-principle (As Low As Reasonable Achievable). In the case of deterministic effects like cataract formation of the eye lens, non-malignant tumours and the destruction of red bone-marrow cells, a threshold dose is assumed to exist beneath which the probability that the effect will occur becomes zero, in contrast with stochastic effects where no threshold dose exists. The assumption of a threshold dose in deterministic effect implies the capability of the cells, which compose the tissue to repair the radiation damage through regeneration. This means the replacement of damaged cells by the regrowth of identical cells. For the processes involved in the regeneration of cells, it is known that the ability to repair radiation induced damage is a function of the radiation dose, elapsed time and type of cell involved. Due to the fact that the type of cell, which composes the tissue, affects the ability to repair radiation damage, the threshold dose differs from one deterministic effect to the other.

To prevent deterministic effects and to limit the risk of stochastic effects, the ICRP recommends dose limits (ICRP 1990), which are either based on the threshold of the deterministic effect or the risk of the stochastic effect, as determined or extrapolated from epidemiological information. This means that the threshold dose for a specific organ must be exceeded before the effect will occur.

An important factor with internal radiation dose is to determine the magnitude of the intake for each detected radionuclide. The first factor that must be determined is the time of intake. Once the time of intake has been determined, knowledge of the dynamic processes by which the radioactive material is transported through the human body, is essential before the magnitude of the intake can be calculated. Dynamic models are necessary to estimate the biological transport of radioactive material through the human body and to take radioactive decay into account. The ICRP composed a compartmental model of the human body which consists of a model of the respiratory track, a model of the gastro-intestinal track and a model for the rest of the body which includes the body fluids and various organs and tissues, like the liver and bone (Van der Woude, 1989).

When radioactive material is inhaled, fractions are deposited in the airways and the lungs and the rest is exhaled. The ICRP model of the respiratory tract includes the several transport processes involved in the transfer of the radioactive material from the respiratory tract to either the gastro-intestinal tract or the body fluids. The model for the rest of body starts at the body fluids by which the radioactive material is transported to the various organs and tissues in the human body. This model also accounts for the elimination of radioactivity through urine and/or faeces.

The complex physical, cellular and biochemical processes involved in the absorption, partial retention and transportation of radioactive material are modelled by associating one or more compartments with each organ in the human body. The transfer of radioactivity from one compartment to another is assumed to be governed by first-order kinetics, which assumes equal exit probabilities for each of the atoms of the radionuclide per unit time from the compartment.

The transport, absorption and clearance of radioactive material in the human body can be considered a study on its own. The purpose of including this section on doses inside the human body is only a brief description of the different models, to provide the reader with a more detailed picture of the different components in the biosphere.

The aim of a safety assessment must be considered as representative indicators of safety. The safety implications of the site, for which the assessment is done, will be demonstrated to a satisfactory level with the exclusion of the transport of radionuclides through the human body.

Table 6-1: Equations, used to calculate the dose to humans through the biosphere pathways.

General parameters		
DF_{ing}	= Dose conversion factor for ingestion	$Sv.Bq^{-1}$
C_s	= Concentration in soil	$Bq.kg^{-1}$
C_w	= Concentration in water	$Bq.L^{-1}$
CMM_{xxx}	= Annual individual consumption	$L.year^{-1}$ or $kg.year^{-1}$
Drinking water dose D_w		
D_w	$= DF_{ing} * C_w * CMM_{water}$	$Sv.year^{-1}$
Dose from milk consumption D_{mi}		
D_{mi}	$= DF_{ing} * CMM_{milk} * DF_{milk} * A$	$Sv.year^{-1}$
DF_{milk}	= Transfer factor for milk	$Days.L^{-1}$
A	$= C_s * CMC_{soil} + CMC_{grass} * C_s * CR_{grass} + CMC_{water} * C_w$	$Bq.day^{-1}$
CMC_{soil}	= Daily soil consumption by cows	$Kg.day^{-1}$
CMC_{grass}	= Daily grass consumption by cows	$Kg.day^{-1}$
CR_{grass}	= Concentration ratio from soil to grass	-
CMC_{water}	= Daily water consumption by cows	$L.day^{-1}$
Dose from meat consumption D_{me}		
D_{me}	$= DF_{ing} * CMM_{meat} * DF_{meat} * A$	$Sv.year^{-1}$
DF_{meat}	= Transfer factor for meat	$Days.kg^{-1}$
A	= As under "dose from milk consumption"	-
Dose from consumption of leafy vegetables D_{bl}		
D_{bl}	$= DF_{ing} * CMM_{leaf} * CR_{leaf} * C_s$	$Sv.year^{-1}$
CR_{leaf}	= Concentration factor from soil to leafy vegetables	-
Dose from cereal consumption D_{get}		
D_{get}	$= DF_{ing} * CMM_{cereal} * CR_{cereal} * C_s$	$Sv.year^{-1}$
CR_{cereal}	= Concentration factor from soil to cereal	-
Dose from consumption of root vegetables D_{wu}		
D_{wu}	$= DF_{ing} * CMM_{root} * CR_{root} * C_s$	$Sv.year^{-1}$
CR_{root}	= Concentration factor from soil to root vegetables	-
Dose from fruit consumption D_{ft}		
D_{ft}	$= DF_{ing} * CMM_{fruit} * CR_{fruit} * C_s$	$Sv.year^{-1}$
CR_{fruit}	= Concentration factor from soil to fruit	-
Dose from poultry consumption D_{pt}		
D_{pt}	$= DF_{ing} * CMM_{poultry} * DF_{poultry} * B$	$Sv.year^{-1}$
$DF_{poultry}$	= Transfer factor for poultry	$Days.kg^{-1}$
B	$= CMH_{cereal} * CR_{cereal} * C_s + CMH_{water} * C_w$	$Bq.day^{-1}$
CR_{cereal}	= See "dose from cereal"	-
CMH_{cereal}	= Daily cereal consumption by hens	$Kg.day^{-1}$
CMH_{water}	= Daily water consumption by hens	$L.day^{-1}$
Dose from egg consumption D_{ei}		
D_{ei}	$= DF_{ing} * CMM_{egg} * DF_{egg} * B$	$Sv.year^{-1}$
DF_{egg}	= Transfer factor for eggs	$Days.kg^{-1}$
B	= See "dose from poultry consumption	$Bq.day^{-1}$
Dose from fish consumption D_{fi}		
D_{fi}	$= DF_{ing} * CMM_{fish} * CR_{fish} * C_w$	$Sv.year^{-1}$
CR_{fish}	= Concentration factor from water to fish	$L.kg^{-1}$

CHAPTER 7

CASE STUDY – RADIOLOGICAL PUBLIC HAZARD ASSESSMENT STUDY FOR FOSKOR (Pty) Ltd.

7.1 GENERAL

The Council for Nuclear Safety (CNS) issued a nuclear licence to Foskor (Pty) Ltd. under the Nuclear Energy Act no. 131 of 1993 and requires that the licensee must conduct a radiological public hazard assessment to demonstrate that the associated activities do not pose a health hazard to humans. The Atomic Energy Corporation of South Africa Ltd. (AEC) was contracted by Foskor to conduct the radiological public hazard assessment of the mining and minerals processing facilities at Foskor for the expected operational period of the mine.

The objective of the investigation was to conduct an integrated radiological public hazard assessment of doses to members of the public via the atmospheric, aquatic and secondary pathways as a result of the mining and mineral processing facilities at Foskor. The time frame for this assessment is the expected mine life. The impact will be assessed in terms of Foskor's contribution to an overall radiation dose along all major pathways.

The radiological protection standards are criteria set to ensure compliance with the basic principles of waste management (IAEA, 1995). The safety indicator set by the CNS for public impact assessments, is an *individual dose limit*. The criteria used with this indicator stated that for events at the facility that are determined to be likely, the projections of doses to members of the public shall not exceed an appropriate fraction of the dose limit (1mSv.year^{-1}) established by the ICRP for members of the public. These values constitute the sum of the external and internal effective doses via the important pathways, integrated over the lifetime appropriate to the identified critical groups. In order to calculate doses to members of the public, critical group(s) has to be identified. For Foskor, the *actual critical groups* are situated south-east of the Selati Tailings Dam, in Phalaborwa and in Namakgale. *Hypothetical critical groups* were defined for scenarios where no actual critical groups exist. The calculation of the doses was done for five age groups within each critical group. These age groups are 0-2 years, 2-7 years, 7-12 years, 12-17 years and adults.

Background information concerning the regional setting of Foskor and a description of the project can be found in Section 7.2. This information is not crucial to the assessment process itself, but provides useful information concerning the mineral deposits in the Palabora Igneous Complex, the extent of the target area and the products of the mining and processing operations at Foskor.

The system description of the Foskor site was compiled to characterise the various pathways in terms of the features, events and processes associated with it. The site is described in terms of climate, topography, geology, surface- and groundwater, demographic features, land and water use as well as natural and anthropogenic vegetation and animal life. These descriptions can be found in Section 7.3.

Scenario development, as it is used in this document, originates from the safety assessment of radioactive waste disposal systems as discussed in Chapter 5. The process of scenario generation will not be repeated in this case study, but the descriptions of the scenarios developed for the Foskor site can be found in Section 7.4.

Model development is devoted to the definition of a conceptual model for the groundwater, surface water and atmospheric pathways, as well as for the different scenarios, and can be found in Section 7.5. The biosphere models attempt to estimate radiation doses by evaluating the *dilution* in surface and groundwater bodies and possible radionuclide *concentration* in certain biosphere "compartments". Doses are calculated in the manner discussed in Section 6.4.

Source terms are required at various stages along the exposure pathways where activity may accumulate. Some of these concentration values have been measured directly through monitoring programmes, others will be inferred from the biosphere equations, and yet others need to be calculated using the available information. A description of the different source terms can be found in Section 7.6, followed by the dose calculations for the scenarios in Section 7.7. The case study is concluded with a discussion of the results in Section 7.8.

7.2 BACKROUND INFORMATION

7.2.1 General

Foskor is one of the major producers of phosphate for the fertiliser industry in South

Africa. The focus of the mining activities is to extract phosphate from the mineral apatite, which occurs in a volcanic pipe structure. Other economic minerals like magnetite, phlogopite, copper and baddeleyite are also mined as by-products. The mineral uranothorianite also occurs in the igneous complex, and contains the radioactive elements U and Th that eventually form part of the waste. Unless otherwise stated, all the information was obtained from the Foskor EMPR (1995).

7.2.2 Regional Setting

Foskor is situated south of the town Phalaborwa in the north-eastern part of the Northern Province of South Africa. Foskor has surface and mining rights on the property that includes the state-owned farms Laaste 24 LU, Schiettoch 25 LU, Wegsteek 30 LU, Makushane 28 LU, Schalk 3 KU, Loole 31 LU and Merensky 32 LU. The site is bounded by Phalaborwa town in the north, the Palabora Mining Company (Pty) Ltd. to the east and the Selati River in the south and the east (see Figure 7-1). The main road in the vicinity of the site is the R40 between Nelspruit and Tzaneen. Phalaborwa is accessed by two roads, which branch of from the R40. These are the R530, a secondary road, which starts 3 km north of Mica, and the R71, a main road that branches from the R40 at Gravelotte. A road extends from Phalaborwa into the Kruger National Park via the Phalaborwa Gate.

7.2.3 Mining, Mineral Deposits, Mining Products and Mine Life Expectancy

The Palabora Igneous Complex, which is mined on the property consists of three main types of mineral deposits. One is the Loolekop pipe, a copper-rich, vertical volcanic intrusion that consists of concentric bands of pyroxene, pegmatoid, phoscorite and carbonatite. The other minerals that are mined are apatite, magnetite, phlogopite, copper and baddeleyite. The mine mainly makes use of the opencast method; currently an underground section was started by the neighbouring Palabora to be able to mine deeper ore reserves economically. The mining product is a fine, crushed apatite mineral that contains the calcium-fluoride-phosphate complex. Precious metals like gold, silver and platinum group metals occur in small quantities in the ore body, which is recovered. The production rate (in 1995) was 4.2 million tonnes ore per annum, another 11 million tonnes was recovered from the adjacent Palabora Mining Company's (Ltd.) ore stockpiles and 9.9 million tonnes of phosphate rich by-products were pumped from the Palabora mine to Foskor for processing (EMPR, 1995). Based on the existing ore reserves, the planned mine life exceeds 100 years.

