APPLICATION OF SAFETY ASSESSMENT METHODOLOGIES IN DISPOSAL OF DISUSED SEALED SOURCES USING BOREHOLE CONCEPT

By

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DECLARATION

I declare that the work in the dissertation entitled 'Application of Safety Assessment Methodologies in Disposal of Disused Sealed Sources Using Borehole Concept' as been performed by me in the Department of Physics under the supervisions of Prof. S.P. Mallam, Prof. T.C. Akpa and Prof. I.I. Funtua.

The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at any university.

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CERTIFICATION

This dissertation entitled 'APPLICATION OF SAFETY ASSESSMENT METHODOLOGIES IN DISPOSAL OF DISUSED SEALED SOURCES USING BOREHOLE CONCEPT' by Aliyu Sa'id meets the regulations governing the award of the degree of Doctor of Philosophy of Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

I would like to dedicate this work to my beloved parents, my wives and children.

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All thanks are to Almighty God for His infinite mercy and immeasurable blessing on me especially for the successful completion of this resourceful work.

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ABSTRACT

This Disertation develops safety assessment model appropriate for use in calculating doses to a resident farmer living in the far future in the vicinity of a borehole disposal facility around Zaria environs. Doses are assumed to arise from potential releases from the disused sources disposed in the borehole facility having inventories typical to those found in the African countries. A list of features, events and processes (FEPs) was developed, relevant to Zaria biosphere and an assumed requirement to calculate doses to the farmer via abstraction well water. An 'interaction matrix' was also developed to help define the FEPs and to identify the relationships between them. These relationships define how radionuclides escape from the container, migrate and accumulate in biospheric media, thereby giving rise to radiation exposure. FEPs were audited for inclusion in the matrix, and either include with an explanation of how, or excluded with an explanation of why. The doses to the farmer were calculated using GoldSim computer model. The model presented is probabilistic in nature that will reflects the current state of knowledge about the site by using probability distributions to capture what is expected (average or central tendency) and the uncertainty (standard deviation) associated with input parameters. The model was then run using Monte Carlo simulation over 100 realisations in each case. Each realization represents a possible combination of input parameter value. The output estimated values of contaminant release rate, concentration in environmental media and resulting doses to human receptors are obtained. Statistical summaries of the result were then compared with regulatory performance objectives (dose constraint). Initially the average value was found to be 0.76mSv/yr, which is greater than the dose constraint (0.3mSv/yr). This was found to be due to the daughters of ^{241}Am radionuclide especially ^{239}Np which has a Total Effective Dose Equivalent (TEDE) of 0.761mSv/yr. The ^{241}Am inventory was

then reduced to a value (2.95MBq) that gives a dose limit of 0.296mSv/yr.

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CHAPTER ONE

GENERAL INTRODUCTION

1.0 Introduction

Radioactive sources can either be unsealed (dispersible) or sealed. A sealed radioactive source is a source containing radioactive substances designed to prevent any dispersal of the substances, under normal conditions of use, and to rule out any possibility of contamination. Sealed radioactive source have been widely in used for decades to the benefit of mankind. They are use in industries, agriculture, medicine and various research fields in both developed and developing countries including Nigeria. At the end of their useful life, these sources are defined as "spent" or disused sealed sources. The activity of a disused source may still be in the order of Giga Becquerel (GBq) or Tera Becquerel (TBq). The high activity and concentration of residual radioactivity of most of these disused sources combine with the long half-life ($T_{½}$) of some of the radionuclides poses radiological hazard if not manage well.

Many of these sources may be lost, stolen or simply abandoned when no longer required. Loss or misuse of sealed sources can give rise to accidents resulting in radiation exposure of workers and members of the general public. They can also give rise to contamination of land, equipment and buildings. In extreme cases the exposure can be lethal. The incidents and accidents that have occurred with a wide range of consequences, including widespread contamination and deterministic health effects, have demonstrated the risk associated with spent radioactive sources if regulatory control and technically sound management are breached (Friedrich, 2002).

An integrated waste management system should include provision for the safe disposal of disused sources. Disposal facility could be of the near surface or deep geological repository type depending on the wastes activity and half-life. Short-live waste tends to be

disposed off in near surface facilities while high activity long-lived wastes are disposed in the later.

A possible disposal method that has been proposed (IAEA, 2002_a) is the so called "Borehole Concept", where by disused sources are placed in holes drilled into suitable rock formations with appropriate engineering barriers where necessary and the holes are then sealed. This should provide sufficient containment over the time period for which the sources would remain hazardous.

It is vital when disposing the waste to make sure that no significant emission into the surrounding environment occurs. Therefore a waste disposal facility should be properly designed so that both the natural and the artificial barrier would be able to isolate the waste from escaping into the environment up to the time the level of activity in it would have decayed to within the acceptable dose limits.

To achieve this acceptability, a repository for radioactive waste should demonstrate through a safety assessment, that it will meet the design objectives, performance standard and regulatory criteria. There are therefore, continued international initiatives to develop, improve and harmonize approaches in assessing and demonstrating the safety of waste disposal facilities. Some of these initiatives include the RADWASS (Radioactive Waste Management Safety Standards) program, ISAM (Improving Safety Assessment Methodologies) group and ASAM (Application of Safety Assessment Methodologies) group, both by International Atomic Energy Agency (IAEA). There are also many other organisation in the waste disposal arena around the world, such as French National Radioactive Waste management Agency (ANDRA) in France, U.S. Nuclear Regulatory Commission (U.S.NRC) in USA, Australian Nuclear Science and Technology Organisation (ANSTO) in Australia and 'Empresa Nacional de Residuos Radioactivos SA' (*ENRESA*) in Spain.

Safety assessment has been developed for many of the disposal facilities, but there are also many facilities that were developed before the present safety assessment methodology were put in place. Many countries, where disposal facilities were developed prior to present safety assessment methodologies were put in place, are now reassessing the safety of their facilities using the current initiatives. The countries include Germany, India, Bulgaria, Russia and other countries in Eastern Europe (IAEA, 2002_b).

The ISAM Group developed a consistent safety assessment methodology which has the following key components.

- Specification of the assessment context
- Description of radwaste disposal system
- Development and justification of scenarios
- Formulation and implementation of conceptual and mathematical models
- Analysis of result and building of confidence.

1.1 Sealed Sources

A sealed source is a small quantity of the radioactive material that is sealed in a metal casing and enclosed in a housing that prevents the escape of the radioactive substance. As long as the source remains sealed with the housing intact, and the devices are handled and used properly, the devices present no health risk from the radioactive source within. In fact, manufacturers of these devices must demonstrate protectiveness in order to receive a license to manufacture and sell them. Purchasers of the devices must be licensed to use the device in the intended manner, and are required to safely and legally dispose of the sources.

Sealed sources within devices are commonly used to deliver a defined dose of radiation, such as that used in cancer therapy or in irradiators that sterilize food and

medical equipment. But there are also other uses such as in: industrial gauges, radioisotope, thermoelectric generators to provide electric power in remote areas, gamma radiography to check welds on pipelines, and well logging to explore coal, oil, and natural gas.

While there are some specific advantages to using sealed sources that are distinct to various industries, the major advantages are essentially the same across all the industries. Sealed sources provide the following advantages for use in industry (EPA, 2002):

- Portable energy source not requiring other sources of energy (e.g., electricity) for operation
- Range of energies.
- Easily transportable.
- Interacts with other media in well-defined manner that facilitates various measurements.
- Does not require contact with other material / media for use.
- Devices are typically easy to use and do not require sophisticated operator training.
- Commercially available from a large number of vendors in a variety of forms and energies.
- Mature technology.

There are a number of disadvantages to the use of radioactive sealed sources that are common to all industries also. These include:

- Need for precautions to prevent exposure of individuals to harmful radiation
- Energy source is always "on", thus requiring significant attention to storage.
- Loss of the source can create an environmental and health hazard.

- "Spent" sources require appropriate disposal.

When radioactive sources are no longer emitting enough penetrating radiation for use or become 'orphan' (see section 1.2) the sources are treated as radioactive waste. These wastes are generally called disused sealed sources (Jankowitsch-Prev, 2003). Disused sources can either be disposed as radiation waste in a disposal facility or hold in an interim storage until they can be exempted. Disposal of spent radiation sources other than as exempted waste includes the following options (IAEA, 1991):

- Sea disposal (though ban since 1983)
- Shallow land repositories, with or without engineered barriers
- Deep geological repositories

Disposal as exempt waste and dilution of radium in mill tailings: Very low activity sealed sources and exempt waste, including some with very low concentrations of long lived radionuclides (e.g. smoke detectors), are often acceptable for disposal in landfill sites used for domestic and industrial wastes. Bulk disposal of such sources in packages is generally not acceptable. Radium was originally extracted from uranium ores. At each major uranium mine, there are huge quantities of tailings (about 100,000 tons or more). In such tailings more than 100g of radium can be found which is comparable to the total quantity of radium sources in all the developing countries. Disused radium sources could be disposed of by opening them and adding the radium to the milling process. The radium is not expected to increase the radium concentration in the tailings significantly.

Sea disposal: Sea disposal has been used since the 1940s (IAEA, 1991) for low-level radioactive waste including sealed source. After some international debate, there has been a moratorium on dumping at sea since 1983. Before the moratorium was imposed, about $5x10^{17}$Bq of radioactive waste (including disused sources), had been disposed of at sea in accordance with the London Dumping Convention (LDC) regulation.

Shallow Land Disposal: there are many shallow land repositories, most of them in developed countries. Some are with engineering barrier (e.g. vault) and some are without (e.g. trenches). Those without engineering barrier are called simple near surface disposal facility. This facility is considered appropriate only for those wastes that will decay sufficiently in-situ within an anticipated period of institutional control (between 100-300years).

The engineering barrier facilities are used for similar types of waste as is used in simple trenches. The barrier is intended to allow ease of waste emplacement and increased efficiency in the management and closure of the repository. Provided a shallow land repository is properly sited, constructed and operated, it may safely be used for the disposal of most disused sources.

1.2 Orphan Sources

High-activity radioactive sources are sometimes abandoned, lost, misplaced or removed without authorisation. These sources are called "orphan sources". Orphan sources like this could be found by persons unaware of the risks which they pose. Records have shown that, in recent years, orphan sources have caused multiple fatalities or serious injuries when unperceived individuals have found them. This problem, along with concern that orphan sources might be acquired for malevolent purposes, has led many countries to consider making concerted effort to improve control over them. Several accidents have occurred in the past involving abandoned radioactive facilities, inappropriate disposed sources use outside regulatory control. The common cause of these accidents was inappropriate control over the radioactive source causing the damage. Lack of control is due to different reasons. But in all cases immediately before the accident no one was responsible of its safety and control.

Instances where orphan sources have become a problem include:

- Measuring and controlling devices containing radioactive materials that were improperly disposed of as scrap metal and taken to metal recyclers;
- Radioactive material used with gauges in industrial processes and in road and building construction that were found by the side of the road or in a river;
- Sealed radioactive sources used in oil and gas exploration, which are no longer wanted but contain radioactive materials that exceed the limits for disposal at commercial low-level radioactive waste disposal facilities.

Orphan radioactive sources must therefore be put in safe conditions and immediately disposed as radioactive waste. The regulatory organisation should consider special mechanisms or procedures to detect orphan sources, and keep out of danger the people involved, well before the first radiological consequences could arise. Prevention measures for orphan radioactive sources must be considered as a necessary complement to a primary control system.

In Argentina the Nuclear Regulatory Authority have agreed with different security, civil service and health organisations, on procedures to promote early detection and response of "orphan" sources in order to prevent or minimise radiological consequences(Tellería, et.al., 1998). The experience shows that the overall risk is properly kept low with this practical criterion. The U.S. Nuclear Regulatory Commission (U.S.NRC) is moving to address the problem of unwanted and uncontrolled radioactive materials (orphan sources). The NRC has been working with the Conference of Radiation Control Program Directors (CRCPD), through its E-34 Committee on Unwanted Radioactive Materials (the E-34 Committee), on the development of the U.S. national orphan source program (William, 1999). The E-34 Committee is currently testing portions of the program as a pilot project. The project includes providing aid in the management of

unwanted and uncontrolled radioactive material by identifying sources of assistance with the handling of the material, and by finding suitable outlets for the material.

Nigeria through the Nigerian Nuclear Regulatory Authority (NNRA) is cooperating with the US-DOE Global Threat Reduction Initiative (GTRI) Program for the following objectives:

- Reduce and Protect "vulnerable" nuclear and other radioactive material located at civilian sites
- Remove and dispose of excess nuclear and radiological materials
- Secure and Protect at-risk nuclear and radiological materials from theft or sabotage (Bello and Ogharandukun, 2009**).**

The NNRA and the US DOE signed the "Basic Ordering Agreement" Contract on 11th March 2005. This was followed by an assessment Mission on 19 - 25 April 2008 under the Nigeria -US-DOE Nuclear Security Cooperation Program. The Mission visited Old Steel factory (Ajaokuta) to assess source removal options for Legacy Radioactive Sources Gamma Irradiation Facility, Radiotherapy Units at EKO Hospital, Lagos. It also visited University College Hospital, Ibadan, Research Reactor at CERT, Zaria and Radioactive Waste Management Facility also at CERT, Zaria for possible physical security upgrades and expansion (Bello and Ogharandukun, 2009).

In 21 –26 July 2008 Team of Experts from the International Atomic Energy Agency (IAEA), Open Joint Stock Company (OJSC), Russia, US DOE, the Nigerian National Nuclear Security Committee (NSC) and the NNRA undertook a Technical Expert Mission to Ajaokuta Steel Company Limited (ASCL). The objective of the mission was to characterize and establish a complete inventory for the over 200 Legacy radioactive sources at Ajaokuta Steel Company Limited (ASCL).

A national strategy for locating and for the management of legacy and orphan sources has now been developed. As part of this plan, an agreement has now been reached between the NNRA and the Operator of the Radioactive Waste Management Facility (CERT Zaria) on the temporary storage of such sources when they are located and collected.

An inventory now exists for the legacy sources at ASCL which are all of Russian origin. The total number of inventoried sources was 234 comprising of 205 Cs-137, 24 Co-60, and 5 Pu-Be mostly of varied activity and manufacturing dates.

1.3 Present Studies

Radwaste are produced in Nigeria. The wastes are produced in Industries, universities, research institutes, hospitals and in the commissioned Nuclear reactor at CERT. The wastes are mostly disused sealed sources and low-level radwaste. The need to manage and dispose the waste with appropriate and optimized approaches so as to keep Nigerians and the living environment away from unacceptable hazard at present and in future is necessary.

The aim of this research is to develop the borehole disposal concept further by testing its suitability in Nigeria, at Zaria, under specific site and land conditions. The study will only assess post-closure safety because of time and financial constrains. The operational safety and closure aspect will thus not be considered. The inventories that would be considered include a variety of heterogonous waste that include a range of low and intermediate level waste arising from the use of radionuclides in research, industries, medicine and education. But primary attention will be focused on disused sealed sources.

Although mining and milling of tin and phosphate generate radwaste in Nigeria, the disposal of such waste is not within the scope of the research. The research will also not consider the disposal of Naturally Occurring Radioactive Material (NORM) waste generated in gas and oil industries. The assessment of the disposal system will only consider radiological impacts of the waste; chemical or biological toxicity will also not be assessed.

CHAPTER TWO

USES OF SEALED SOURCES, THEIR BIOLOGICAL EFFECTS AND THE MANAGEMENT OF THE DISUSED SEALED SOURCES.

2.0 Introduction

The use of radiation released by radioactive nuclide has brought a lot of benefits to mankind. It is used in the diagnosis and treatment of diseases. It is also used for sterilization of medical equipment. In industry, radionuclides are used in industrial radiography, measuring devices, process and control, material analysis, civil engineering projects and oil and mineral exploration. In agriculture, radionuclides are used for crops improvement, preservation of food, pest control and animal production. They are also used to measure soil moisture, erosion rates, salinity, efficiency of fertilizer uptake in the soil, and are used in research to help reduced the quantity of pesticides used by farmers. Despite the designed safety features, some sealed source devices may produce a potentially lethal amount of radiation if used improperly.

2.1 Sealed Sources

2.1.1 Uses of Sealed sources

i. *Gauges:* Intensity of radiation is reduced by matter and the reduction can be measured by a detector. This principle can be used to measure (gauge) the presence or absence, the quantity or density of material. Gauges are also used to monitor and control the flow of materials in pipes, distillation columns etc. Depending upon the specific application, gauges may contain relatively small quantities of radioactive materials, or may contain sources with activities

approaching 1TBq. The devices generally are not large, but may be located some distance from the radiation detector, which may have electrical or electronic components located within the detector.

ii. *Well Logging:* Radioisotopes are used in well logging to assist in determining whether a drilled well has certain rocks or minerals, oil, gas, or other substances of consumer value. Well logging generally uses Sealed Sources containing radioactive materials that emit gamma rays or neutrons. The sources are usually contained in long (1-2m), but thin (<10cm in diameter) devices that also contain detectors and various electronic components. The devices are heavy (even though the source is small) due to the ruggedness needed for the environments in which they are to be used. Gamma emitters and neutrons sealed sources especially cobolt-60 and americium-241/beryllium are used.

iii. *Industrial Radiography:* In Industrial Radiography radiation is used to inspect pipes, walls, and variety of structures to look for defects. The Radiation source can be sealed source (Iridium-192) or an X-ray machine.

iv. *Sterilization:* Radiation sources are used to sterilize consumer products. These sources are called irradiators and generally contain a gamma emitting sealed sources that emit very high amounts of radiation and required significant shielding. They are used to sterilised hospital equipment and supply, and mails. If bacterial or viral diseases (biological compounds) are being used as terrorist devices and sent in the mail, irradiation of mail will sterilize those compounds, rendering them ineffective.

v. *Food Irradiation:* Food irradiation is done to destroy food-borne bacteria and parasites and extend the shelf-life of some foods. Food irradiation facilities use radiation-emitting devices that will expose the food products to a very high dose

or radiation. Over the past 60 years, food irradiation has been used in military, in the space program, in medicine for bone marrow transplant patients and more (RadiationAnswers.org, 2007). Because of the significant impact that food irradiation can have on decreasing food-related illness, food irradiation has been endorsed by such well-respected agencies as World Health Organisation (WHO), American Medical Association, American Dietetic Association, etc.

vi. *Medical uses:* There are many uses of radiation in medicine. The most well-known is using X-ray to see area whose bones are broken and this is called radiology. Mammography, computerized tomography (CT) and nuclear medicine are special areas of radiology. Both X-ray sources and sealed sources are used in radiology. Another area of X-ray use is called cardiology, where special X-ray pictures are taken of the heart. There are additional areas in medicine that uses radiation sources called Radiotherapy. Radiotherapy is a process used in the treatment of disease or cancer. For example, the use of radioactive iodine to treat thyroid problems, including thyroid cancer. The study and treatment of cancer is known as radiation oncology.

vii. *Security Device:* There are few common devices used for security that involve Radiation. Cabinet X-ray systems are one of the common devices used for security. They are found primarily at airports. Computerized tomography (CT) machines are used to scan luggage at the airport and cargo coming on planes or ships.

viii. *Scientific Uses:* Radioisotopes are used as tracers in many research areas. Most physical, chemical and biological systems treat radioactive and non-radioactive forms of an element in exactly the same way, so a system can be investigated with the assurance that the method used for investigation does not itself affect

the system. An extensive range of organic chemicals can be produced with a particular atom or atoms in their structure replaced with an appropriate radioactive equivalent. Using tracing techniques, research is conducted with various radioisotopes which occur broadly in the environment, to examine the impact of human activities. The age of water obtained from underground bores can be estimated from the level of naturally occurring radioisotopes in the water. This information can indicate if groundwater is being used faster than the rate of replenishment. Trace levels of radioactive fallout from nuclear weapons testing in the 1950s and 60s are now being used to measure soil movement and degradation. This is assuming greater importance in environmental studies of the impact of agriculture.

ix. *Power Generation:* Radiation sources are used to produce electrical or thermal power especially where stringing electrical lines proves difficult, for instance, in remote areas. Radiation source is used to power spacecraft and satellites, the light on ocean buoys, and remote weather stations. Radioactive sources are also used to generate electrical power for consumer use, as is done in a nuclear power plant.

2.1.2 Categorisation of Sealed Sources

IAEA, in 2005, developed a system to categorise radioactive sources, ranking them in terms of their potential to cause immediate harmful health effects if the source becomes "orphaned". It uses five categories, where Category 1 sources are potentially the most dangerous and Category 5 sources are most unlikely to be dangerous.

Category 1

Sources in this category are considered to be extremely dangerous if not used or stored and secured properly. The sources could lead to the death or permanent injury of individuals who are in close proximity to the source for a short period of time

Table. 2.1 Example of Category 1 Sources

Source	Usage	Typical Radionuclides	Typical Activity Range
Irradiators	Used to sterilize foodstuffs, cosmetics, medical products and supplies, and for other specialized applications such as research applications or for blood irradiation.	Cobalt-60 (^{60}Co)	56 to 560,000 TBq (1500 to 15,000,000 Ci)
		Caesium-137 (^{137}Cs)	37 to 190,000 TBq (1000 to 5,000,000 Ci)
Teletherapy	Used for cancer therapy and commonly found in medical institutions, such as hospitals or clinics	Cobalt-60 (^{60}Co)	37 to 560 TBq 1000 to 15,000 Ci
		Caesium-137 (^{137}Cs)	19 to 56 TBq (500 to 1,500 Ci)
Fixed Multi-beam Teletherapy	Used to focus gamma radiation from an array of over 200 sources on brain lesions. (gamma knife) these are commonly found in hospitals or clinics.	Cobalt-60 (^{60}Co)	150 to 370 TBq (4000 to 10,000 Ci)
Radioisotope Thermoelectric Generators	Used to provide low amounts of electric power. These devices are used primarily for military purposes and space exploration, but have also been used to supply low levels of power in remote areas (eg. for beacons).	Strontium-90 (^{90}Sr)	330 to 25,000 TBq (9000 to 680,000 Ci)
		Plutonium-238 (^{238}Pu)	1 to 10 TBq (28 to 280 Ci)

(minutes to hours). Such sources are normally used in specially designed facilities and equipment that provide sufficient shielding from radiation. Examples: radioisotope thermoelectric generators, irradiators, teletherapy machines, and fixed multi-beam teletherapy machines (Table 1.1).