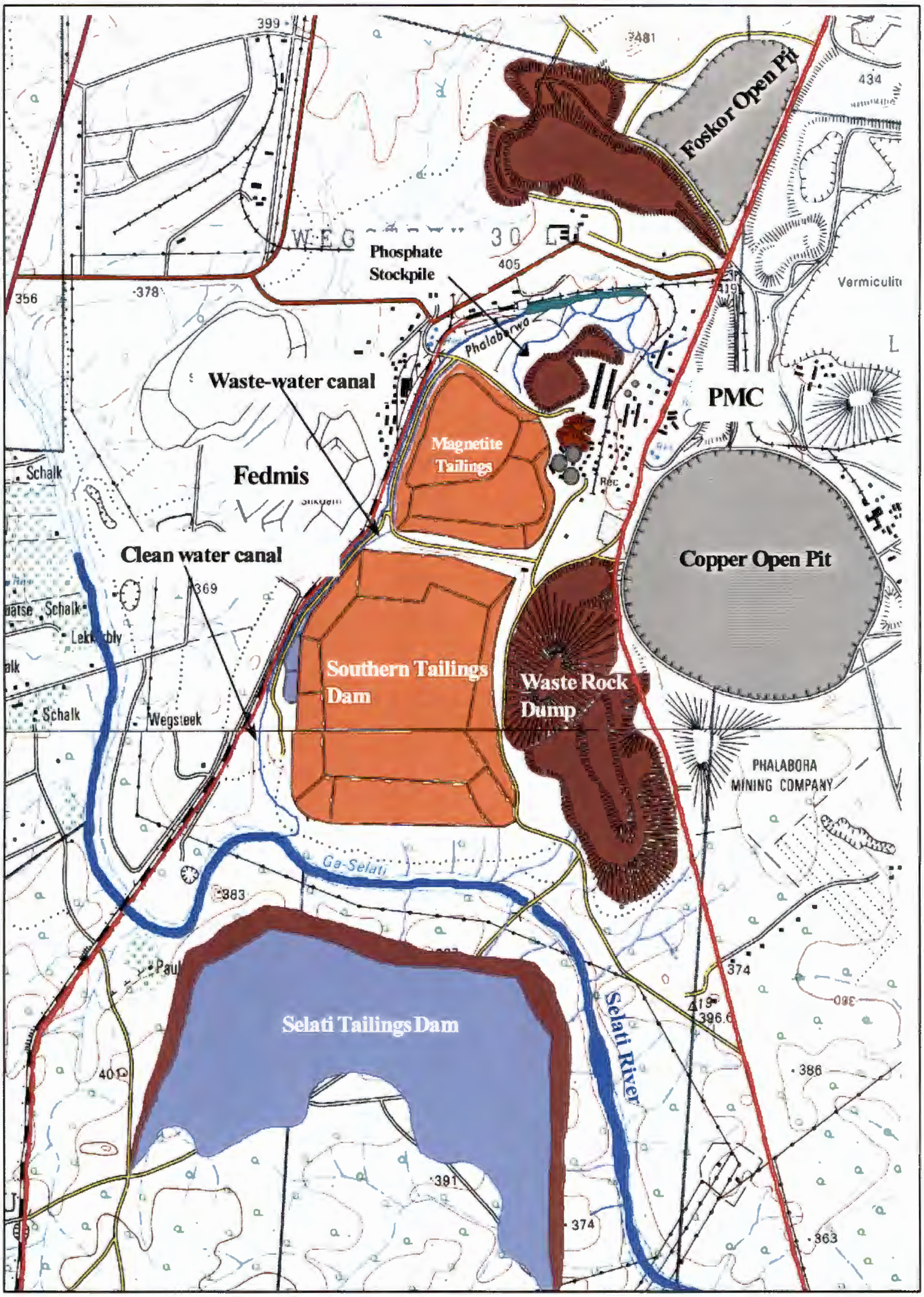


Figure 7-1: Map of Foskor and Surroundings.

7.3 SYSTEM DESCRIPTION

7.3.1 General

The characterisation of the Foskor site is done in terms of the various environmental exposure pathways that can be followed by radionuclides. Radionuclides contained in the waste rock dumps and tailings dams may follow routes through the atmosphere, surface water, the geosphere and biosphere, which may cause exposure to humans (see Figure 7-2). Radionuclides may enter these pathways (e.g. the groundwater system) and pose a threat to humans in the future when released from the system. The migration of radionuclides through these pathways must be quantified to a degree of certainty. In order to simulate the migration of radionuclides through the system, it is characterised in terms of its physical properties. The geosphere and biosphere pathways will be described in more detail than the atmospheric pathway, as the latter was modelled by Parc Scientific (Pty) Ltd. (Strydom, 1998). However, in the final dose assessment, the contribution of the atmospheric pathway as obtained from Parc Scientific (Pty) Ltd. is included.

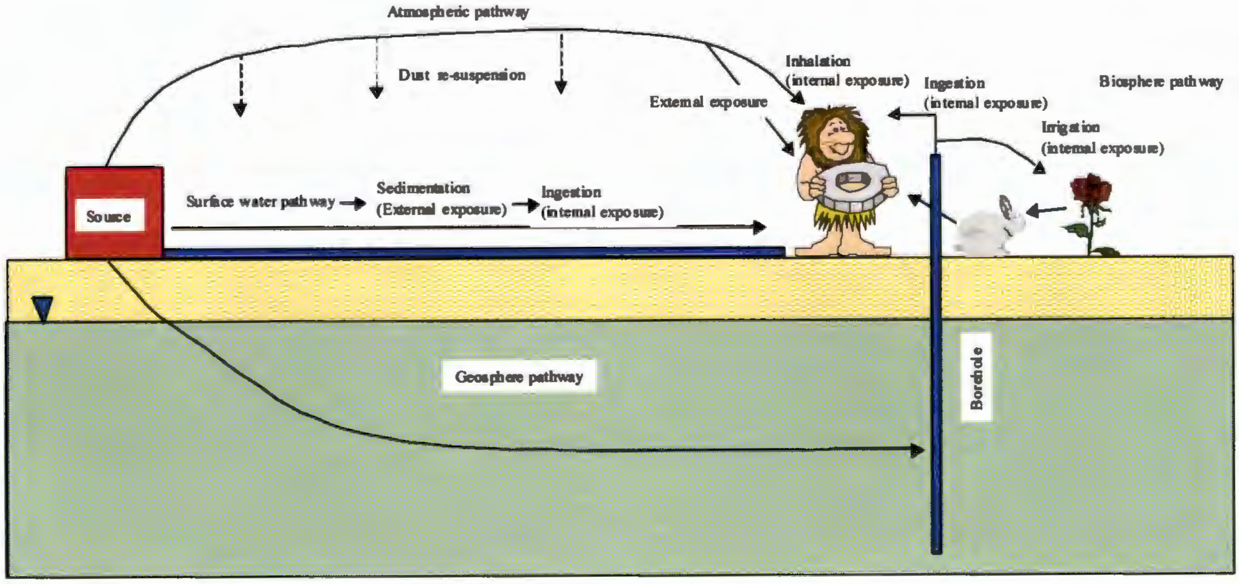


Figure 7-2: **Schematic illustration of some of the direct and indirect pathways that may lead to internal and/or external exposure.**

7.3.2 The Atmospheric Pathway

7.3.2.1 General

Radionuclides may enter the atmosphere from the various waste rock dumps, stock piles and roads. Once they enter the atmosphere, they may be transported by the prevailing winds towards nearby settlements. The dose to humans from this pathway can either be external or internal through inhalation.

7.3.2.2 Climate

The climate is sub-tropical with summer rain that reaches a maximum between December and January every year.

7.3.2.3 Temperature

During summer it is very hot and daily temperatures frequently exceed 38 °C. The highest average daily temperatures occur in January (31.6 °C) and the lowest average daily temperatures in June and July (9.8 °C).

7.3.2.4 Wind Directions

The general wind direction is south-east for 70 % of the time, at an average speed of 4.6 $m.s^{-1}$.

7.3.2.5 Rainfall

Rainfall generally originates from thunderstorms and the maximum intensity measured in 1 hour was 122 mm. The average annual rainfall (calculated between 1967 to 1991) was 570.65 mm, with the highest average rainfall month being December and the lowest in July (EMPR, 1995).

7.3.2.6 Evaporation

The average annual potential evaporation measured with a Symonspan, is 1 550 mm with the maximum during the month of October, and the minimum during June. The annual potential evaporation therefore exceeds the annual precipitation. The largest difference between the average precipitation and evaporation is during September.

7.3.3 The Surface Water Pathway

7.3.3.1 General

Surface water is one of the important pathways through which radionuclides may cause exposure to humans. When water from precipitation falls on the waste rock dumps, tailing dams or the waste-water dams, radionuclides may be transported to nearby streams and rivers. The radionuclides in surface water may cause internal exposure through ingestion or external exposure through sedimentation. It is therefore important to consider the surface water as a potential pathway for exposure.

7.3.3.2 Topography and Drainage Systems

The surface water runoff depends on the local topography. Phalaborwa is situated in the Lowveld region on the flat lowlands between the Drakensberg plateau escarpment and the Lebombo Mountains. The Lowveld area is situated at an average elevation of 360 mamsl, which is considerably lower than the surrounding highveld. The site is situated in the Selati River drainage, which is a tributary of the Olifants River. The Olifants River flows through the Kruger National Park and eventually joins the Limpopo River to the east. The Olifants and Selati Rivers are slow flowing rivers (except during flood conditions) with a general gradient of 0.003 to the east. The pre-mining topographical setting of the site is typical of the central Lowveld. It features open stretches of relatively low-lying, gently undulating land occasionally interrupted by prominent koppies.

Hills on the site rise up to elevations of 460 – 480 mamsl. The hills are conical in form and rocky in nature. Of the seventeen prominent hills on the site, mining has disturbed four. One of these is Loolekop, which has been completely removed by mining. Two koppies are completely covered and one partially covered by the waste rock dump. Watercourses naturally dissect the land on the site. Most watercourses in the northern region of the site drain into the Loole Creek, a non-perennial tributary of the Selati River, which flows across the site in a southerly direction. The copper open pit is already below sea level and approximately 3 968 kℓ of water is pumped into Loole Creek per day. Watercourses in the southern region of the site drain directly into the Selati and Olifants Rivers.

7.3.4 Surface Water Pathway: Source Description

7.3.4.1 General

The surface water forms one of the most important pathways for radionuclide migration. Contaminants that are dissolved by rainwater migrate to the Selati River via the surface water drainage systems. A source can be described as any physical entity that may cause radiation exposure to the public, for example, by emitting ionising radiation or releasing radioactive material (IAEA, 1995).

7.3.4.2 Tailings Disposal Facilities

There are three tailings dams used by Foskor, where fine material is disposed of in the form of a saturated sludge. These are the Pyroxenite-, Magnetite- and Southern Tailings Dams that are situated north of the Selati River. The Selati Tailings Dam is the latest and biggest and is situated south of the Selati River. These dams are saturated and in hydraulic connection with the underlying aquifers. The tailing dams, therefore, form the most important source for contaminant leachate generation (Vivier and Van Blerk, 1999).

There are four solid waste rock dumps at Foskor. These rock dumps consist of fine to coarse material and are essentially dry. Contaminants are generated only after rainfall events. The importance of the waste rock dumps in terms of radionuclide sources is small compared to the tailing dams.

There are three stockpile facilities on the Foskor premises. These are the plant stockpile, and the coarse- and fine stockpiles. The stockpile facilities are partially saturated and leachate generation from these facilities is expected to be very smaller than the tailing dams. The stockpiles are more important for radon gas emanation, which is covered by the atmospheric pathway assessment (Strydom, 1998).

7.3.5 The Geosphere Pathway

7.3.5.1 General

Radionuclides may enter the geosphere by infiltration or by sedimentation. They may also be transported by erosion and cause exposure after sedimentation. Deposited radionuclides can cause external exposure through the soil or internal exposure after absorption through the biosphere. Interaction of the geosphere with the atmospheric- and the surface water pathways is important. The importance of the geosphere is that long-lived radionuclides may enter the groundwater system at present and decant at a spring or in a river in the future. Therefore it is important to assess the behaviour and possible migration pathways through the geosphere.

7.3.5.2 Soil Types

The general soil type in the Phalaborwa area is a shallow layer of Mispah soil type, which is a weathering product of the underlying granite-gneiss bedrock. Deeper weathering products of granite-gneiss follow this layer. Along the rivers, thick alternating layers of sand occur between outcrops of granite-gneiss. Where the underlying rock mass consists of pyroxenite, white calcrete has formed as a weathering product. The general weathering profile varies between zero and fifty meters. The very deep weathering zones are associated with phlogopite-rich serpentine and pyroxenite associated with vermiculite.