If a Category 1 source became unshielded, it would be likely to cause permanent injury to a person who handled it or who was otherwise in close proximity to the source for more than a few minutes. It would probably be fatal to be close to this amount of unshielded radioactive material for a period in the range of a few minutes to an hour.

Category 2

Category 2 sources are considered also to be very dangerous if not used or stored and secured properly. The sources could lead to the death or permanent injury of individuals who are in close proximity to the source for a longer period of time than for Category 1 sources. Examples: industrial gamma radiography equipment and high/medium dose-rate brachytherapy (Table 1.2). If a source of this category was not safely managed or securely protected, it could cause permanent injury to a person who handled it or who was otherwise was in contact with it for a short time (minutes to hours). It could possibly be fatal to be close to this amount of unshielded radioactive material for a period of hours to days.

Table. 2.2 Example of Category 2 Sources

source	Usage	Typical radionuclides	Typical activity range
Industrial radiography	Used to test the integrity of various materials, as well as for testing welds in pipes and tanks in the petrochemical industry.	Cobalt-60 (^{60}Co)	0.41 to 7.4 TBq (11 to 200 Ci)
		Iridium-192 (^{192}Ir)	0.19 to 7.4 TBq (5 to 200 Ci)
		Selenium-75 (^{75}Se)	3 TBq 80 Ci
		Ytterbium-169(^{169}Yb)	0.093 to 0.37 TBq (2.5 to 10 Ci)
		Thulium-170 (^{170}Tm)	0.74 to 7.4 TBq (20 to 200 Ci)
High/medium dose rate brachytherapy	Used for cancer therapy and commonly found in medical institutions, such as hospitals or clinics	Cobalt-60 (^{60}Co)	0.19 to 0.74 TBq (5 to 20 Ci)
		Caesium-137 (^{137}Cs)	0.11 to 0.3 TBq (3 to 8 Ci)
		Iridium-192 (^{192}Ir)	0.11 to 0.44 TBq (3 to 12 Ci)

Category 3

Category 3 sources are defined as being dangerous. If not safely managed or securely protected, the sources could lead to the permanent injury of individuals who are in close proximity to the source for a longer period of time than Category 2 sources. Sources in Category 3 could, but are unlikely to, lead to fatalities. Examples: fixed industrial gauges (level gauges, dredger gauges, conveyor gauges, and spinning pipe gauges) and well logging gauges (Table 1.3).

TABLE. 2.3 Example of Category 3 Sources

Source	Usage	Typical Radionuclides	Typical activity range
Fixed industrial gauges	Used for process control; for measurement of flow, volume, density, or material presence; and may be placed in locations unsuitable for continuous human presence.	Cobalt-60 (^{60}Co)	0.0037 to 0.37 TBq (0.1 to 10 Ci)
		Caesium-137 (^{137}Cs)	0.00011 to 1.5 TBq (0.003 to 40 Ci)
		Californium-252 (^{252}Cf)	0.0014 TBq (0.037 Ci)
Well logging gauges	Used in areas where exploration for minerals is occurring, such as coal, oil natural gas.	Americium241/beryllium (^{241}Am/Be)	0.019 to 0.85 TBq (0.5 to 23 Ci)
		Caesium-137 (^{137}Cs)	0.037 to 0.074 TBq (1 to 2 Ci)
		Californium-252 (^{252}Cf)	0.001 to 0.0041 TBq (0.027 to 0.11Ci)

Category 4

Sources in this category are unlikely to be dangerous and it is very unlikely that anyone would be permanently injured by these sources. However, this amount of unshielded radioactive material, if not safely managed or securely protected, could lead to the temporary injury of individuals who may be in close proximity to the source for many hours, or who was close to it for many weeks. Examples of category 4 sources are: low dose-rate brachytherapy sources, thickness gauges, portable gauges, and bone densitometers.

Category 5

Category 5 sources are most unlikely to be dangerous and no one could be permanently injured by these sources. These sources could, but are unlikely to, cause minor temporary injury of individuals. Examples: X-ray fluorescence devices, static eliminators, and electron capture devices.

2.1.3 Biological and Health Effect of Radiation

Biological effect begins with ionization of atoms. The mechanism by which radiation causes damage to humans or any other material is by ionization of the atoms in the body or material. The radiation exposure affects people by depositing energy in the body, which can causes cell damage or cell death. In other cases the cell may survive but become abnormal, either temporarily or permanently. Both large and small doses of radiation can cause cellular damage. The extent of the damage depends upon the total amount of energy absorbed, the time period and dose rate of exposure, and the particular organ exposure.

By damaging the genetic material (DNA), Radiation causes cancer. If it is directly exposed to the genetic material in reproductive cells genetic mutation can happen that can be passed on to future generation (genetic effect). In rare occurrence where there is a large amount of radiation exposure, sickness or even death can occur within a short time (acute effect).

When radiation is incident on a material it deposits some or all of its energy on the material. The energy of the radiation causes excitation or ionization of the atoms or molecules of the material depending on the radiation energy.

Acute effect are most often seen in cases of high doses of radiation delivered in a short period of time and do not occur routinely in workplace but only seen in accident situations. An example of acute effect was observed in Japan, many atomic bomb survivors and emergency workers responding to the 1986 Chernobyl nuclear power plant accident (NRC, 2004). About 134 plant workers and fire-fighters suffer from acute radiation sickness and 28 died from their radiation injuries after receiving high radiation doses.

The health effect on living things especially humans was better expressed by Profio (1979) as prompt personal effect (acute effect), delay effect (late effect) and genetic effect.

2.1.4 Radiation Protection

Radiation protection is defined as the science of protecting people (both workers and the general public) from receiving unnecessary radiation. It is a special aspect of the control of environmental health hazard by engineering means. Other names like radiation safety, radiological health, health physics and radiation hygiene are used instead of radiation protection. The exercise for protecting the radiation hazard on people started about 100 years ago (Oliver, 1973).

Radiation protection is normally classified into two: external radiation protection and internal radiation protection. The external radiation protection is the protection of radiation hazard that arises from sources of radiation outside the body e.g. radiation from x-ray machines and sealed radionuclide sources. Applying one or more of the following three methods controls this type of radiation hazard:

(i) Minimizing exposure time.

(ii) Maximizing distance between a person and the source.

(iii) Shielding the radiation source.

While the internal radiation protection is the protection against personal contamination resulting from inhaled, injected or tactically transmitted radioactivity. Internal radiation protection is concerned with preventing or minimizing the deposition of radionuclide on people. This is achieved if the contamination of the environment is kept within acceptable limits and at levels as low as practicable. The basic control of internal radiation hazard is either to block the portal of entry into the body or to interrupt the transmission of radionuclide from the source to man. Proper collection and management

of radioactive waste is an inherent part of contamination control and internal radiation protection.

Radiation protection ethics: is that everyone using ionizing radiation has a normal obligation both to themselves and the rest of the population, both present and future, to ensure their safety from the effect of radiation

2.1.5 Principles of Radiation Protection.

There are three principles of radiation protection as published in ICRP publication No. 26 (1977). They are:

Justification- All activities involving the exposure to ionizing radiation of either workers or members of the public have to be justified by a net benefit. That is ionizing radiation is not used unless there is a net benefit from their use. That it is also not used when the effect can be achieved more safely by some other means.

Optimization- the second principle try to ensure that radiation workers and the general public were not over exposed by optimizing the dose that will be received as low as reasonably possible, that is all exposures shall be kept as low as reasonably achievable, social and economic factors being taken into account (ALARA). This means that procedures, equipment, processes and other operational factors should be designed and followed to minimize the radiation exposure.

Dose Limitation- the dose equivalent to individual from all practices should not exceed the applicable dose limit. These dose limits are in addition to the doses from the natural background and medical exposures. Some recommended doses were published by ICRP for radiation workers and the general public for whole body and some sensitive organs. No specific dose limits were recommended for medical practices. Three levels of dose limitation are envisaged: Dose limits, dose constraints for

optimization and reference levels (Skornik, 1995).

Dose limits apply to practices by defining the frontier between what is allowed and what is proscribed. Dose constraint is a value of individual dose to be established to restrict the range of options considered in the process of optimization of protection for a given source of installation. It is a restriction on individual exposures resulting from a particular source or task. The value of constraints is in there to limiting too much variation in individual exposures and their prospective value in setting optimization goals. Reference or investigation levels are guides that help in taking certain steps such as giving an alert, investigation and intervention in a particular situation. ICRP (ICRP, 2007) recommend a dose of 1mSv/yr for dose limit, 0.3mSv/yr for dose constraint and 10mSv/yr for reference level.

In radiation protection of sealed radioactive sources, people that are using sealed source devices must be trained and knowledgeable about their proper, safe and secure use. In untrained hands, such devices can injure and kill. Malevolent acquisition and use of radioactive sources may cause radiation exposure or dispersal of radioactive material into the environment. Such an event could cause significant social, psychological and economic impacts.

If the source becomes too weak for its use, it does not mean that the source is safe. Many accidents have resulted from sources that are no longer being used for their original purpose. The following are but a few of the accidents that have occurred and resulted in serious injuries and deaths:

i. In December, 2001, three woodsmen found two heat-emanating ceramic objects near their camp site in the remote Inguri river valley of Georgia. Two of the woodsmen carried the containers on their backs and experienced nausea, vomiting and dizziness within hours of exposure. The third carried the source

attached to a wire. The woodsmen were diagnosed at hospital in Tbilisi, Georgia with radiation sickness and severe radiation burns. A Georgian team recover the sources in 2002 with the assistance of IAEA.

ii. A farmer in Cairo, Egypt, picked up a 3TBq radioactive source and took it home. Later the farmer and his 9 year-old son went to a local doctor that prescribed medication for a viral or bacterial infection. The farmer and his youngest son died and the rest of the family members showed severe depression of white blood cell count on test.

iii. A serious accident also happens in morocco that results in the death of eight people. This happen when a passer-by picked up a tiny source of iridium for radiography. Over several months, many people were exposed and died. Only after eighth person died was radiation suspected as the cause.

iv. In December 2002, two americium-241/beryllium sources used for well logging were stolen from an oil company truck while it was in transit in the southern Niger Delta region here in Nigeria. Such sources are typically of about 0.7 TBq of activity. Public announcements, police efforts and increased border vigilance were all instigated in an attempt to find the sources. Health care workers were also warned to keep a lookout for anyone with prolonged nausea or skin burns. Some eight months later the sources were detected in a scrap metal shipment in Europe. Even though no one was injured or died due to the loss of these sources, but if not that their lost were detected earlier similar effect would have happen.

2.2 Waste and waste management

2.2.1 Waste.

Waste is a name given to the entire different thing that people throw away every day, such as cans, paper, vegetables, glass, plastic, etc. Items that people no longer need or do not have any further use, therefore fall in the category of waste.

Since the beginning of creation, man has been generating waste from the food he eats and things he uses for shelter. With the progress of civilization, the wastes generated become more complex in nature.

Waste can be broadly classified as control and non-controlled waste (Skitt, 1972). Controlled wastes are wastes that are regulated by an Agency e.g. household, commercial and clinical waste. While those that are not regulated by the agency are called non-control waste e.g. agricultural, mines and quarries wastes.