7.3.5.3 Geology

The characteristics and composition of the ore bodies and the geological formations in the immediate surrounding areas of Foskor have an influence on the composition of the tailings dams and overburden. The waste dumps have the potential to produce leachate when water percolates through them. This could result in contamination of surface- and ground water. The possibility of using the geological materials in the rehabilitation of disturbed areas is also a consideration. The geological characteristics of the area influence the flow of the ground water and its ability to transport radionuclides. The mineral deposits of the Phalaborwa area occur within the Palabora Igneous Complex (PIC) which intruded into the surrounding granite-gneiss. A more detailed description of the geology of Foskor can be found in Vivier and Van Blerk (1999).

7.3.5.4 Groundwater, Springs and Groundwater Quality

The occurrence and movement of groundwater is controlled by the geology of the subsurface. The hard rock (fractured) aquifer system at Foskor consists mainly of granite-gneiss that forms weathered basins. The occurrence of groundwater within the granite-gneiss is controlled by pegmatite bands. Intrusive rocks, like syenite and dolerite form impermeable zones that have an important influence on the groundwater flow. The dolerite dykes occur in the form of north-east to south-west trending swarms that are visible on the aerial photograph of the area. The dyke-contact zones could form preferential (fracture) flow zones. Primary aquifers occur in the loose sand bed of the Selati River.

Two natural springs occur south of the Selati Tailings Dam. One of these is a hot water spring, suggesting deep-water circulation.

The groundwater quality was evaluated from 57 samples. The analysis revealed that the SA Drinking water standard was exceeded by the following chemical species: calcium, magnesium, sodium, sulphate, fluoride and chloride. The excess total dissolved solids in the groundwater is associated with the location relative to the tailings dams, benefaction plant and to a lesser extent the magnetite dump. The most important contaminants are magnesium, sodium and sulphate. Depth profile samples were taken at several boreholes to determine the variation in chemistry with depth. This indicated that there was no chemical stratification of the groundwater.

7.3.6 The Biosphere Pathway

7.3.6.1 General

It follows from Figure 5-1 that the results from the geosphere (in the form of concentration values) and the characteristics of human behaviour form the basis for the biosphere. As the radionuclides reach the biosphere through different pathways, it can be transported via soil, the atmosphere, terrestrial and aquatic ecosystems and different food chains to ultimately reach human beings. Radionuclides may become diluted or concentrated in some parts of the biosphere.

7.3.6.2 Natural Flora

The vegetation occurring naturally in the Phalaborwa region is tolerant of the relatively low rainfall and hot climate. It is of a bushveld nature and can be classified as Arid Lowveld. The veld features scattered trees and shrubs, interspersed with tall, tufted grasses and a wide variety of forbs. The vegetation changes remarkably near watercourses. The density of trees and shrub-species increases sharply to form dense thickets. The composition of these species varies considerably.

Tree species, which are common to Arid Lowveld, include *Acacia nigrescens,* *A.totilis, Sclerocarya birrea, Colospermum mopane, Combretum apiculatum* and *Combretum imberbe.* The dominant grasses are *Digitaria eruantha* and *Themeda triandra.* Under grazing pressure, wiry grasses such as *Aristida congesta, Eragrostis trichophera, Perotis patens, Pogonarthria squamosa* and *Schmidtia papporphoroides* become more common.

A variety of weed species have become established on land disturbed by mining on the property. Among these are *Lantana camara* (lantana), *Tecoma stans,* (yellow bells), *Ricinus communis* (castor oil bush), *Xanthium strumarium* (large cocklebur), *Chromolaena odarata* (triffid weed) and *Opuntia sp.*

7.3.6.3 Fauna

Foskor has a sensitive location in terms of game conservation. It adjoins the Kruger National Park to the east and the Klaserie Nature Reserve to the south. Few animals are permanently residents within the mining area, although there is movement of game between the adjoining game conservation areas and the mining area. A great diversity of mammal and bird species occur in this reserve.

The mine keeps records of large mammalian game and of birds occurring on the site. No detailed records of small mammals, reptiles, amphibians, fish and insects are available. Predominant among the large game occurring on the mine are elephant, buffalo, hippopotamus, zebra and impala. All of these species are herbivorous. Other herbivorous species, which are commonly observed on the mine, are kudu, waterbuck and giraffe. Predators observed on the mine are lion, leopard, hyena, caracal, african wild dog and black backed jackal.

A bird count was conducted in September 1992 and 168 different species were recorded. From the results of the count, it was concluded that the bird population on the mine was diverse and flourishing.

7.3.6.4 Aquatic Ecology

The aquatic ecology of the Selati and Olifants Rivers, downstream from the mining activities in Phalaborwa, has been disturbed to a significant extent from its pristine condition. It has been shown that seepage from the various tailings dams into the Selati River has a considerable impact on the Olifants River, where the river flows to the Kruger National Park. The high sulphate and total dissolved solid load found in the Selati River, have limited the species composition of fish and other aquatic fauna in the ecosystem. Commonly occurring fish species in this river include the large scale yellow fish (*Barbus marequensis*); red spotted labeo (*Labeo congoro*); red nose labeo (*Labeo rosae*); sharptooth catfish (*Clarias gariepinus*), as well as the blue kurper (*Oreochromis mossambicus*). A wide variety of other fish species occuring further downstream in the Olifants River are absent from the Selati River, mainly as a direct result of high pollutant loads in the river.

7.3.7 Human Behaviour

The neighbouring community consists mainly of subsistence and commercial farmers and nature reserves. Game farming is the most important farming activity, while crop irrigation farming is common along the banks of the Selati River. Most of the inhabitants of the Phalaborwa area live on farms and in scattered settlements. The closest neighbour to Foskor is a commercial farmer to the south-west, across the Selati River. A subsistence farming community is situated, south-east of Foskor, also across the Selati River. The town of Phalaborwa is to the north of the mine, and the Namakgale Township is further to the north-west. These communities will form the present critical groups in the Foskor study.

7.4 SCENARIO DEVELOPMENT

7.4.1 General

As discussed in Chapter 5, the scenarios will take into consideration the relevant FEPs to define a normal evolution scenario, as well as a few alternative and disruptive scenarios. No intrusion scenario will be defined, because it is assumed that safety from control at Foskor exists for the duration of the assessment period. From the definition of a scenario, it is clear that a scenario is developed to address the uncertainty in the future state of the site. In a time scale of 100 years, it is possible to anticipate the future state of the site with relative certainty without major expected changes in the climate, geological environment or human behaviour. Alternative scenarios in the context of this project will thus focus on those scenarios that can be anticipated and justified.

The impact of concern to all members of the critical group is an individual dose limit of 250 μSv.year^{-1}. The impact to the critical group will be assessed for a period of 100 years, over a spatial domain that includes the Foskor site boundary, as well as Phalaborwa and Namakgale. It will be assumed that present day designs, operations and administrative control of the facilities will remain the same for the duration of the assessment period. The same assumption is made concerning human practices, technologies and activities. Finally, the regulatory requirements and exclusions as presented in *Guideline on the assessment of radiation hazard to members of the public from mining processing facilities* (LG-1032), will be applicable to all scenarios.

Five scenarios were considered for the Foskor public hazard assessment:

(a) Scenario 1 is a normal scenario for an actual critical group, which includes a family living in Phalaborwa.

(b) Scenario 2 is also a normal scenario for an actual critical group that is represented by a family living in Namakgale.

(c) Scenario 3 is a normal scenario for an actual critical group living south-east of the Selati Tailings Dam.

(d) Scenario 4 is done for a hypothetical critical group living on western boundary of Foskor along the Selati River.

(e) Scenario 5 is a disruptive or unplanned flooding event.

The positions of the defined critical groups can be seen in Figure 7-3.

7.4.2 Scenario 1: Actual Critical Group in Phalaborwa

Scenario 1 represents the central case, which is the most realistic scenario. A normal scenario as part of a public impact assessment defines all operational and human activities that are expected, i.e. it excludes any abnormal, disruptive or unplanned events. This also means that for Scenario 1 an *actual* critical group will be considered, which in the case of Foskor, is situated adjacent to the town of Phalaborwa. In the case of other actual critical groups identified within close proximity of the site, the actual behaviour, characteristics and habits of that group will also be considered. If the possibility exists that a particular pathway does not have any impact on the actual critical group, then no assumptions will be made to allow contribution of that pathway to the total dose. No assumptions will thus be necessary regarding future hypothetical behaviour patterns of the critical group. What will be required, is to define Scenario 1 in terms of actual, realistic behaviour and characteristic patterns of the critical group.

Specific assumptions necessary for the definition of Scenario 1 include:

(a) The family lives in the town of Phalaborwa, at a point bordering the mine property. The composition of the family is such that each age group is represented by at least one member.

(b) Average climatic conditions (e.g. temperatures, wind and rainfall) prevail at the site for the duration of the assessment period. No disruptive events in terms of flooding are considered.

(c) The critical group that lives in Phalaborwa obtains their water from the Phalaborwa Water Board (*)

(d) The general direction of groundwater flow as well as the surface water flow patterns in the area suggests that it is unlikely that the aquatic pathway will contribute to any dose to the critical group in Phalaborwa.

(e) The critical group maintains a small vegetable and fruit garden (using Water Board water (*)) which fulfils their daily fruit and vegetable consumption requirements (See Table A-2, Appendix A for annual consumption rates).

(f) The critical group fishes in the Selati Tailings Dam, the Van Reissen Dam and in the Selati River. The fishing pathway will be included in the scenario development phase, but due to the fact that it is still under investigation no dose calculations will be done.

(*) *Note: Water Board water is not affected by Foskor.*

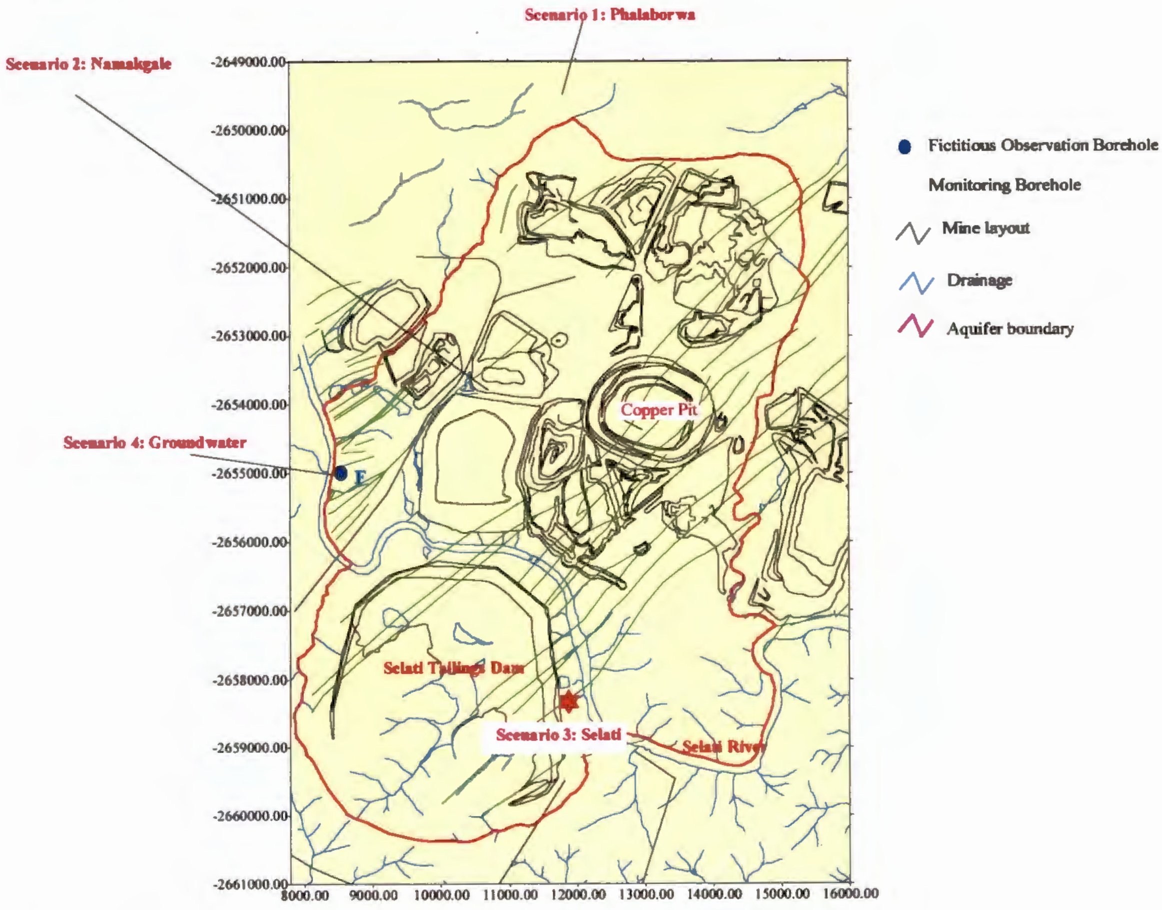


Figure 7-3: Locations of the critical groups at Foskor (Pty) Ltd.

7.4.3 Scenario 2: Actual Critical Group in Namakgale

Scenario 2 is an extension of the central case defined in Scenario 1. All the assumptions made for Scenario 1 are the same for Scenario 2, except that the critical group also consumes livestock products that are subjected to radiation exposure (through the different pathways). These livestock products are enough to supply the critical group with their daily quota of meat and poultry products. The livestock are fed grass from the area that is subjected to deposition. In addition to fruit and vegetable gardens, the critical group also maintains a small piece of land for their daily supply of cereals. This scenario is more applicable to people living in the Namakgale area. The assumption will be made that an informal settlement has established them south of Phalaborwa, on the border of Foskor. The air concentration and deposition quantities used in Scenario 1 are, therefore, also applicable to Scenario 2. The Phalaborwa Water Board will supply the drinking water.

7.4.4 Scenario 3: Actual Critical Group South-East of the Selati Tailings Dam

Scenario 3 considers an actual critical group that lives on the banks of the Selati River, south-east of the Selati Tailings Dam. They are farm workers who live adjacent to the Selati Tailings Dam. The critical group, which lives there for the duration of the assessment period, consists of at least one member for each age group. The drinking water is obtained from a borehole in the vicinity. In this case, it is assumed that borehole KGM-B5 is used for this purpose.

The volume of water that will be used is just enough for human and livestock consumption. A volume of 2 $m^3 \cdot d^{-1}$ is assumed to be extracted from the borehole. This is a conservative assumption because dilution effects due to extraction are minimised. Fish caught in the Selati River and the Selati Tailings Dam form part of the daily diet of the critical group. The critical group will also be subjected to external radiation from working on contaminated land (e.g. ploughing) along the Selati River. Swimming in the Selati River is ruled out due to the presence of crocodiles. It is assumed that the critical group has a small garden where vegetables and corn are produced. Supplements for their diet are provided externally by the farmer, therefore no irrigation takes place.

Average climatic conditions (e.g. wind, temperature and rainfall) prevail at the site for the duration of the assessment period. No disruptive events in terms of flooding will be considered. No releases of surface water from the site (waste-water dams and Weir 3) to the Selati River take place. These releases only take place during unplanned (e.g flooding) events.

7.4.5 Scenario 4: Alternative Critical Group

Scenario 4 considers a small farm system located outside the Foskor site boundary on the banks of the Selati River near borehole "F" (see Figure 7-3). The system consists of a small group of individuals (less than 50) relying on the local resources in order to constitute an agricultural community. The critical group, which lives there for the duration of the assessment period, consists of at least one member for each age group. Due to its characteristics, the average amount of water required to sustain such a system is 10 000 $m^{3}\cdot year^{-1}$. This volume of water will be used for human and livestock consumption, as well as for irrigation of land planted with products for human and livestock consumption. In Scenario 4, it is assumed that (1) the Selati River is dry and that the 10 000 $m^{3}\cdot year^{-1}$ is extracted from the above-mentioned borehole and that (2) the 10 000 $m^{3}\cdot year^{-1}$ is extracted from the Selati River. The critical group will also be subjected to external radiation from working on contaminated land (e.g. ploughing). Average climatic conditions (e.g. wind, temperature and rainfall) prevail at the site for the duration of the assessment period. No disruptive events in terms of flooding will be considered. The annual water and food consumption parameters that will be applied to the critical group can be seen in Table A-2, Appendix A. Swimming is again ruled out due to the presence of crocodiles.

7.4.6 Scenario 5: Disruptive Events (High Rainfall Event)

One of the requests of the CNS, as expressed in LG-1032, is to include scenarios that represent disruptive but realistic events. For this purpose, a scenario is defined that includes an abnormal rainfall event equal to a 1:100 years flood. This will result in a fair amount of run-off along the clean and waste-water streams. This may also lead to an overflow of Weir 3 and discharge to the Selati River. All the other assumptions for Scenario 5 are the same as for Scenario 3.

7.5 MODEL DEVELOPMENT

7.5.1 General

Once the scenarios are developed, the consequences in terms of the assessment context must be analysed. This requires that the scenarios be organised into a form that is amenable to mathematical representation. A set of model-level assumptions about dimensionality, boundary conditions, features, events and processes are needed for each scenario. These assumptions are formed within the conceptual model.

The conceptual model for each scenario is expressed in a mathematical form as a group of algebraic and differential equations that need to be solved. These equations may be empirically and/or physically based, depending upon the level of understanding and information concerning the processes represented. These equations and their associated parameters form the basis for the mathematical models.

The conceptual model for the different scenarios represents a description of the movement of radionuclides through the atmosphere, geosphere and biosphere, where the critical group will eventually be reached.

7.5.2 Scenario 1

In Scenario 1, the critical group can potentially receive a dose through human inhalation, human ingestion, as well as external air and soil exposure. The flow diagram of the conceptual model for Scenario 1 is presented in Figure 7-4. The atmospheric pathway presented in this flow diagram is of primary importance. Note that the water from Phalaborwa Water Board contains small concentrations of activity and will, therefore, contribute to the overall dose to the public. This contribution is not from Foskor operations and can be considered as a background dose for the water pathway.

7.5.3 Scenario 2

In Scenario 2, the critical group receives a potential dose through human inhalation, human ingestion, as well as external air and soil exposure. The human ingestion pathway is extended, to include the dose contribution from animal product consumption. This contribution is from both the water pathway and the atmospheric pathway. The flow diagram of the conceptual model for Scenario 2 is presented in Figure 7-5.

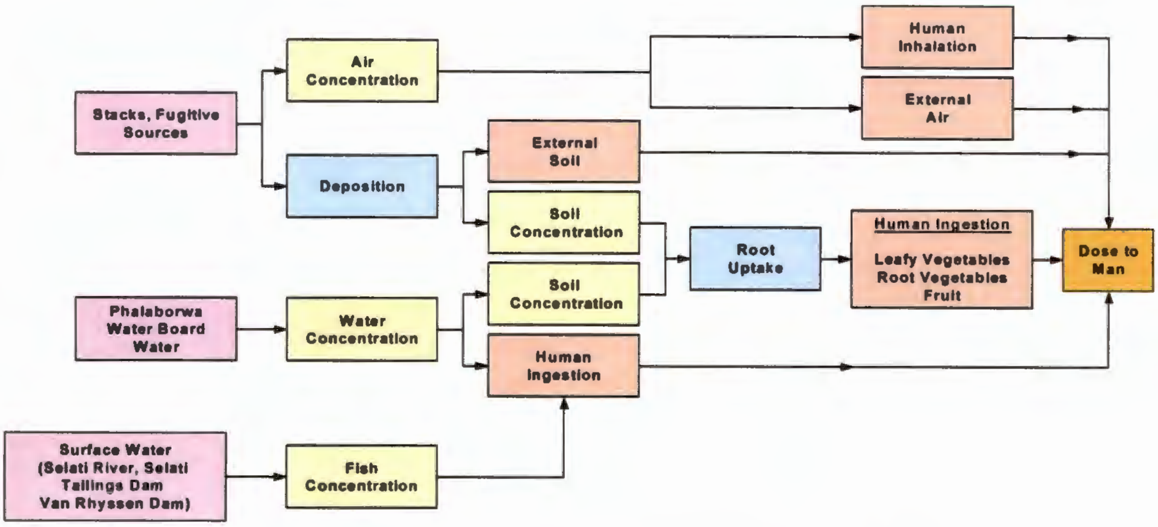


Figure 7-4: A flow diagram of the conceptual representation of Scenario 1

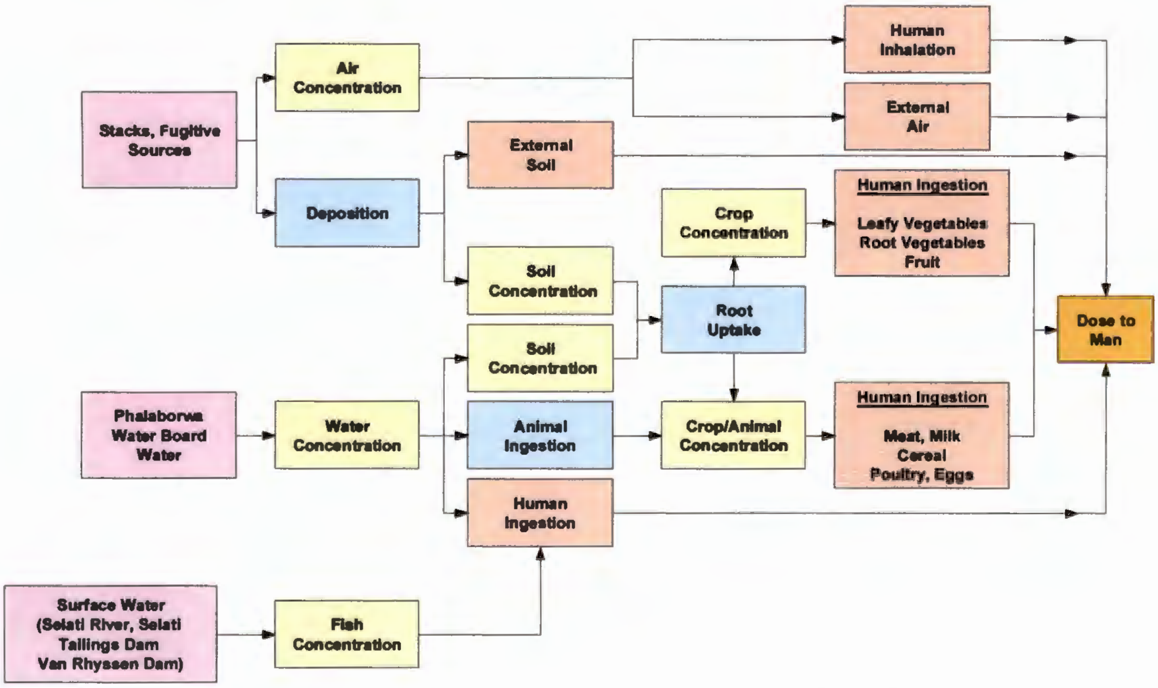


Figure 7-5: A flow diagram of the conceptual representation of Scenario 2

7.5.4 Scenario 3

In Scenario 3, the critical group receives a potential dose through human inhalation, human ingestion, as well as external water and soil exposure. The description of the scenario makes provision for the contribution of radon gas inhalation and it is assumed that the critical group obtains all its water from borehole KGM-B5. Note that the human ingestion pathway is extended to include the dose contribution from fish consumption. The flow diagram of the conceptual model for Scenario 3 is presented in Figure 7-6.