2.2.2 Radioactive Waste (Radwaste)

Radioactive waste is defined as material that contains or contaminated with unstable elements that decay by emitting alpha, beta or gamma rays at concentrations or activities greater than clearance level as established by a nuclear regulatory body, and for which no use is foreseen. Radwaste arises from mining industries of radioactive and other ores, and in the final use of most radioactive materials. Radwaste are also generated in the luminizing industries, where radium, tritium, strontium, or other radioisotopes are used to make dials and luminous devices. Other ancillary sources of radwaste include medical, research and industrial activities involving radioactive materials.

2.2.3 Classification of Radioactive Waste

Radioactive wastes (Radwaste) are classified according to different criteria. It can be classified according to radiological properties (quantity and type of radioactivity), physical properties (solid, liquid or gas) and also whether it is heat producing or not. The hazard involved as well as the final disposal method to be used for the waste also plays a part in the classification. For the purpose of this research the classification of radioactive waste was considered as:

i) *Exempt waste (EW):* this contains such a low concentration of activity that it does not need to be treated differently from ordinary non-radioactive waste.

ii) *Low level waste (LLW):* This is the type of waste generated from hospitals, laboratories, industries and nuclear fuel cycle. The waste is not dangerous to handle, but must be disposed of more carefully than non-radioactive waste.

iii) *Intermediate-level waste (ILW):* This contain higher amount of radioactivity and may require special shielding. Intermediate-level waste comprises of chemical sludge, resins, reactor components and contaminated material from reactor decommissioning. The manufacturing process for machine parts, plastics, smoke detectors, emergency signs and other consumers of goods produces some of these LLW. The wastes are basically materials used in areas where radioactive substances are handled.

iv) *Short Live Waste:* Contain mainly radionuclides with relatively short half-lives (less than 30years), with only very low concentration of long lived radionuclides.

v) *NORM Waste:* This consists of large amount of waste containing fairly low concentration of naturally occurring radionuclides (though these concentrations are often higher than those found in nature). This type of waste is generated in the mining and processing of uranium and other minerals, such as phosphates used in fertilizer.

vi) *High Level Waste:* This refers to spent reactor fuel and highly active liquid produced when spent fuel is reprocessed. The volume of this type of waste is very low, but it activity is so high that it generates considerable heat.

2.2.4 Radioactive Waste Management

The objective of radioactive waste management is 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. This objective was elaborated in IAEA safety series No. 111-F (IAEA,1995$_a$) as nine principles. These principles and their explanations are summarized in Appendix A.

There are three general strategies that are employed in the management of radioactive waste: Concentrate and contain, dilute and disperse, and delay and decay.

- 'Delay and decay' involves holding the waste in storage until the desired reduction in activity has occurred through radioactive decay of the radionuclides contained in the waste.
- 'Concentrate and contain' means reduction of volume and confinement of the radionuclide contents by means of a conditioning process to prevent dispersion in the environment.

- 'Dilute and disperse' means discharging waste to the environment in such a way that environmental conditions and processes ensure that the concentrations of the radionuclides are reduced to such levels that the radiological impact of the released material is acceptable.

The first two options often involve the holding of waste in a storage facility or the emplacement of waste in a disposal facility. Radioactive waste therefore has to be processed, as necessary, in such a way that it can be safely placed and held in a storage facility or a disposal facility. The two options were adopted at present to achieve the objective and to isolate the disused sealed sources from the *biosphere*.

2.2.6 Basic steps in radioactive waste management

Effective management of radwaste involves the following steps as part of a total system, from generation to disposal. The steps are pre-treatment, treatment, conditioning and disposal of the waste.

Pre-treatment of radwaste as the first step in the waste management consist of collection of the waste, segregation, chemical adjustment, decontamination and a period of interim storage. The step is important in providing the opportunity to segregate radwaste for geological and near surface disposal.

Treatment is the second step in radwaste management. It basic concepts are volume reduction, radionuclide removal and change of composition.

The next step is conditioning of radwaste which involves immobilization of radwaste, placing it into containers and providing additional packaging which will make the waste suitable for handling, transportation, storage and disposal.

Disposal is the final stage in the radwaste management. It consists mainly of the emplacement of the waste in a repository with a reasonable assurance for safety, without

reliance on long term surveillance and maintenance. This safety is mainly achieved by concentration and containment which involves the isolation of suitably conditioned radioactive waste in a disposal facility.

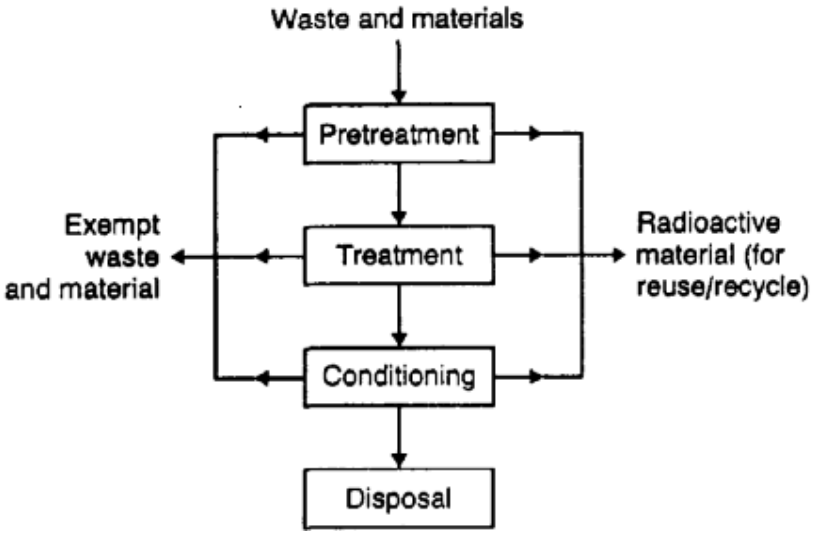


FIG. 2.1. Basic Steps in Radioactive Waste Management.

Deep geological repositories: There are sealed sources that cannot be disposed in near surface disposal facilities because they are too powerful (very high activity) and/or too long-lived for disposal in such facilities. Such sources must be contained and isolated from humans and the environment for many thousands of years. Deep geological disposal is considered favourable for the waste providing security and safety in a manner that does not require active monitoring, maintenance and institutional controls (Nuclear Energy Agency, 1999).

But their small volume makes disposal in a deep geological repository uneconomical. In fact there is no deep geological repository in operation anywhere in the world, nor will there be for at least the next 10 years (Waller, 2002). Many countries have these high

activity or long-lived sources in storage. The storage of these sources is not an ideal situation because they will need to be looked after for hundreds or even thousands of years to avoid any threat to people alive now and generations to come. Their presence in store can lead to increased risk of degradation of the physical integrity of the sources (corrosion, damage of the encapsulation or packaging, etc.), and the loss of control (abandoned and orphaned sources, theft, misuse, etc.). Therefore, the eventual solution for the final management of disused sources should be disposal. To address this issue, the IAEA contacted the South African Nuclear Energy Corporation (Necsa) to develop a practical engineered solution (Crossland, 2005). The outcome of this work is the BOrehole disposal of Sealed Radioactive Sources (BOSS) System. The BOSS system is a safe, simple to construct and cost-effective solution for the disposal options for small volume of waste such as radioactive sources. The sources are placed inside two high integrity stainless steel containers (one inside the other) and sealed within a 30-100 metre deep, specially engineered borehole in the suitable host geological media. The probability of human intrusion should also be very low because of the small diameter of the borehole. This would provide a relatively simple and inexpensive 'repository' for countries whose only needs for geological disposal relate to disused sources. However, although this approach might simplify the assessment process, it would not remove the need for a comprehensive safety assessment.

2.2.7 Radioactive Waste Management in Nigeria

The radioactive waste management policies in Nigeria are prescribed in the Act 19 of 1995 and in the National Radioactive Waste Management Policy and Strategy. The framework for the policy stipulates that Nigeria will comply with the basic principles developed by the IAEA for safe management of radioactive materials (Okafor, 2010).

Nigerian Nuclear Regulatory Authority (NNRA) gazetted ten (10) Regulations amongst which is the 'Nigeria Radioactive Waste Management Regulations (2006)'. There is only one Radioactive Waste Management Facility (RWMF) in the country. It is located in the Centre for Energy Research and Training (CERT), Zaria, Kaduna State. It has a Memorandum of Understanding (MOU) with the Authority on Management of the RWMF.

Nigeria does not have spent fuel presently, no reprocessing plant but has robust and rapidly growing peaceful nuclear applications. These include about seven sectors of the Nigerian economy. The sectors are petroleum industry, mining industry, manufacturing industry, construction industry, agriculture/ water resources, education/research and health. NNRA require all users of Radioactive Sources to have a written agreement with manufactures to take back the sources when they become disused.

However in anticipation of spent fuel from the research reactor (NIRR-1) in CERT and the proposed acquisition of nuclear power plants in the country, NNRA has set up a technical Advisor Committee (TAC) on preparation of regulatory and guidance document on the management of the Spent Nuclear Fuel. Nigerian government and the vendors have a Project Supply Agreement (PSA) that the spent fuel for NIRR-1 shall be taken back to the manufacturer.

2.2.8 Disposal of Low Level Waste (LLW)

As explained above, LLW is industrial and ordinary research waste that are contaminated with/by radioactivity. They are the waste generated by universities, research institutes, hospitals, radioisotope manufacturers and all users of radioactive materials.

LLW is generally in solid form; although some liquid wastes are also generated e.g. hospitals and research centres generate liquid waste used in diagnostic testing and medical treatment. The manufacturing process of machine parts, plastics, smoke alarms, emergency signs and other consumer goods produce some of the LLW.

The safe disposal of LLW is essential to protect the health and safety of the public. LLW is characterized by relatively low levels of radioactivity, generally requiring little shielding and no cooling and usually representing a potential hazard of limited duration. Disposal of LLW has been done by sea dumping or by disposal in land repositories. Sea disposal has been used since 1940's and has taken place at various sites in the oceans (IAEA, 1999_d). Following the UN conference on Human Environment, held in Stockholm in 1972, the convention on the prevention of Marine Pollution by dumping of wastes and other matters entered into force in 1975 (Kirsti-Liisa and Gordon , 1994). Since then the land disposal of radwaste became the only option.

2.3 Radioactive waste Disposal Facilities

Development of facilities, which provide final disposal of LLW, must be consistent with the established national strategy and objectives. Such objectives include:

- Protection of the general public from releases of radioactivity.
- Protection of individuals during facility operation.
- Protection of individual from intrusion after the facility has been closed.
- Long-term stability of the disposal site after closure to provide for effective isolation of the waste from its environs.

When undertaking a safety assessment for disposal to a near surface facility, the life cycle of the disposal facility (the time during which a radioactive waste disposal site will remain active) is divided into four main periods:

1) Pre-closure (operational) period that is the time of development of a disposal site and a few years after closure of the site. This is usually a period of 30-60years. Closure occurs after waste receipts stop, operations are completed and the site satisfied the entire requirement for the institutional control period to begin.
2) Institutional control period: this is the period after the operational period and extended to the time the waste would not pose any further threat to humanity and the environment. The control period is intended to apply for a period of several decades to a few hundred years (IAEA, 1999_c). At this period the site is not acceptable for the public and various kinds of monitoring are done. The ISAM safety case group proposed 30years for Borehole case, 300years for RADON and 200years for Vault safety case (IAEA, 2004_b), as a reasonable period over which such controls may be reliable.
3) The post-institutional (or passive institutional control) refers to societal memory of the disposal site and last for about 100years.
4) The last period is the absence of any control. It means that enough records and knowledge about the site are lost to permit the possibility of intrusion. Its duration is limited only with safety assessment time frames. Table 2.1 below shows the summary of life time of the disposal facility.