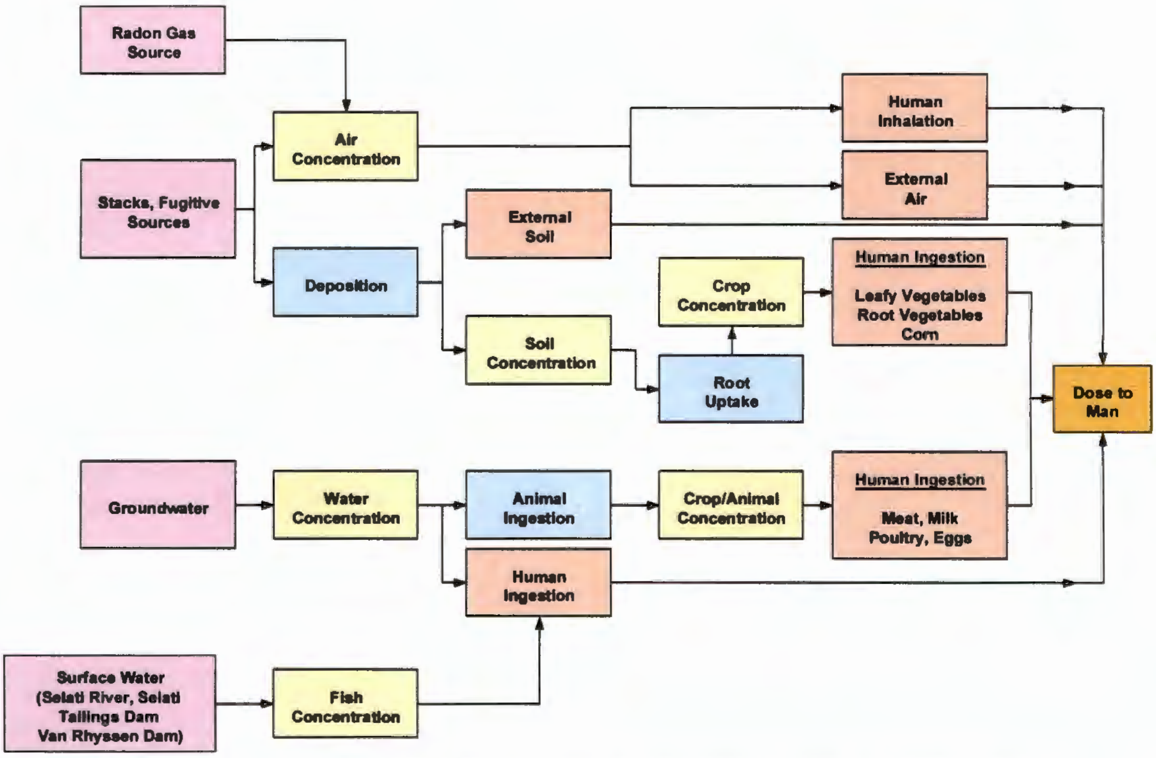


Figure 7-6: A flow diagram of the conceptual representation of Scenario 3

7.5.5 Scenario 4

In Scenario 4, the critical group receives a potential dose through inhalation, ingestion and external soil exposure. In this scenario, the surface- and groundwater pathways are of primary importance. The description of the scenario makes provision for the contribution of radon gas inhalation and it was assumed that the critical group obtains all its water from (1) borehole F (see Figure 7-3) and (2) the Selati River. The flow diagram of the conceptual model for Scenario 4 is presented in Figure 7-7.

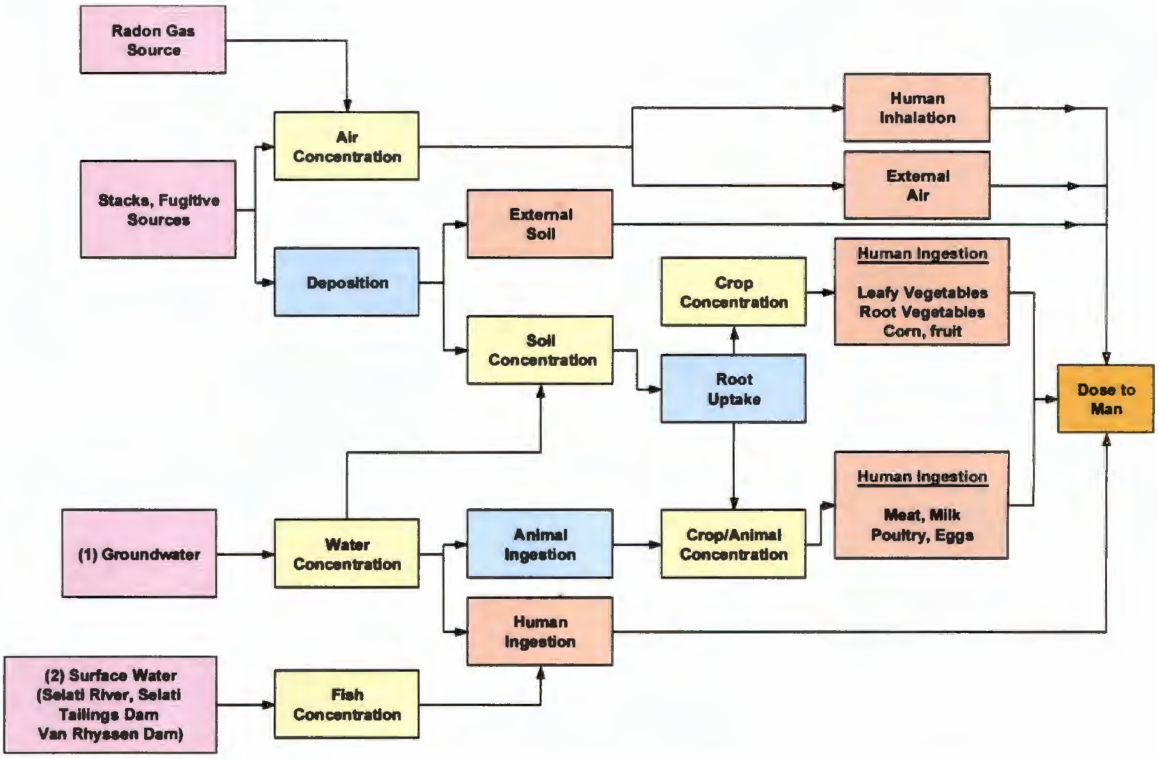


Figure 7-7: A flow diagram of the conceptual representation of Scenario 4

7.5.6 Scenario 5

Scenario 5 makes provision for a disruptive event. The conceptual model for this scenario is essentially the same as for Scenario 3. Scenario 5 was defined as the consequences of a 1:100 years rainfall event, which will result in the overflowing of Weir 3. The larger dam structures such as the Selati Tailings Dam are designed to withstand such flood events.

The exposure will not be for a whole year (365 days). The effects of flooding will cause the contaminated sediments in the waste-water canal and Dams 3 to 5 to be transported down the Selati River. Deposition can also take place. The main effects of flooding will be to dilute the activity. On the basis that Scenario 3 will form the bounding case, no dose assessments will be done for the flooding scenario. *The bounding case as mentioned here means the case that results in the highest impact or dose.* It is however included here for completeness. In addition, the probability that such an event will take place is only 0.01. Therefore the effective dose is given by the calculated dose multiplied by the probability, which in this case is 0.01.

7.6 SOURCE TERM ANALYSIS

7.6.1 General

The developed exposure scenarios represent the potential pathways along which the public might be exposed to radiation because of the mining and mineral processing activities at Foskor. The requirements are to assess the consequences of the scenarios to members of the critical groups in terms of a radiation dose.

The first step as part of the consequence analysis is to calculate the source term at various stages along the exposure pathways. In Figure 7-4 to Figure 7-7 this is represented by the different concentration boxes. Some of these concentration values were measured through monitoring programmes, whereas other values will be inferred from the biosphere equations given in Table 6-1.

7.6.2 Groundwater Pathway

7.6.2.1 General

The importance of the groundwater pathway to the project relates to the use of groundwater for human activities that might lead to a radiation dose particularly outside the Foskor site boundary. The various compartments relevant to this pathway and the interaction between them are presented in Figure 7-7.

Within the context of Scenario 4, groundwater is extracted at the point of impact and used for the following purposes:

(a) For human consumption (e.g. drinking water).
(b) Irrigation of crops for human consumption.
(c) Irrigation of grass for livestock consumption.
(d) Water supply to livestock (e.g. cattle).

To assess the groundwater pathway contribution at the point of impact, it is necessary to assess the groundwater concentration within the domain of interest. Each pathway has unique uncertainties associated with it. The uncertainties in the groundwater pathway are related to the lack of visual observation and measurements associated with it.

As part of environmental monitoring for regulatory requirements, Foskor performed a borehole-sampling programme to characterise concentration values in the groundwater. The values are an indication of the groundwater concentration values at selected points and over time. These do not provide one with an overall distribution of concentration values within the domain of interest and as a function of time. This shortcoming can be solved through the process of groundwater modelling. Groundwater concentration values at the point of impact can be obtained by simulating the movement of groundwater flow, with transport of radionuclides, from the various sources. This provides one with a real representation of concentration values over the domain of interest. What would be required, is the definition of initial groundwater concentration values at the various sources.

7.6.2.2 Initial Groundwater Concentrations

To simulate the movement of radionuclides from the different sources through the geosphere requires the definition of initial groundwater concentrations. In this study, the assumption will be made that all the groundwater pathway sources are hydraulically connected with the water table. This means that a constant source of contamination seeps to the groundwater. The concentration of the seepage from each source to the groundwater constitutes the source term for the groundwater pathway (Vivier *et al.* 1999).

To facilitate the input of initial concentration values in the groundwater flow and mass transport code that was used in this study (See Vivier and Van Blerk (1999)), it is necessary to express all concentrations in mg.L^{-1}. This requires that all activity values (Bq) be converted to gram (g) using the following conversion:

$$Bq = \frac{6.023x10^{23} * \ln(2) * g}{MW * T_{1/2}} \qquad \textbf{Equation 1}$$

where

6.023 x 10^{23} = Avogadro number

MW = Molecular weight of the isotope

$T_{1/2}$ = Half-life of the isotope (seconds).

If radionuclide concentrations are available only for solid material like sediments or soil (in μg.g^{-1} or mBq.g^{-1}), the radionuclide concentrations in the associated pore water (mg.L^{-1}) can be calculated by using the following equation:

$$C = \frac{I}{\theta R_d} = \frac{I}{\theta + \rho K_d} \quad \left(R_d = 1 + \frac{\rho K_d}{\theta} \right) \qquad \textbf{Equation 2}$$

where

C = Concentration in water [mg.m^{-3} or mg.L^{-1}]

I = Initial concentration of material [mg.m^{-3}]

R_d = Retardation coefficient [-]

ρ = Dry Bulk Density [kg.m^{-3}]

θ = Volumetric moisture content [m$^{3}\cdot$m^{-3}]

K_d = Distribution coefficient (adsorption coefficient) [m$^{3}\cdot$kg^{-1}].

Per definition, the distribution coefficient can be defined as the ratio of radionuclides in the solid- and liquid phases:

$$\frac{\text{Bq per kg soil}}{\text{Bq per L solution}} = L.kg^{-1} \quad or \quad m^3.kg^{-1}$$

Thus, to use Equation 2 to calculate the activity in solution using the concentration in a corresponding sediment sample, requires a K_d-value for the different isotopes and the sediment (e.g. tailings material, waste rock material, etc.). No measured K_d-values are available for the soil and sediments at Foskor and, therefore, literature values are used.

7.6.2.3 Soil Concentration

If groundwater is used as the only source of water supply, then irrigation of land will lead to an increase in the activity of the soil. This will result in an increase in the amount of activity (i.e. a source) available for uptake by different types of crops, which will eventually reach the critical group through the various pathways as presented in Figure 7-7.

To derive soil concentrations from groundwater used for irrigation, the assumption is made that a state of equilibrium exists between the concentration in water and the concentration in the soil at an average irrigation rate. Given the concentration in water, the concentration in soil can be calculated using the following equation (See Equation 2):

$$I = \frac{C(\theta + \rho K_d)}{\rho}$$ **Equation 3**

where

I	= Concentration in the soil	[$mBq.kg^{-1}$]
C	= Concentration in groundwater	[$mBq.m^{-3}$]
ρ	= Dry Bulk Density	[$kg.m^{-3}$]
θ	= Volumetric moisture content	[$m^3 \cdot m^{-3}$]
K_d	= Distribution coefficient (adsorption coefficient)	[$m^3 \cdot kg^{-1}$].

From Equation 3, it is clear that the distribution coefficient is an important parameter in determining the soil concentration. A high K_d-value will lead to higher soil concentrations and vice versa. The uncertainties that exist in K_d-values are transferred to the soil concentrations and, therefore, to the dose assessment.

7.6.3 Atmospheric Pathway

7.6.3.1 General

The atmospheric pathway influences the dose assessment via the inhalation of contaminated air by the critical group and the deposition of activity outside the site boundaries. The various compartments relevant to this pathway and the interaction between them are presented in Figure 7-7.

To assess the atmospheric pathway contribution for the different scenarios, it is necessary to determine the air concentration ($Bq.m^{-3}$) from stack emissions and from atmospheric releases via fugitive sources (e.g. dust and radon) from Foskor. The deposition quantities from the same sources ($Bq.m^{-2}$) will be used to calculate the increase in soil concentration at the point of impact. Parc Scientific (Pty) Ltd. (Strydom, 1998) calculated the air concentrations and deposition values that will be used in the project.

7.6.3.2 Soil Concentration

Deposits from the atmosphere in the area of impact will increase the activity at ground level. Through the process of re-suspension, the activity can serve as a new source and be distributed further. If this area is used for gardening or agricultural activity, the radionuclide activity will be distributed through the top layer of the soil. Consequently, the amount of activity available for uptake by plants, for example, will increase. The soil then serves as a source for the distribution of activity, which could reach the critical group through the various pathways.