Table 2.4. Timeframes and Assumed Activities ($IAEA_a$, 2001; $IAEA_b$, 2001; $IAEA_d$, 2001)

Activity	Time frame (years)		
	Borehole	RADON	Vault
1) Operational period	0-60	0 - 60	30
2) Active institutional control-include final capping and subsequent monitoring	60-90	60 - 300	0 - 200

3) Passive institutional control- withdrawal of active controls.	90-200	300 - 400	200 – 300
4) No control: all records/knowledge assume to be lost.	> 200	> 400	> 300

2.3.1. Types of Radioactive Waste Disposal Facilities

There are two types of radioactive waste disposal facilities:

Near surface disposal facilities: this is a disposal facility located at or within a few tens of meters of the earth's surface (IAEA, 2000a)

Geological disposal facility: Is a facility that is located underground (usually several hundred meters or more below the surface) in a stable geological formation to provide long term isolation of radionuclides from the biosphere (IAEA, 2000a)

Near surface disposal facility is further divided into minimum-engineered repository and engineered repository. Minimum engineered repository (disposal facility without engineered barrier) is the oldest and simplest method. It consist of placing a waste in trenches below surface without engineered barrier and covering the waste with a layer of soil and the area kept under institutional control for a period of time. Examples of this type of repositories are trenches for lower activity waste at the Barwell site in USA (Hixon, 2001) and Drigg site in UK (LLW Repository Limited, 2009).

Engineered-near-surface disposal facility differs from a minimum-engineered facility because of the presence of engineered barrier design to improved radiological and environmental safety of the disposal option. The improvement has resulted in increasing the delay radionuclide migration from the repository. For example concrete vaults, backfilled with some matrix of concrete or cement mortar is used. This facility can be situated above or below the ground too. The Bore-hole disposal facility, with the depth

that varies between 30-100m and which is currently under development in South Africa, is also considered as engineered near surface disposal facility (Van Blerk et al, 2000)

2.3.2 Borehole Disposal Facility.

The borehole disposal facility covers a range of design concept with depth ranging from a few meters to several hundred of metres. Their diameters can vary from a few centimetres to more than one metre (IAEA, 2003_b & IAEA, 1999_b). Widely available drilling technologies provide adequate technical tools for implementation of the borehole disposal concept.

The design been considered, IAEA's AFRA project (IAEA,1999b), has a series of engineering barriers as illustrated in fig. 2.2 - 2.5. The borehole is drilled using rotary air percussion method. The top of the borehole has a diameter of 305mm and 254mm at the bottom of the borehole to allow the trouble-free insertion of casing that will be fitted down to the bottom of the borehole. A Polyvinyl Chloride (PVC) casing or High-Density Polyethylene (HDPE) is used in the design. A bottom plug is provided to ensure that the disposal volume is dry during the operational period. A waste package is lowered to the plug and backfilled with cement/bentonite to fill the gap between the waste and the casing wall as well as the top of the waste to about 750mm from the waste. The next waste package is then lowered into the borehole and the process is repeated. Waste packages would continue to be placed into the borehole until the waste acceptance limit or the cut-off depth is reached. Each emplacement configuration is thus in the order of one meter (1m) as shown in Fig. 2.5. Once the waste packages have been emplaced in the borehole, the remaining casing at the top of the waste is cut and removed from the borehole and then is filled up with cement/bentonite to a depth 5m below the ground surface. The 5m depth is filled with the native soil. The depth from

the ground surface and the disposal zone would be about 30m which is beyond human intrusion.

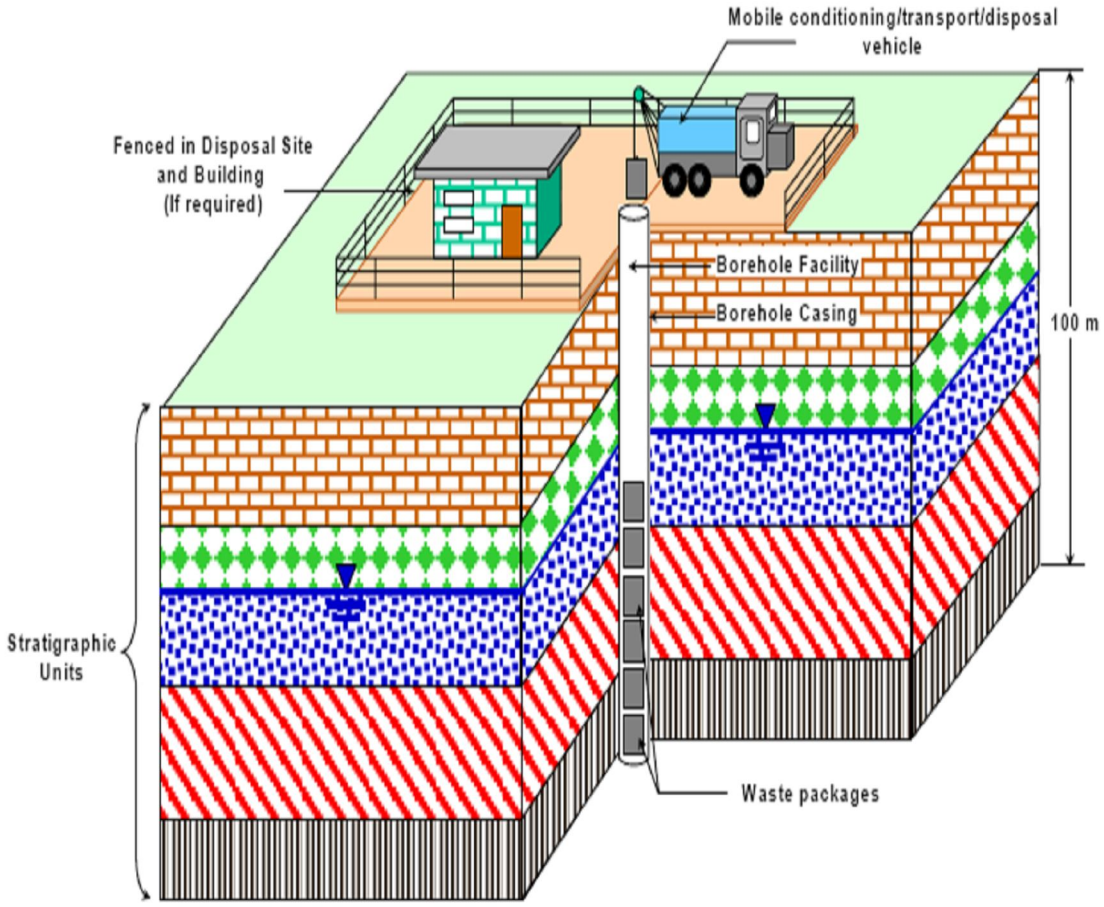


Fig 2.2 A Schematic Presentation of the Repository Area of the Borehole Disposal Concept (IAEA, 2004_b)

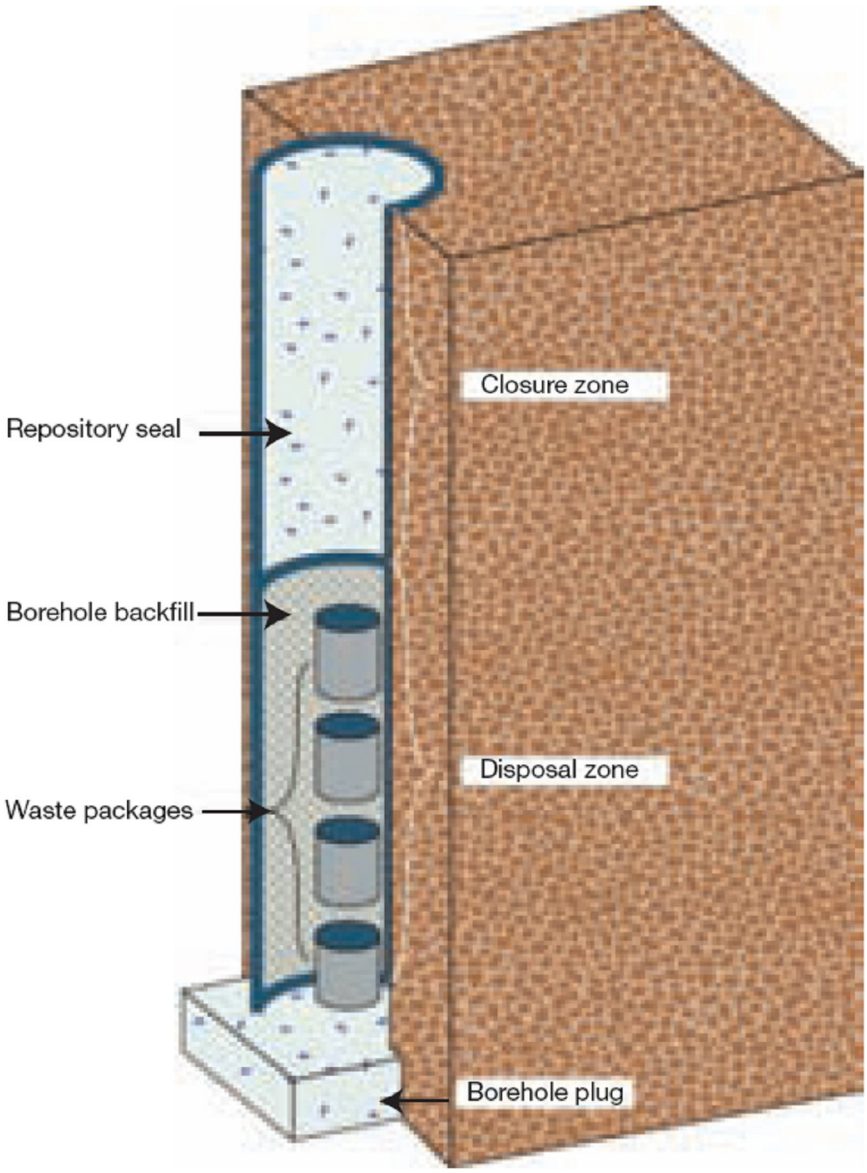


FIG. 2.3 A Conceptual Borehole Based on NECSA Work (NECSA, 2003).

disposal operations. After the active institutional control period the site becomes accessible and no records or knowledge of the existence of the site remains.

The facility aims to achieve safety by a contribution of natural and engineered barriers that would contain the activity of the waste until it decay to insignificant levels that assure level of protection for human and the environment.