To derive soil concentrations from the deposition values, the assumption is made that the deposition values (Bq.m^{-2}) are distributed evenly through the top 0.15 m of the soil (e.g. through ploughing). This will result in an activity per volume (Bq.m^{-3}). If the activity per volume is divided by the density (ρ) of the soil (kg.m^{-3}), the activity per mass in the soil is obtained. The assumption is made that the activity in the soil as a result of deposition, stays in equilibrium relative to the fraction that is leached to a greater depth by infiltration (i.e. a constant source).

7.6.4 Surface Water Concentrations

7.6.4.1 General

Under normal operating conditions, the surface water at Foskor operates in a closed circuit and no surface water flow from the site reaches the Selati River. The surface water concentrations that will be used in the project were determined as part of the monitoring programme at Foskor. In particular, the samples taken at positions upstream and downstream of the site boundaries will be used.

7.6.4.2 Soil Concentration

If surface water is used as the only source of water supply, irrigation of land will lead to an increase in the activity of the soil. This will result in an increase in the activity (i.e. a source) available for uptake by different types of crops. If surface water (e.g. from the Selati River) is used as an irrigation source, then Equation 2 can be used to calculate the resulting concentration in the soil.

7.6.5 Secondary Pathway Concentrations

Concentrations for the secondary pathways were derived from the equations presented in Table 6-1.

7.7 DOSE CALCULATIONS

7.7.1 General

The final step as part of the consequence analysis is to characterise the movement of radionuclides through the biosphere. This involves analysis of all exposure pathways defined in the scenarios, as well as the calculation of doses to the critical group.

In this section, the results of the dosimetry analysis for the different exposure scenarios as defined in Section 7.4, will be presented. Deposition, airborne concentrations and inhalation doses from stack and fugitive sources and the radon/thoron gas concentrations for the different scenarios were calculated by Parc Scientific (Pty) Ltd. (Strydom, 1998).

7.7.2 Scenario 1

Scenario 1 represents the dose to an actual critical group, situated adjacent to Foskor, in the town of Phalaborwa. The reason for choosing this point is that Scenario 1 concentrates on the atmospheric pathway and a point adjacent Foskor and part of Phalaborwa town will represent the most critical point for airborne activity exposure. In other words, this is a critical pathway. Since fishing is a common activity at Phalaborwa, this secondary pathway will be included in the scenario development phase, but for the purpose of this case study, no dose calculations will be done on this pathway. The fish consumption rates at Foskor are still under investigation, and this pathway will be included at a later stage in a second phase report

Parc Scientific (Pty) Ltd. (Strydom, 1998) calculated the respirable long-lived activity as well as the short-lived radon daughter concentrations at discrete receptor points. At the point of interest for Scenario 1 the long-lived gross-alpha activity concentration is 0.148 $mBq.m^{-3}$. According to Parc Scientific (Pty) Ltd., all the long-lived nuclides in the uranium and thorium chains were in equilibrium, and the ratio of Th to U nuclides is about 2 on average. The nuclide specific activity concentrations can hence be derived. These nuclide specific concentrations are used to calculate the age dependent committed dose due to inhalation.

The soil concentration, as a result of deposition from fugitive sources, was calculated using the approaches described in Section 7.6.3. Parc Scientific (Pty) Ltd. (Strydom, 1998) presented an annual average deposition flux density at various receptor points.

At the point of interest for Scenario 1 the deposition rate, in terms of gross-alpha activity, is 1.750 $\mu Bq.m^{-2}.s^{-1}$. This value results in a deposition of 55.188 $Bq.m^{-2}$ per annum. The resulting nuclide specific soil depositions are calculated using the same equilibrium assumptions as above. If it is assumed that the ploughing depth is 0.15 m, which will result in 0.15 m^3 over 1 m^2, and that the soil density is 1500 $kg.m^{-3}$, then the soil activity concentration from fugitive source deposition can be calculated.

For Scenario 1, water from the Phalaborwa Water Board, which represents a background contribution, is used as water supply. This background contribution will result in an increase in the activity in soil, and a method to calculate the resulting soil concentration was represented in Section 7.6.3.2, Equation 3. The dry bulk density used is 1500 $kg.m^{-3}$, while a porosity of 0.3 is used. The K_d-values for U, Ra and Th are 30.2, 102 and 502 $L.kg^{-1}$ respectively.

The radon concentration for Scenario 1was calculated in Parc Scientific (Pty) Ltd. (Strydom, 1998) as 0.038$Bq.m^{-3}$, and the corresponding thoron concentration is 0.001$Bq.m^{-3}$.

Radon/Thoron concentrations present at any location, specifically in a house, originate from the floor (subsoil) of the building, the building materials, and radon gas brought into the house from outside. The latter component is of importance because it represents the radon/thoron contribution by sources such as mine waste impoundment's. South African houses are well ventilated and it can be shown that the house structure does not afford any retardation to the entry of the outside radon/thoron gas. The dose conversion factors provided in ICRP 65 can then be applied directly. These assume that a person resides indoors for 7000 hours per annum, and 1760 hours outdoors, with equilibrium factors of 0.4 and 0.8 for indoor and outdoor radon. The dose conversion factor used in this document is 0.025 $mSv.a^{-1}/Bq.m^{-3}$. All calculated radon/thoron gas concentrations were multiplied by this factor to obtain the radon/thoron dose. This factor will be retained although, for assessments in this document, an exposure period of only 7000 $h.a^{-1}$ is assumed.

The nuclide specific airborne concentration for the fugitive sources can be used to calculate the dose due to inhalation. To do this, it is necessary to make certain assumptions concerning the behaviour of the exposed group of people (critical group).

(a) It is assumed that the critical group is exposed for a period of 7000 hours per year to the contaminated air.

(b) Different breathing rates ($m^3.h^{-1}$) are used for the different age groups and the daily-inhaled volumes are calculated and shown in Table 7-1.

(c) The dose conversion factors (Sv.Bq^{-1}) are taken from the ICRP-72 (See Appendix A).

The dose contribution from the Phalaborwa Water Board water was calculated in four different pathways, from drinking the water, from eating leafy vegetables, root vegetables and fruit that has been irrigated with Water Board water.

The equations in Table 6-1 have been used to calculate the doses received by the public through the different pathways.

The dosimetry analysis results for Scenario 1 are presented in Table 7-2. See Vivier *et al.*, (1999) for more detailed tables.

Table 7-1: Calculation of daily-inhaled volumes for different age groups.

Type of Activity	**Age = 0 – 2 a**			**Age = 2 – 7 a**			**Age = 7 – 12 a**			**Age = 12 – 17 a**			**Adults**		
Remarks (1)	**T**	**B**	**T*B**	**T**	**B**	**T*B**	**T**	**B**	**T*B**	**T**	**B**	**T*B**	**T**	**B**	**T*B**
Sleep	14	0.2	2.1	12	0.2	2.9	9	0.3	2.8	8	0.42	3.36	8	0.45	3.6
Sitting	5	0.2	1.1	6	0.3	1.9	6	0.4	2.3	6	0.48	2.88	6.5	0.54	3.51
Light exercise	5	0.4	1.8	6	0.6	3.4	6	1.1	6.7	8	1.38	11.04	8.5	1.5	12.75
Heavy exercise	-	-	-	-	-	-	1	2.2	2.2	2	2.92	5.84	1	3	3
Total per day	24		4.95	24		8.2	22		14	24		23.12	24		22.86
Average per hour			**0.21**			**0.34**			**0.64**			**0.96**			**0.95**

(1) T = Hours per day (from ICRP-66, Table 6 for adults and self-estimated for children)

B = Inhalation rate (m^3.h^{-1}) as per ICRP-66, Table 8

Table 7-2: The dose to the different age groups as calculated for Scenario 1.

Pathway		Dose (μSv.a^{-1}) for the different Age Groups (years)				
		0 – 2	2 – 7	7 – 12	12 – 17	Adults (>17)
Foskor Contribution						
Inhalation	Air	9.57E+00	1.05E+01	1.19E+01	1.71E+01	1.56E+01
	Radon	9.75E-01	9.75E-01	9.75E-01	9.75E-01	9.75E-01
Ingestion	Leafy Vegetables	2.68E-01	2.00E-01	2.54E-01	4.67E-01	1.00E-01
	Root Vegetables	7.70E-01	5.72E-01	7.38E-01	1.38E+00	2.72E-01
	Fruit	3.12E-01	2.31E-01	3.05E-01	5.82E-01	1.05E-01
External	Air					5.19E-07
	Soil					4.46E-03
Total Foskor Contribution		**1.19E+01**	**1.24E+01**	**1.42E+01**	**2.05E+01**	**1.71E+01**
Background Water Contribution						
Ingestion	Water	2.88E+01	2.10E+01	1.96E+01	3.32E+01	2.43E+01
	Leafy Vegetables	6.08E+00	5.27E+00	5.38E+00	8.05E+00	5.76E+00
	Root Vegetables	8.30E+00	6.48E+00	7.46E+00	1.30E+01	4.89E+00
	Fruit	2.43E+00	1.86E+00	2.30E+00	4.39E+00	1.18E+00
Total Background Contribution		**4.56E+01**	**3.46E+01**	**3.47E+01**	**5.86E+01**	**3.61E+01**

7.7.3 Scenario 2

Scenario 2 is very similar to Scenario 1, except that the food ingestion pathway has been extended to include the dose received from livestock product consumption. The positioning of the critical group in Scenario 2 stays the same as in Scenario 1, although an informal settlement community south of Phalaborwa, on the border of Foskor represents it.

The airborne and soil activity concentrations are the same as for Scenario 1, and therefore the resulting dose from inhalation will also be the same as in Scenario 1. The reason for choosing the same air and soil concentrations as in Scenario 1, is that this will represent the most critical case scenario. The extended biosphere pathways, as defined for Scenario 2, will result in increased doses from ingestion. For Scenario 2, water from the Phalaborwa Water Board, which represents a background contribution, is used as water supply. This background contribution will result in an increase in the activity in livestock products, fruit and vegetables.

The doses received by the public, for the different age groups, from ingesting meat, milk, cereal, poultry and eggs has been calculated. The dose contribution from Phalaborwa Water Board Water is calculated for the ingestion of meat, milk, cereal, poultry and eggs. The dosimetry analysis results for Scenario 2 are presented in Table 7-3.

Table 7-3: The dose to the different age groups as calculated for Scenario 2.

Pathway		**Dose (μSv.a^{-1}) for the different Age Groups (years)**				
		0 – 2	**2 – 7**	**7 – 12**	**12 – 17**	**Adults (>17)**
Foskor Contribution						
Inhalation	Air	9.57E+00	1.05E+01	1.19E+01	1.71E+01	1.56E+01
	Radon	9.5E-01	9.5E-01	9.5E-01	9.5E-01	9.5E-01
Ingestion	Leafy Vegetables	2.68E-01	2.00E-01	2.54E-01	4.67E-01	1.00E-01
	Root Vegetables	7.70E-01	5.72E-01	7.38E-01	1.38E+00	2.72E-01
	Fruit	3.12E-01	2.31E-01	3.05E-01	5.82E-01	1.05E-01
	Meat	1.86E+00	2.97E+00	3.81E+00	5.33E+00	2.84E+00
	Milk	4.57E+00	2.49E+00	2.01E+00	2.10E+00	5.89E-01
	Cereal	3.54E-01	2.65E-01	3.04E-01	5.03E-01	1.46E-01
	Poultry	1.07E-01	1.68E-01	2.43E-01	3.01E-01	2.01E-01
	Eggs	3.60E-02	6.10E-02	8.50E-02	1.01E-01	6.70E-02
External	Air					5.19E-07
	Soil					4.46E-03
Total Foskor Contribution		**1.88E+01**	**1.84E+01**	**2.06E+01**	**2.88E+01**	**2.09E+01**
Background Water Contribution						
Ingestion	Water	2.88E+01	2.10E+01	1.96E+01	3.32E+01	2.43E+01
	Leafy Vegetables	6.08E+00	5.27E+00	5.38E+00	8.05E+00	5.76E+00
	Root Vegetables	8.30E+00	6.48E+00	7.46E+00	1.30E+01	4.89E+00
	Fruit	2.43E+00	1.86E+00	2.30E+00	4.39E+00	1.18E+00
	Meat	1.31E+01	2.24E+01	2.75E+01	3.69E+01	2.51E+01
	Milk	2.28E+01	1.25E+01	1.00E+01	1.06E+01	3.03E+00
	Cereal	6.36E+00	4.98E+00	5.19E+00	7.76E+00	3.74E+00
	Poultry	1.10E-01	1.72E-01	2.49E-01	3.08E-01	2.06E-01
	Eggs	3.75E-02	6.24E-02	8.73E-02	1.03E-01	6.90E-02
Total Background Contribution		**8.80E+01**	**7.47E+01**	**7.78E+01**	**1.14E+02**	**6.83E+01**

7.7.4 Scenario 3

The aim of Scenario 3 is to quantify the contribution of Foskor to the total dose that a critical group will receive from water out of the Selati River. The water sample used for the analysis represents a sample from borehole KGM-B5, and the simulated radionuclide activity values can be found in Table 15, (Vivier and van Blerk, 1999). Parc Scientific (Pty) Ltd. (Strydom, 1998) calculated the airborne activity concentration. At the point of interest for Scenario 3 the concentration is 0.329 $mBq.m^{-3}$. Using the same equilibrium assumptions as in Scenario 1, the nuclide specific results can be derived.