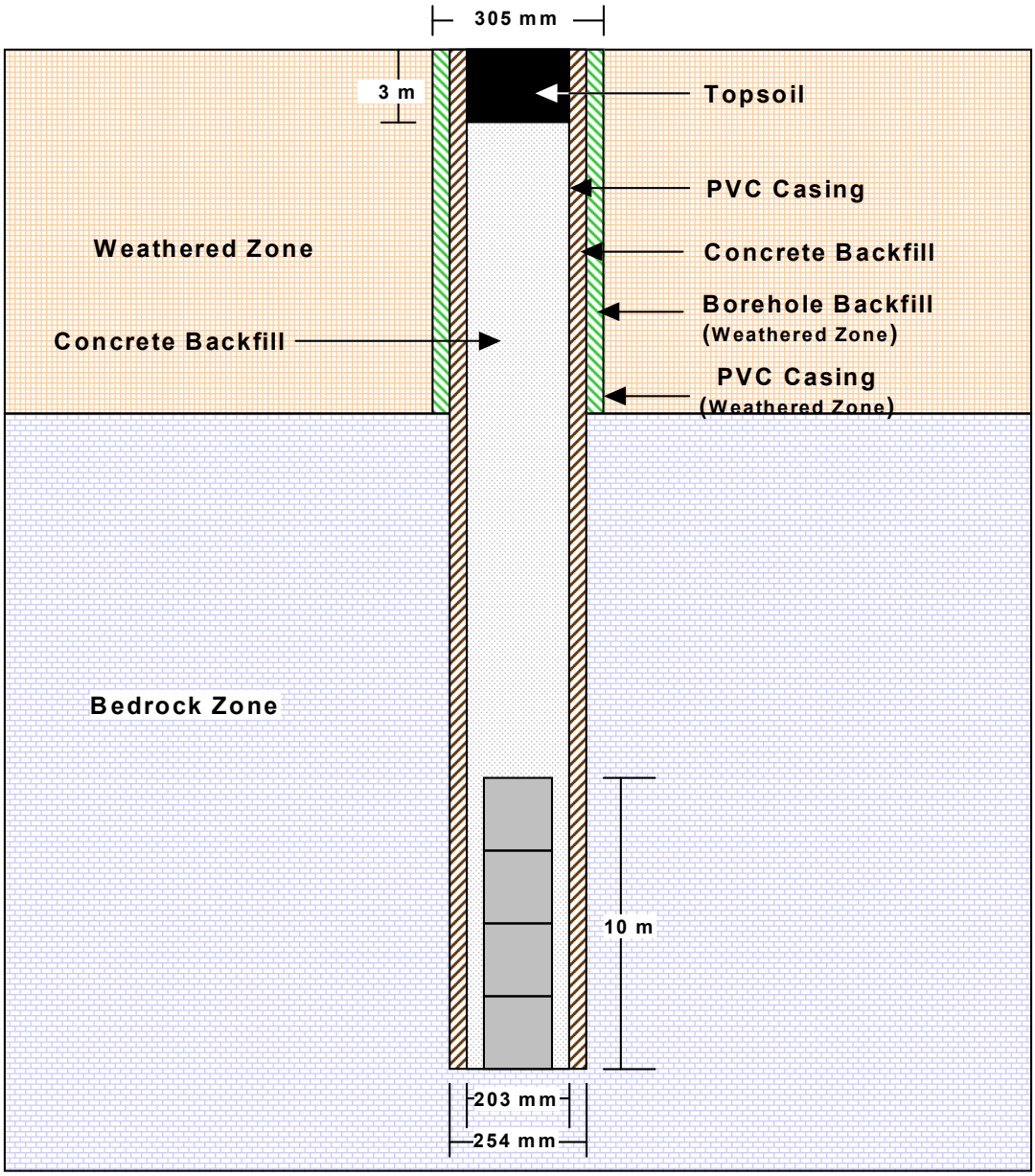


FIGURE 2.4 Borehole Disposal Facility (NECSA, 2003).

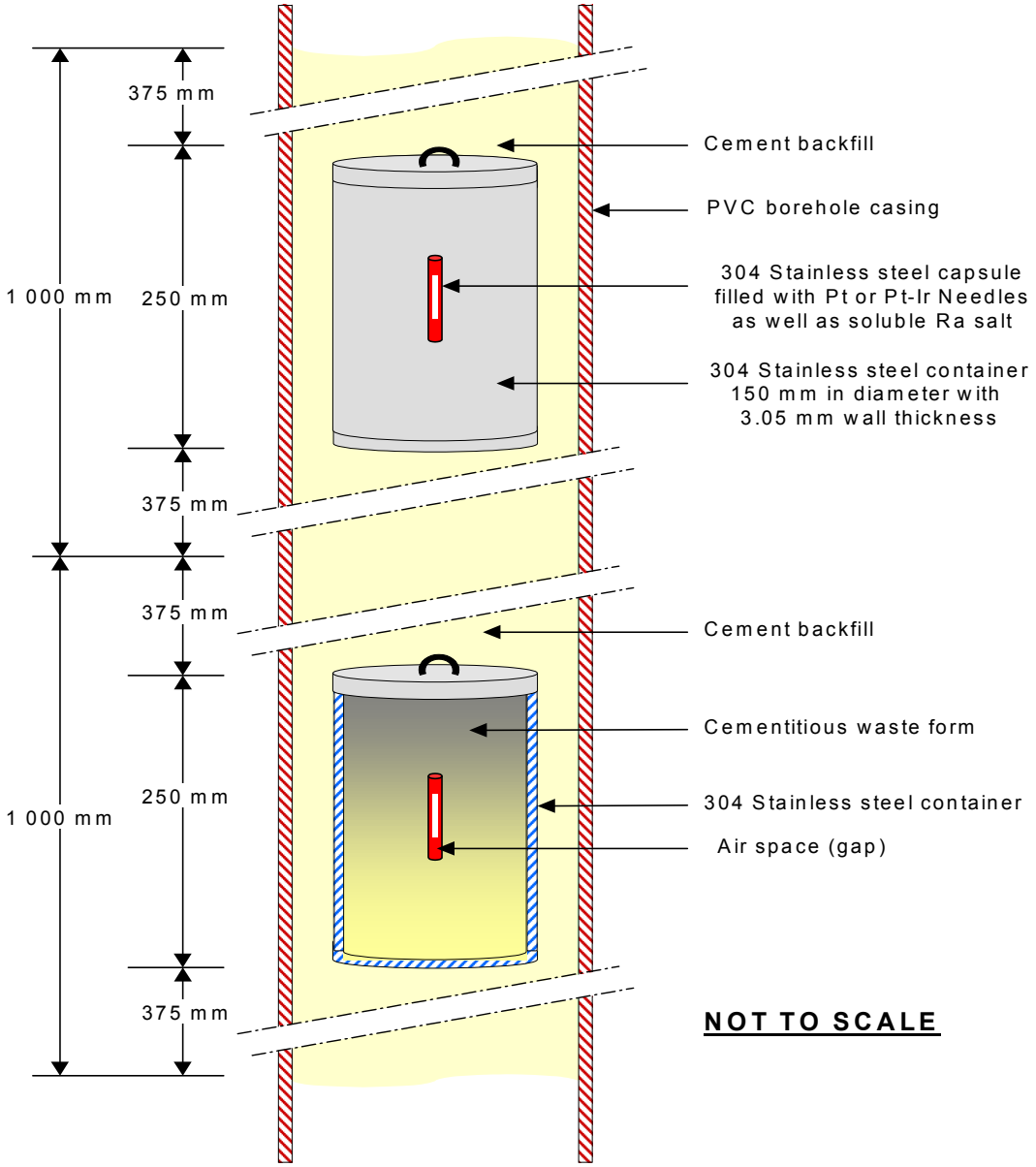


Fig. 2.5 Schematic Description of the Waste Emplacement Configuration for the Borehole Disposal Concept (IAEA, 2002_b).

2.4 Safety Assessment

Safety assessment is defined as a process used to assess risk (or hazard). It is a process of identifying unacceptable risk and the selection of means of controlling or eliminating the risk (http:en.wikipedia.org). Safety assessment is present in the everyday life of every person and in every profession.

In radioactive waste disposal, safety assessment is defined as a procedure for evaluating the performance of a disposal system and its potential radiological impact on human health and the environment. The radiological impact covers the period of operation and post-closure phase. The impact may arise from gradual processes, such as degradation of barrier and from discrete events that may affect the isolation of the waste. It is also the primary tool available for evaluating the acceptability of post disposal practice, assessing the need for changes in disposal practices or with a view toward deciding whether remedial activities are needed. The result provides an assurance that a repository will meet the design objectives, performance standards and regulatory criteria. It also demonstrate that a process or activity can operate safely, even if an assume failure should occur.

Safety assessment plays a role in site selection, establishing waste acceptance criteria, and designing and optimizing engineered barriers. In each of these areas, safety assessment plays a key role in focusing decisions on issues related to the long term safety of the disposal system.

The International Atomic Energy Agency's (IAEA, 2002_a) coordinated a research project on "Improving Long Term Safety Assessment Methodologies for Near Surface Radioactive Waste Disposal Facilities" (ISAM) which was launched in 1997 and completed in the year 2000 (IAEA,2002). The primary focus of ISAM is on the methodological aspect of safety assessment with emphasis on the practical application of these methodologies. For these reason one of the main components of the program was to develop safety cases. Three safety cases were developed in the program (IAEA, 2004):

- Vault safety case: this is based on proposed disposal to hypothetical engineered vaults with a Vaalputs geosphere and biosphere.

- RADON safety case: this is based on the past disposal to a 'RADON' type facility in the Russian federation.

- Borehole safety case: this is based on the AFRA borehole disposal concept with Vaalputs geosphere and biosphere.

These were based on current practices (vault facility), older practices (RADON1 facility), and a proposed future disposal option for disused sealed sources (borehole facility). The safety cases have provided a reference for some stakeholders when developing their own safety cases.

As part of the ISAM project, a consistent safety assessment methodology was developed (IAEA, 2004a), which has the following key components:

a) Specification of the assessment context.

b) Description of the radwaste disposal system.

c) Development and justification of scenarios.

d) Formulation and implementation of conceptual and mathematical models.

e) Analysis of results and building of confidence.