The soil activity concentration for Scenario 3 was calculated using the same approach as in Scenario 1. At the point of interest for Scenario 3 the deposition rate is $3.855 \mu Bq.m^{-2}.s^{-1}$ (Strydom, 1998). This value results in a deposition of 121.57 $Bq.m^{-2}$ per annum. If it is assumed that the ploughing depth is 0.15 metres, which will result in $0.15m^3$ over $1m^2$, and that the soil density is 1500 $kg.m^{-3}$, then the resulting soil activity concentration from fugitive source deposition can be calculated. The resulting nuclide specific soil concentration can thus be derived using the same equilibrium assumptions as in Scenario 1. There is also a contribution of the atmospheric pathway in the form of radon/thoron daughter concentration. The radon concentration at the point of interest for Scenario 3 was calculated in Parc Scientific (Pty) Ltd. (Strydom, 1998) as 0.039 $Bq.m^{-3}$, and the corresponding thoron concentration is 0.197 $Bq.m^{-3}$. To obtain the radon/thoron dose contribution, the same approach as in Scenario 1 was followed.

To calculate the internal dose that a person will be exposed to through inhalation, the same assumptions as for Scenario 1 were used. The age dependent doses received by the public from ingestion of leafy vegetables, root vegetables, fruit, ingestion of meat, milk, cereal, poultry and eggs sere calculated. The external exposure from soil and air is calculated the same way as in Scenario 1. The dosimetric results for Scenario 3 are presented in Table 7-4.

Table 7-4: The dose to different age groups as calculated for Scenario 3

Pathway		Dose ($\mu Sv.a^{-1}$) for the different Age Groups (years)				
		0 – 2	2 – 7	7 – 12	12 – 17	Adults (>17)
Foskor Contribution						
Inhalation	Air	2.13E+01	2.33E+01	2.64E+01	3.81E+01	3.48E+01
	Radon	5.90E+00	5.90E+00	5.90E+00	5.90E+00	5.90E+00
Ingestion	Water	5.72E+02	3.79E+02	3.88E+02	7.39E+02	2.73E+02
	Leafy Vegetables	5.91E-01	4.41E-01	5.60E-01	1.03E+00	2.20E-01
	Root Vegetables	1.70E+00	1.26E+00	1.63E+00	3.05E+00	5.99E-01
	Fruit	6.87E-01	5.09E-01	6.72E-01	1.28E+00	2.32E-01
	Meat	1.68E+01	2.42E+01	3.21E+01	4.80E+01	1.55E+01
	Milk	8.59E+01	4.59E+01	3.66E+01	3.76E+01	9.96E+00
	Cereal	7.80E-01	5.84E-01	6.69E-01	1.11E+00	3.23E-01
	Poultry	2.31E-01	3.56E-01	5.11E-01	6.30E-01	4.11E-01
	Eggs	9.67E-02	1.51E-01	1.99E-01	2.23E-01	1.50E-01
External	Air					1.15E-06
	Soil					9.82E-03
Total Foskor Contribution		**7.06E+02**	**4.83E+02**	**4.93E+02**	**8.76E+02**	**3.41E+02**

7.7.5 Scenario 4

Scenario 4 represents the dose to a critical group situated west of Foskor, outside the site boundary, on the banks of the Selati River near borehole "F". In this scenario there are two water sources. In the first case the water for irrigation, livestock consumption and drinking is extracted from borehole "F", and in the second case the water is extracted from the Selati River.

The airborne activity concentration was calculated in Parc Scientific (Pty) Ltd. (Strydom, 1998). At the point of interest for Scenario 4 the concentration is 0.200 $mBq.m^{-3}$. Using the same equilibrium assumptions as in Scenario 1, the nuclide specific results can be derived.

The soil activity concentration due to fugitive dust, for Scenario 4, was calculated using the approach described in Scenario 1. Parc Scientific (Pty) Ltd. (Strydom, 1998) presented an annual average deposition flux at various receptor points. At the point of interest for Scenario 4 the deposition rate is 2.082 $\mu Bq.m^{-2}.s^{-1}$. This value results in a deposition of 65.66 $Bq.m^{-2}$ per annum. The resulting soil concentration from fugitive dust deposition can be derived, in the same way as in Scenario 1.

For Scenario 4, water can be extracted either from borehole "F" or from the Selati River. Both water sources will result in an increase in the activity in the soil due to irrigation. The same method to calculate the resulting soil concentration as in Scenario 1 was used and the resulting soil concentration from borehole "F" and the Selati River was calculated.

In Scenario 4 there is also a radon/thoron daughter contribution. The radon concentration at the point of interest was calculated in Parc Scientific (Pty) Ltd. (Strydom, 1998) as 0.068 Bq.m^{-3}, and the corresponding thoron concentration is 0.108 Bq.m^{-3}. The same approach as in Scenario 1 was followed to obtain the radon/thoron dose contribution.

The internal dose that a person will be exposed to through inhalation can be calculated using the same assumptions as for Scenario 1. The age dependent doses received by the public from inhalation can then be derived.

The age dependent doses received by the public from ingestion of leafy vegetables, root vegetables, fruit, meat, milk, cereal, poultry and eggs, using only borehole "F" as water source, was calculated, and the same calculations was done for using only the Selati River Water as water source. The external exposure from air and soil was calculated the same way as in Scenario 1. The dosimetry analysis results for Scenario 4 are presented in Table 7-5.

7.7.6 Scenario 5

Scenario 5 represents the disruptive scenario, which was defined as the consequences of a 1:100 year flood. This will result in an overflow of Weir 3. The conceptual model for Scenario 5 is essentially the same as for Scenario 3. Since Scenario 3 will form the bounding case, no dose assessments will be done for the flooding scenario.

Table 7-5: The dose to the different age groups as calculated for Scenario 4

Pathway		**Dose (μSv.a^{-1}) for the different Age Groups (years)**				
		0 – 2	**2 – 7**	**7 – 12**	**12 – 17**	**Adults (>17)**
Groundwater extracted from borehole "F"						
Inhalation	Air	1.26E+01	1.38E+01	1.57E+01	2.26E+01	2.06E+01
	Radon	4.40E+00	4.40E+00	4.40E+00	4.40E+00	4.40E+00
Ingestion	Water	5.63E+02	3.88E+02	3.87E+02	7.13E+02	3.46E+02
	Leafy Vegetables	1.46E+02	1.14E+02	1.26E+02	2.03E+02	8.49E+01
	Root Vegetables	3.26E+02	2.39E+02	2.83E+02	4.92E+02	1.25E+02
	Fruit	1.26E+02	9.20E+01	1.12E+02	1.99E+02	4.35E+01
	Meat	2.47E+02	3.87E+02	5.09E+02	7.37E+02	3.18E+02
	Milk	7.61E+02	4.21E+02	3.70E+02	4.15E+02	8.69E+01
	Cereal	1.61E+02	1.22E+02	1.32E+02	2.05E+02	7.49E+01
	Poultry	9.69E-01	1.51E+00	2.19E+00	2.71E+00	1.80E+00
	Eggs	3.41E-01	5.62E-01	7.78E-01	9.13E-01	6.09E-01
External	Air					6.84E-07
	Soil					2.99E-02
Total Borehole "F" Contribution		**2.35E+03**	**1.78E+03**	**1.94E+03**	**2.99E+03**	**1.11E+03**
Water extracted from Selati River						
Inhalation	Air	1.26E+01	1.38E+01	1.57E+01	2.26E+01	2.06E+01
	Radon	4.40E+00	4.40E+00	4.40E+00	4.40E+00	4.40E+00
Ingestion	Water	5.73E+01	3.65E+01	3.15E+01	5.11E+01	2.90E+01
	Leafy Vegetables	6.94E+00	5.42E+00	5.94E+00	1.02E+01	4.26E+00
	Root Vegetables	1.52E+01	1.15E+01	1.32E+01	2.45E+01	8.15E+00
	Fruit	4.39E+00	3.35E+00	4.12E+00	8.51E+00	2.45E+00
	Meat	1.23E+01	1.80E+01	2.15E+01	3.12E+01	1.42E+01
	Milk	7.20E+01	3.80E+01	2.71E+01	2.59E+01	9.45E+00
	Cereal	2.00E+01	1.51E+01	1.57E+01	2.32E+01	9.74E+00
	Poultry	3.26E-02	4.99E-02	7.10E-02	8.70E-02	5.66E-02
	Eggs	1.49E-02	2.28E-02	2.96E-02	3.26E-02	2.15E-02
External	Air					6.84E-07
	Soil					8.43E-04
Total Selati River Water Contribution		**2.05E+02**	**1.46E+02**	**1.39E+02**	**2.02E+02**	**1.02E+02**

7.8 DISCUSSION OF SCENARIO RESULTS

In the Foskor Radiological Public Hazard Assessment, Scenario 1 was included in the project to represent the most realistic scenario. Under these normal conditions, the highest dose contribution comes from the water. This is followed by the inhalation of air and radon/thoron daughters. This water represents a background contribution for water and is not influenced by any Foskor activities. The external dose from activity in the soil and air is negligible.

In Scenario 2, an extension of Scenario 1, the livestock pathways were included. With this inclusion, the biggest dose contribution comes again from the water pathways relating to background values, followed by the inhalation of air and radon/thoron daughters. The total dose for Scenario 2 is below the dose limit. For an informal settlement, the livestock pathway is unlikely, or if animals are kept, they may rather drink water from a nearby surface stream, but the purpose of Scenario 3 is to see what the impact of Foskor on livestock is.

Scenario 3 was included in this project because it was felt that a lot of the surface and groundwater drainage across Foskor is towards the Selati River. The biggest dose contribution comes from the drinking of borehole KGM-B5 water, which results in a dose above the dose limit. For both Scenarios 3 and 4 the use of the borehole or river water for irrigation of a small family garden is suggested. Only part of the annual intake (e.g. 50%) could be from this source. (See also scenarios recently suggested in draft IAEA report as well as the family farm scenario by Kennedy and Strenge, 1992.)

In Scenario 4, a comparison was done between water extracted from a borehole and water extracted from the Selati River. In the first case the borehole was the only water source for drinking and irrigation purposes, and in the latter case the Selati River was the only water source for all purposes. The total dose for all the pathways is below the dose limit for water extracted from the Selati River. In the case of water extracted from borehole "F" the biggest dose contribution comes from drinking the water and is well above the dose limit. The increase in dose contributions from the other food chain pathways is due to the higher water concentration used for irrigation and drinking by livestock.

It is also important to note that all the transfer coefficients and concentration ratios provided in LG-1032 (See Appendix A) are very conservative and represent the highest published values (See IAEA (1994), for an example). If no site-specific values are available, then a conservative route has to be followed.

The fishing pathway needs to be added to the total dose, because it is a major pathway through which radioactive concentrations can accumulate in the human body.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 GENERAL

The main objective of radioactive waste management is to ensure that human health and the environment are protected now and in the future, without imposing an undue burden on future generations (IAEA, 1995*a*). This implies that the impact that the disposed waste will have on individuals and their environment must be determined as a function of time. The term used for this procedure is safety assessment and is a relatively new concept, introduced by the IAEA roundabout 1981 (IAEA, 1981) in an attempt to provide guidelines for the solution of one of the harshest problems in the world, namely the disposal of radioactive waste.

South Africa produces radioactive waste through the full nuclear fuel cycle and the application of radioactive materials in industry, research and medicine. TE-NORM waste, due to a wide variety of mining and mineral processing facilities, is characterised by large volumes but low activity concentrations. Radioactive waste does not have any economical value and must finally be disposed. The impact that the disposed radioactive waste will have on future generations needs to be assessed in such a manner that the safety of the public will be ensured. This public assurance must be in accordance with internationally accepted safety practices.