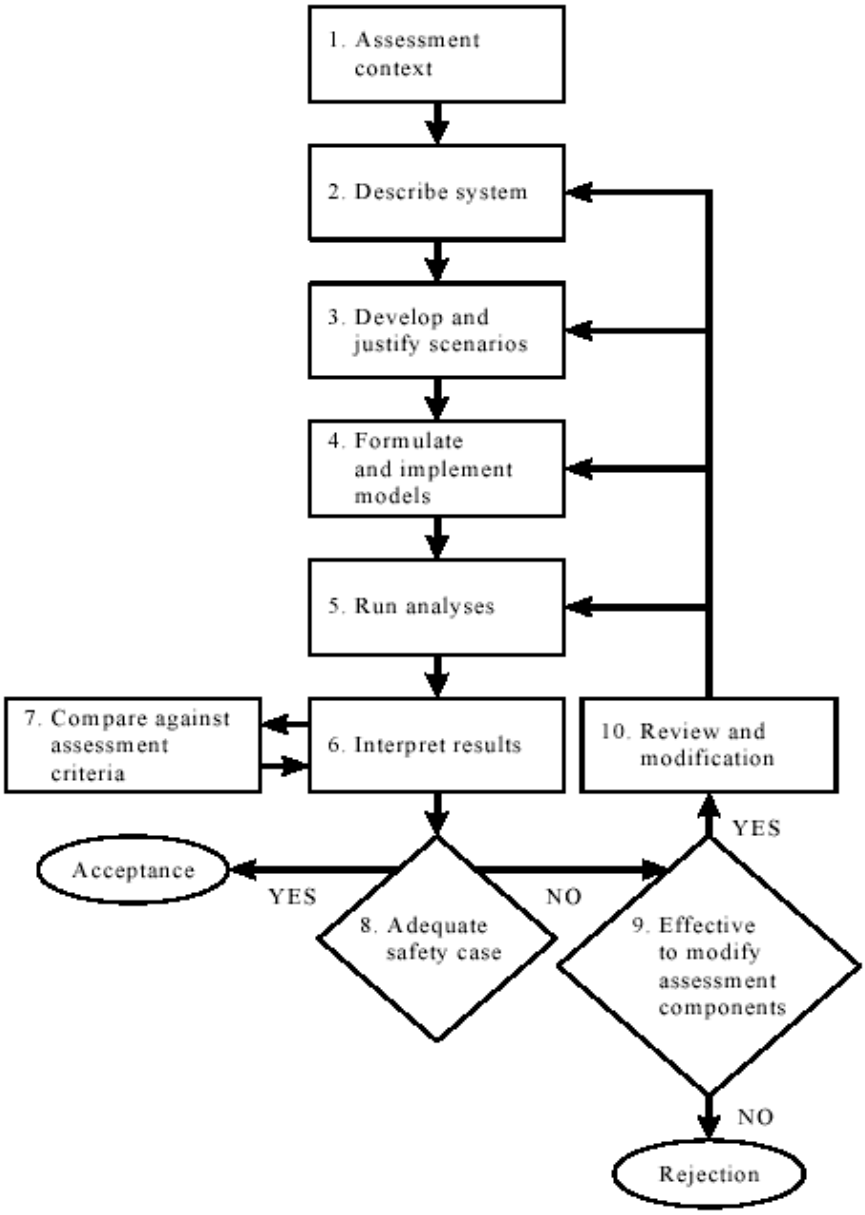


Fig. 2.6. The ISAM Safety Assessment Methodology

After the end of the ISAM project, the IAEA forms another group that would work on the "Application of Safety Assessment Methodology for near-surface Radioactive Disposal Facility (ASAM) when it saw the need to investigate further application of the ISAM methodology to a range of practical issues. The objective of ASAM was to build

on the experience of the ISAM project with special emphasis on the application of ISAM methodology to address practical problem of interest.

2.4.1 Description of the Disposal System

The disposal system is defined as a framework that describes the disposal method and site of a disposal facility in detail. It provides a framework necessary to determine how radionuclide may escape from the disposal facility, the path it can migrate and the effect it will have on humans. The disposal system consist of the waste, the engineered and natural barriers (the near-field), the geology, surface environment (the geosphere) and human behavior necessary to provide an estimate of the movement; and the potential exposure of human beings to the radionuclides on the longer term (the biosphere). It can also be considered to contain information on the following components:

(a) *The near field* – e.g. waste types, waste forms, waste inventory, disposal practices, engineered barriers (chemical and physical characteristics), facility dimensions;

(b) *The geosphere* – e.g. lithology, flow and transport characteristics; and

(c) *The biosphere* – e.g. exposure pathways, climate characteristics, human habits and behaviour.

2.4.2 Development and Justification of Scenarios

Scenarios are description of alternative, future evolutions and condition of waste disposal system. It can be considered as a hypothetical sequence of processes and events leading to human exposure, and is one of a set devised for the purposes of evaluating a safety case. Scenarios are intended to portray alternative future states of the system. Scenario handles future uncertainty by describing alternative futures and allow for a mixture of quantitative analysis and qualitative judgment (IAEA, 2004b).

Scenario development and analysis are used to address uncertainties in the future evolution and condition of waste disposal system such as habit and behaviour of people in the future, as well as natural and human induced disruptive events and processes.

Consideration must be given to safety of a disposal system in the period of post institutional control (when active institutional control is no longer being maintained or assumed not to be fully effective). In this period the safety of the disposal system depend on the present day assessment of the robustness and its future performance (scenario development). The principal means of estimating performance in this period, as stated in IAEA publication (2002), are:

- An assessment of the situations selected from a systematic review of the features, events and processes likely to affect the safety of the repository. Modelling the future behaviour of the repository system, its contents and the surrounding environment carries out the assessment.
- A review of the anticipated performance of the various barriers and other components of the disposal system, in these situations, with account taken of the quality of the design and construction of the repository.

The Longman Dictionary (1999) defines features, processes and evens as:

Feature – a prominent or distinctive part or characteristic (of the repository or its environment);

Event – a qualitative or quantitative change or complex of changes located in a restricted portion of time and space;

Process – a phenomena marked by gradual changes that lead towards a particular result.

In principle it is possible to identify specific features (e.g., engineered cap, concrete walls, etc.), events (e.g., rainfall, waste emplacement, backfilling, etc.) and processes (e.g., climate change, groundwater flow) for a safety assessment using these definitions. Scenario generation is important to the safety assessment for several reasons:

- Scenarios provide the context in which safety assessments are performed. One cannot analyse the long term performance of a radioactive waste disposal system without considering future conditions of the site;
- Scenarios influence model development and data collection efforts;
- They provide an important area of communication between repository developers and regulators, and other stakeholders with an interest in repository safety; and
- They have become a very important aspect of confidence building for the post-closure safety assessment and therefore also a focal point of independent reviewers of the assessment.

A common element in many scenario generation methodologies is the initial construction of a comprehensive list of the Features, Events and Processes (FEPs) that could directly or indirectly influence the disposal system and the migration and fate of radionuclides within it.

2.4.3 Model Development

Once the scenario have been developed, a set of model level assumptions about dimensionality, boundary conditions, features, events, processes, etc., would have to be made. These assumptions are what form the conceptual model. The conceptual model is then expressed in mathematical form as a group of algebraic and differential equations forming mathematical models.

Conceptual Model:

A conceptual model can be defined as a set of qualitative assumptions used to describe a system or subsystem for a given purpose (IAEAa, 2004). Conceptual model is regarded as a word pictured of sufficient detail that can be developed into mathematical equations and data requirements (OECD, 1999). The model provides information concerning the scope and its interaction with the other part of the system. It also describes the features, Events and Processes (FEPs) in a scenario. In effect, it is a development of the scenario at a more detailed but still largely qualitative level, organizing the scenario into a form that is amenable to mathematical representation. In safety assessment of radwaste disposal, it describes qualitatively how radionuclides are release from the disposal facility and transported into the biosphere and the geosphere, and through what exposure pathways they lead to environmental contamination and/or dose to man.

A number of tools are available for developing conceptual models including Interactive Matrices (IMs), Influence Diagram (PIDs) (Lee at al, 2009.), the PROSA Methodology (used in the EU EVEREST project) (ECN, RIVM & RGD., 1993) and the ANDRA approach based on functional analysis (IAEA, 2001_b)

	1	2	3	4	5	6	7	8	9
1	**Waste Package**	Diffusion, Advection (include radon)							
2	Percolation	**Unsaturated zone**	Advection, Diffusion, Dispersion	Diffusion Gas advection					
3			**Saturated zone (well water)**	irrigation	evaporation	Irrigation, interception	Ingestion of water	Water supply	Drinking water Ingestion, Immersion
4		Infiltration	leaching	**Soil**	Resuspension, Soil erosion, Evaporation	Root uptake, Rain splash	Ingestion of soil		Soil Ingestion, External irradiation
5				Deposition (wet and dry), Infiltration, Wind erosion	**Atmosphere**	Particulate Deposition(wet and dry)	Inhalation		Ingestion of particulates
6				Death and decay, Harvest removal	Transpiration	**Flora (plants**	Ingestion of forage crops		Ingestion of crops
7				Bioturbation, Fertilisation	Exhalation,	Fertilisation	**Fauna (Animals)**		Ingestion (Animal product)
8			Water abstraction	Ploughing Irrigation (drip)		Cultivation, Harvesting		**Human activities**	Exposure mechanisms
9									**Dose to exposure Group(s)**

Table 2.5 The Total System Interaction Matrix as Compiled for the BSC Safety Assessment.

Mathematical Model:

Mathematical model translate the conceptual model of how a radioactive material may migrate from the disposal facility, the path along which it can migrate and the effect that it will have on humans, into mathematical terms. Usually a set of coupled algebraic, differential and/or integral equation with appropriate initial and boundary conditions in a specified domain is used to solve the mathematical model.

The conceptual model for each scenario is expressed in mathematical form as a group of algebraic and differential equations. The equations are solved to give the temporal and spatial dependence of the quantities of interest. ISAM (IAEA, 2002_a) expresses three approaches that can solve the equations in the mathematical models:

- Analytical method which provide exact solution to the differential equations describing flow and transport of radionuclides.
- Numerical methods used for solving the flow and transport equation.
- Semi-analytical methods, which solve two-dimensional flow problems in a uniform, flow field with arbitrary number of sources and sinks.

Groundwater is the transporter of the radioactive waste from a repository to the biosphere. The basis of modelling groundwater flow is built on the physics of fluid flow though porous media and the governing equations for the groundwater flow are based on two physical laws: Darcy's law of flow through a porous media and law of mass balance.

Darcy's law state that the flow rate, Q, is proportional to the cross-sectional area, A, and the hydraulic gradient, $(h_1-h_2)/L$.

The mass balance principle state that in a fixed closed volume, the variation per unit time of fluid mass it contains is equal to the algebraic sum of the mass flux crossing the surface volume in questions.

From Darcy's law,

$$Q \propto \frac{A(h_1 - h_2)}{L}$$

or

$$Q = \frac{A(h_1 - h_2)}{L} \qquad 2.1$$

where the proportionality constant K is known as the hydraulic conductivity of the medium

Darcy's law can be expressed in terms of piezometric head as,

$$Q = \frac{-KA(\varphi_1 - \varphi_2)}{L} \qquad 2.2$$

The minus sign means that the flow is opposite in direction to that of increasing piezometric pressure (i.e. extraction).

Where

$$\varphi - z + \frac{p}{\rho g} \qquad 2.3$$

z is the elevation, P is the fluid pressure under the influence of gravity, ρ is the fluid density and g the acceleration due to gravity

The flow described by Darcy's law, is the total flow through the area A. The volume of water flowing through a unit cross-sectional area normal to the area is known as the Darcy velocity defined by,

$$q = -K\nabla\varphi \qquad 2.4$$

The piezometric difference ($\varphi_1 - \varphi_2$) over the distance (L) is represented by the piezometric gradient ($\nabla\varphi$). The Darcy velocity defined here is actually a flux and not a velocity. The flow equation as expressed by Darcy's law is

$$q = I = -K(\theta)\left[\frac{\partial\varphi}{\partial z} - 1\right] \qquad 2.5$$

Where

q is the Darcy flux in "z" direction (m y^{-1}); I is the recharge, or infiltration (m); $K(\theta)$ is the hydraulic conductivity at moisture content, θ (m y^{-1}); φ is the matrix potential (m); z is the depth co-ordinate, z is positive downward (m); $\frac{\partial\varphi}{\partial z}$ is the matrix potential gradient (–).