The implementation of a safety assessment is a highly technical exercise, but also contains vital social and political elements. Many of the elements, especially the technical elements, will not be known at the beginning of the assessment. Moreover, it is highly unlikely that a disposal concept can be introduced without the active participation of the population. It is therefore of the utmost importance that the assessment should be performed in conjunction with a research and development programme aimed at reducing the unknown, and promoting public awareness of the assessment.

A radioactive waste disposal system can conveniently be divided into two classes, namely external and internal components. The external components are usually the components over which people have the least control, like geological and climatic processes. The internal components are those situated within the spatial and temporal boundaries of the system. Site information, physical, chemical, biological and radiological properties of the waste, engineered barrier system information and human behaviour are used in combination with the external components to define the migration of dissolved waste through the near-field, geosphere and biosphere. The biosphere, defined as that portion of the environment normally inhabited by humans and other living organisms, are important because it is in the biosphere that the impact of the disposal system can be quantified, in terms of exposure pathways to ultimately pose a dose to humans.

8.2 CONCLUSIONS

The treatment of the biosphere in a safety assessment framework was demonstrated in a case study to assess the impact of the Foskor (Pty) Ltd. site in terms of the overall radiation dose along all major pathways to members of the public. For this purpose, a site description of the Foskor site was compiled to characterise the various pathways in terms of the features, events and processes associated with them. The site was described in terms of climate, topography, geology, surface- and groundwater, demographic features, land and water use as well as natural and anthropogenic vegetation and animal life. Monitoring of radioactivity at Foskor is a safety related activity and quite a few studies have been conducted to quantify the extent of radioactivity in the environment at Foskor. Although not comprehensive, sufficient data were available, a database of all the radioanalysis done at Foskor was compiled and digitally archived.

The mining activities at Foskor produce waste products that are disposed of on the slimes dams and waste rock dump. The radionuclides contained in the waste products are available for transport via various pathways through the environment. The major isotopes in terms of concentration and half-life are ^{238}U, ^{232}Th, ^{224}Ra and ^{226}Ra. Surface water forms one of the most important pathways for radionuclide migration at Foskor. Contaminants that are dissolved by rainwater migrate to the Selati River via the surface water drainage systems. A source can be described as any physical entity that may cause radiation exposure to the public, for example, by emitting ionising radiation or releasing radioactive material (IAEA, 1995).

Of the three tailings dams used by Foskor, the Selati Tailings Dam is the most recent and biggest and is situated south of the Selati River. These tailings dams are saturated and in hydraulic connection with the underlying aquifers, and therefore the most important source for contaminant leachate generation. The importance of the four solid waste rock dumps in terms of radionuclide sources is small when compared to the tailings dams, because contaminants are only generated after rainfall events. The three stockpile facilities at Foskor are important for radon gas emanation, which forms part of the atmospheric pathway.

The biosphere has been characterised and its interaction with the other pathways was considered in the dose assessment. Site specific scenarios were developed for Foskor. Five scenarios were developed for the Foskor hazard assessment. A normal evolution scenario was defined, as well as a few alternative and disruptive scenarios.

The contribution of the Selati River to a total dose was assessed at points upstream and downstream of Foskor. Empirical equations were used to calculate the source term values at activity concentration points along the secondary pathways.

Scenario 1 was included in the project to represent the most realistic scenario. Under these normal conditions, the highest dose contribution comes from the water. This is followed by the inhalation of air and radon/thoron gas. This represents a background contribution for water and is not influenced by any Foskor activities. The external dose from activity in the soil and air is negligible.

In Scenario 2, an extension of Scenario 1, the livestock pathways were included. With this inclusion, the biggest dose contribution comes again from the water (relating to background values), followed by the inhalation of air and radon/thoron daughters. The total dose for Scenario 2 is below the dose limit. Scenario 3 was included in this project because it was felt that a lot of the surface and groundwater drainage across Foskor is towards the Selati River. The biggest dose contribution comes from the drinking of borehole KGM-B5 borehole water, which results in a dose above the dose limit.

In Scenario 4 a comparison was done between water extracted from a borehole and water extracted from the Selati River. In the first case the borehole was the only water source for drinking and irrigation purposes, and in the latter case the Selati River was the only water source for all purposes. The total dose for all the pathways is below the dose limit for water extracted from the Selati River. In the case of water extracted from borehole "F" the biggest dose contribution comes from drinking the water, and is well above the dose limit. The increase in dose contributions from the other food chain pathways is due to the higher water concentration used for irrigation and drinking by livestock.

For both Scenarios 3 and 4 the use of the borehole or river water for irrigation of a small family garden is suggested. Only part of the annual intake (e.g. 50%) could be from this source. (See also scenarios recently suggested in draft IAEA report as well as the family farm scenario by Kennedy and Strenge, 1992.).

8.3 RECOMMENDATIONS

The importance of the biosphere in a safety assessment framework is clearly demonstrated in this case study by the identification of the different pathways through which radioanuclides can impose a dose to humans. It is therefore important to consider the biosphere in every study where the future impact of waste disposal needs to be quantified.

Certain recommendations were concluded after considering all the potential exposure routes at the Foskor (Pty) Ltd. site. On the basis of the scenario dose calculations, the fish pathway needs to be addressed and the dose from this pathway needs to be added to the total dose. A detailed investigation is needed to determine the fishing activities at the Foskor (Pty) Ltd. site. The amount or mass of fish consumed by people that catch fish, either for leisure or use as a food source must be quantified. In order to determine transfer of activity from the water to the fish, nuclide specific radioanalysis must be done on the Selati Tailings Dam water and sediment, as well as on fish from the tailings dam.

APPENDIX A

EQUATIONS USED TO CALCULATE THE DOSE TO HUMANS THROUGH THE BIOSPHERE PATHWAYS, DOSE CONVERSION FACTORS, CONSUMPTION PARAMETERS AND TRANSFER COEFFICIENTS

Table A-1: Dose conversion factors for ingestion and inhalation *(ICRP 72).*

Age Group (Years)	**Ingestion Dose Coefficient (Sv.Bq^{-1})**					**Inhalation Dose Coefficient (Sv.Bq^{-1})**				
	0 – 2	**2 - 7**	**7 - 12**	**12 - 17**	**Adults**	**0 - 2**	**2 - 7**	**7 - 12**	**12 - 17**	**Adults**
^{232}Th	4.50E 07	3.50E 07	2.90E 07	2.50E 07	2.30E 07	5.00E 05	3.70E 05	2.60E 05	2.50E 05	2.50E 05
^{228}Ra	5.70E 06	3.40E 06	3.90E 06	5.30E 06	6.90E 07	4.80E 05	3.20E 05	2.00E 05	1.60E 05	1.60E 05
^{228}Th	3.70E 07	2.20E 07	1.50E 07	9.40E 08	7.20E 08	1.30E 04	8.20E 05	5.50E 05	4.70E 05	4.00E 05
^{224}Ra	6.60E 07	3.50E 07	2.60E 07	2.00E 07	6.50E 08	9.20E 06	5.90E 06	4.40E 06	4.20E 06	3.40E 06
^{238}U	1.20E 07	8.00E 08	6.80E 08	6.70E 08	4.50E 08	2.50E 05	1.60E 05	1.00E 05	8.70E 06	8.00E 06
^{234}U	1.30E 07	8.80E 08	7.40E 08	7.40E 08	4.90E 08	2.90E 05	1.90E 05	1.20E 05	1.00E 05	9.40E 06
^{230}Th	4.10E 07	3.10E 07	2.40E 07	2.20E 07	2.10E 07	3.50E 05	2.40E 05	1.60E 05	1.50E 05	1.40E 05
^{226}Ra	9.60E 07	6.20E 07	8.00E 07	1.50E 06	2.80E 07	2.90E 05	1.90E 05	1.20E 05	1.00E 05	9.50E 06
^{210}Pb	3.60E 06	2.20E 06	1.90E 06	1.90E 06	6.90E 07	1.80E 05	1.10E 05	7.20E 06	5.90E 06	5.60E 06
^{210}Po	8.80E 06	4.40E 06	2.60E 06	1.60E 06	1.20E 06	1.40E 05	8.60E 06	5.90E 06	5.10E 06	4.30E 06

Table A-2: Annual water and food consumption parameters

Category	**0-2 years**	**2 – 7 years**	**7 – 12 years**	**12 – 17 years**	**Adults**
Litres					
Water	260	300	350	600	720
Milk	300	300	300	300	250
Kilogram per year fresh weight					
Freshwater Fish	1	5	10	10	25**
Meat	20	50	75	100	100
Poultry	15	35	60	75	75
Eggs	6	15	25	30	30
Cereals and Grains	60	75	90	128	150
Root Crops	68	85	102	144.5	170
Leafy Vegetables	22	27.5	33	46.75	55
Fruit	30	37.5	45	63.75	75

(**)Recreational and subsistence fishermen

Table A-3: Transfer factors from soil to various types of grass, vegetables and fruit.

From Soil to …	**Isotope**									
	^{232}Th	**^{228}Ra**	**^{228}Th**	**^{224}Ra**	**^{238}U**	**^{234}U**	**^{230}Th**	**^{226}Ra**	**^{210}Pb**	**^{210}Po**
CR$_{grass}$ – Pasture grass browse and forage	1.000E 01	4.000E 01	1.000E 01	4.000E 01	2.000E 01	2.000E 01	1.000E 01	4.000E 01	5.000E 01	1.000E 01
CR$_{cereal}$ – Grains and cereals [1]	1.000E 03	1.000E 02	1.000E 03	1.000E 02	1.300E 03	1.300E 03	1.000E 03	1.000E 02	5.000E 02	2.000E 03
CR$_{leaf}$ – Leafy vegetables	1.000E 02	4.000E 02	1.000E 02	4.000E 02	1.000E 02	1.000E 02	1.000E 02	4.000E 02	3.000E 02	2.000E 03
CR$_{root}$ Root vegetables	8.000E 04	4.000E 02	8.000E 04	4.000E 02	3.000E 02	3.000E 02	8.000E 04	4.000E 02	2.000E 02	2.000E 03
CR$_{fruit}$ – Fruit	4.000E 04	4.000E 02	4.000E 04	4.000E 02	4.000E 04	4.000E 04	4.000E 04	4.000E 02	1.000E 02	1.000E 03
From Water to …										
DR$_{fish}$ - Fish (L.kg^{-1})	1.000E03	2.000E02	1.000E03	2.000E02	5.000E01	5.000E01	1.000E03	2.000E02	2.000E03	5.000E02

(1) For example maize wheat barley sunflower seeds

Table A-4: Transfer factors from animal feed to animal products.

From Animal Feed ...(e.g. Pasture, Grass, Forage) to ...	**Isotope**									
	^{232}Th	**^{228}Ra**	**^{228}Th**	**^{224}Ra**	**^{238}U**	**^{234}U**	**^{230}Th**	**^{226}Ra**	**^{210}Pb**	**^{210}Po**
DF$_{meat}$ – Edible animal products [(1)]	5.000E 03	5.000E 03	5.000E 03	5.000E 03	3.000E 02	3.000E 02	5.000E 03	5.000E 03	9.100E 04	5.000E 03
DF$_{poultry}$ – All types of poultry	4.000E 03	9.900E 04	4.000E 03	9.900E 04	1.200E00	1.200E00	4.000E 03	9.900E 04	2.000E 03	4.000E 03
DF$_{egg}$ – Eggs	2.000E 03	2.000E 05	2.000E 03	2.000E 05	1.000E00	1.000E00	2.000E 03	2.000E 05	2.000E 03	1.800E 02
DF$_{milk}$ – Animal milk [(2)]	5.000E 06	1.300E 03	5.000E 06	1.300E 03	6.100E 04	6.100E 04	5.000E 06	1.300E 03	3.000E 04	3.000E 03

[(1)] For example beef cow pigs goats and game

[(2)] Including cow goat sheep

Table A-5: Dose conversion factors for immersion from soil and air concentrations.

Conversion Factors from Air Concentration	**Isotope**									
	^{232}Th	**^{228}Ra**	**^{228}Th**	**^{224}Ra**	**^{238}U**	**^{234}U**	**^{230}Th**	**^{226}Ra**	**^{210}Pb**	**^{210}Po**
(mSv h^{-1} / kBq m^{-3})	3.14E 08		3.32E 07	1.70E 06	1.23E 08	2.76E 08	6.27E 08	1.14E 06	2.03E 07	1.50E 09
Conversion Factors from Soil Concentration										
(mSv h^{-1} / kBq m^{-2})	1.98E 09		8.46E 09	3.43E 08	1.98E 09	2.69E 09	2.70E 09	2.32E 08	8.95E 09	2.97E 11

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