The radionuclide concentration at the water table is

$$C_{wt} = C_s e^{-\mu T} \qquad 2.6$$

Where,

C_{wt} is the concentration at the water table (Bq m^{-3}); Cs is the concentration at the source (bottom of borehole) (Bq m^{-3}); μ is the decay coefficient (y^{-1}). T is the time of travel of radionuclide to the water table and can be calculated using the equation:

$$T = \frac{d}{v} \qquad 2.7$$

Where d is the distance to the water table (m) and v is the Darcy velocity.

The most common representation for transport of radionuclide from a container via diffusion is Fick's first law of diffusion, which says that a diffusive flux for contaminant I is linearly proportional to concentration gradient:

$$j_i = -D\nabla C_i \qquad 2.8$$

where j_i is the flux of contaminant i through the grout ($Bq.m^2.y^{-1}$), D is the effective diffusion coefficient of the contaminant in the grout matrix ($m.y^{-1}$), and C_i is the aqueous concentration of contaminant i ($Bq.m^{-3}$).

The release rate, q_i ($Bq.y^{-1}$) from the container is given by:

$$q_i = \frac{pLfD_e a_s r_c^2}{(r_c - r_s)} \qquad 2.9$$

Where r_c is the radius of the container (m), r_s is the radius of the source, L is the length of the container (m), f is the fraction of the container that fails by crevice corrosion, and a_s is the solubility limit for the contaminant ($Bq.m^{-3}$).

Transport in the Unsaturated Zone

In unsaturated flow, hydraulic conductivity and its associated gradient are both functions of the state of saturation of the soil. In this case Darcy's law for vertical component of the flow takes the form:

$$V_w = -K(\theta)\left\{\frac{\partial \varphi}{\partial z} + 1\right\} \qquad 2.10$$

This equation together with the conservation of mass principle forms the basis for unsaturated flow model. However, dissolved solute molecules do not travel at the Darcy velocity but rather at pore water velocities which is obtained by dividing the Darcy velocity by the moisture content in the case of unsaturated zone and by the effective porosity in the saturated zone.

Transport in Saturated Zone.

The transport of radionuclide through a saturated zone to a well, in one dimension can be calculated using the transport equation:

$$R\frac{\partial c}{\partial t} - D\frac{\partial^2 c}{\partial x^2} - v\frac{\partial y}{\partial x} - \lambda c \qquad 2.11$$

Where c is the concentration (Bq m^{-3}), R is the retardation factor, v is the average pore-water velocity (m y^{-1}); D is the dispersion coefficient; x is the space coordinate (m).

Computer codes are then used to solve the mathematical models developed to assess the impact of the disposal facility. The computer codes were grouped into four categories: near field codes (source term), far field codes, biosphere codes and system-level codes as shown in figure 3.1 below.

TABLE 2.6 Example Computer Codes used in the Safety Assessment of LLW Disposal Facilities (IAEA, 2002_C)

Near-field	**Geosphere**	**Biosphere**	**System level**
BARRIER	DRAF	GENII	AMBER
DUST	FEMWATER	RESRAD	PRESTO-EPA-CPG
HELP	GRDFLX	TAME	GTM-1
SOURCE1 and SOURCE2	MIGRAD		GOLDSIM
UNSAT-H	MODFLOW-96		
	PORFLO		
	TOUGH2		
	VAM2D		

2.4.4 Analysis of results.

On completion of the calculations, the results found from the computer codes, need to be collated and analysed. The results should be compared with calculation end-points identified when developing assessment context. When analysing the results it is important to recognise that there are a number of sources of associated uncertainties that must not be ignored (future, model and data/parameter uncertainties). Because of this, the results should not be seen as absolute values and any subsequent decisions should be undertaken with this firmly in mind.

Once the result have been analysed, there is a need to determine the adequacy of the safety assessment. If it is considered that the assessment is not adequate, further iteration of the entire process or parts of the process can be undertaken to improve its adequacy.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 INTRODUCTION

In safety assessment procedure for the low-level radioactive waste, the repository design for the borehole was simulated and tested using site and waste form specific data. Both waste, site and repository design data was fed into a computer code to solve the mathematical models derived from the scenario generated. The calculation undertaken was used to assess the impact of the disposal facility, with time, to the environment. The result was then analysed and compared with the applicable criteria from the assessment context.

3.2 Simulation Tool Data.

The data needed for the simulation tool was mostly collected from literature to cover most of the critical laboratory and in-situ measurement.

3.3 Assessment Context Data.

The assessment context comprises of a set of high-level assumptions and constraint that reflect the regulatory framework, purpose and focus of the assessment. Therefore, the purpose of the assessment, the radiological protection criteria, the calculational end-points, the assessment philosophy and the time frame are as stated below.

3.3.1 Purpose.

The purpose of the safety assessment is to develop a borehole disposal concept further from the ISAM by testing its suitability at the selected area (Zaria), under the site and land conditions. Only currently available information found in literature will be used. The most important uncertainties will be identified, with suggestions about further data collection and/or alternative conceptual models that may be the subject of further safety assessment iterations. Other important objectives of the assessment are mention in chapter one.

3.3.2 Regulatory Framework.

The regulatory framework used for this assessment is the broadly accepted international principles (IAEA 1999_a). The dose limit for members of the public from all practices is an effective dose of $1mSv.y^{-1}$ (BSS. 1996). To comply with this limit, a borehole disposal facility (consider as a single source) is designed so that the estimated average dose to members of the public who may be exposed in the future as a result of activities involving the disposal facility does not exceed a dose constraint of not more than 0.3 $mSv.y^{-1}$(ICRP 77 (1998) and ICRP 81 (1998).

3.3.3 Assessment (Calculational) endpoint

The calculational endpoint for this illustration is the individual effective dose, which will be calculated to demonstrate compliance with regulatory requirement of dose limit of $1mSv.y^{-1}$ or a dose constraint of $0.3mSv.y^{-1}$.

3.3.4 Assessment Philosophy

The assessment philosophy depends on the knowledge of the disposal system and availability of the data needed for calculations and modelling. The objective of the research was to use realistic approach where real data were found and for some data that were not available at some steps of the assessment process, a cautious assumption was applied. A cautious assumption is an assumption that will not result in the calculation end points being underestimated. This means that safety is provided by ensuring that nobody will ever receive anything more than dose constraint from the disposal system.

Uncertainties caused by natural data variability or by lack of data were addressed using probabilistic modelling techniques with probability density functions defined from site data or from literature (see section 4.2 for detail).

3.3.5 Assessment Timeframe

There is currently, no international consensus among regulatory bodies, standard setting organizations or developers that have development programs for managing long-lived radioactive waste that have a unique time frame for evaluation of the safety of repositories (Witherspoon and Bodvarsson, 2001).

Reviews of literature of more than 30 countries indicate that several of these countries have a time frame that ranges from 1000 years to 1,000,000 years (NRC, 2005). Many of these countries use 10,000 years as their time frame including IAEA.

The main time period proposed as reasonable for the main quantitative assessment period for post-closure impact is 10^4 years. Simple bounding calculations could be carried out for longer time periods. The duration of the institutional control period after closure of the disposal facility is 30 years.

3.4 DESCRIPTION OF THE DISPOSAL FACILITY

The disposal system is described in terms of:

— The wastes;

— The engineered and natural barriers expected to contain the waste for a period of time;

— The potentially contaminated geology and surface environment; and

— The geology, surface environment and human behaviour necessary to provide an estimate of the movement and the potential exposure of human beings to the radionuclides on the longer term.

3.4.1 Waste Inventory

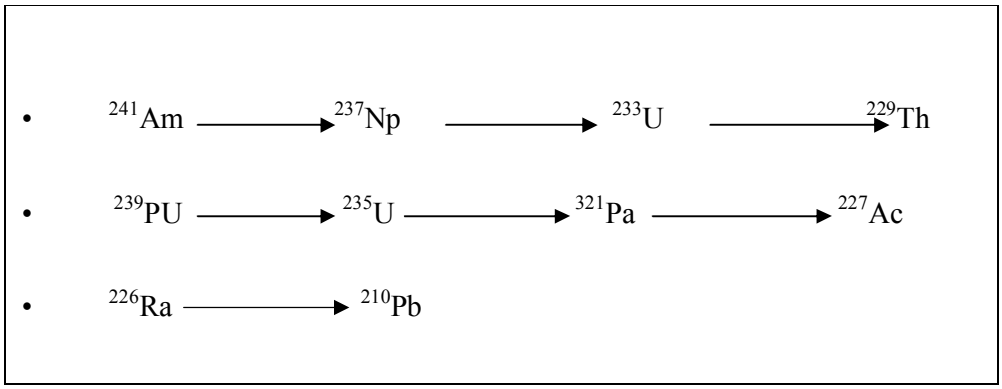
Table 3.1, below, show the inventory used in the research with the half-life, expected maximum activity and the application associated with the activity. The inventory used was similar to the inventory used in Draft (0.5) Safety Report Series (IAEA, 2005) and ISAM Group (IAEA, 2004b). It was decided to use this inventory because at the time of the research there is no certified inventory of the sealed radioactive source in Nigeria and it may not be more than this value because of the 'return to supplier' policy of the Nigerian regulatory body (all radioactive sources used in the country are imported and all spent or disused sources are exported back to their manufacturers). This Waste is typical of what are found in African countries (IAEA, 2005). It has a vast diversity of applications in medicine, agriculture, research, industry and consumer products. The radionuclides in the table where classified into 3 groups according to the range of their half-life. First Group has a half-life less than 100 days, Group 2 has between 100 days to 30 years and Group 3 has half-life greater than 30 years.

Table 3.2. Disused Sealed Sources Considered for the Borehole Disposal (IAEA, 2005 and IAEA, 2004b).

Radionuclide	Half-life	Maximum Expected Activity (MBq)	Application
Group 1	**Half-life < 100 days**		
Tc-99	5.96 hr	4.99E+03	Medicine
Au-198	2.7 d	1.5.E+03	Medicine
Y-90	2.7 d	5.0.E+02	Medicine
I-131	8 d	1.5.E+03	Medicine
P-32	14.3 d	2.0.E+02	Medicine
Pd-103	17 d	1.5.E+03	Medicine
Sr-89	50.5 d	1.5.E+02	Medicine
I-125	60 d	1.0.E+04	Bone dosimetry
Ir-192	74 d	5.0.E+06	Industrial radiotherapy
Group 2	**100 days ≤ Half-life ≤ 30 years**		
Po-210	138 d		Static Electricity Removal
Gd-153	242 d		Bone dosimetry
Co-57	271.7 d	5.0E+05	Markers and Medicine
Ru-106	1.0 y	5.0E+04	Medicine
cd-109	1.27y	4.44E+02	X-Ray fluorescence
Cf-252	2.6 y	5.0E+03	Calibration facilities
Pm-147	2.62 y	5.0E+05	standards in instruments
Co-60	5.3 y	5.0E+04	Sterilization, food preservation and Gauge
Kr-85	10.8 y		Thickness gauge
H-3	12.3 y	5.0E+06	Tritium targets
Sr-90	29 y	5.0E+04	Level gauges
Cs-137	30.1 y	5.0E+05	Sterilization, food preservation and Well Logging
Group 3	**Half-life > 30 years**		
Pu-238	87.7 y	3.7E+03	Static electricity removal
Ni-63	100 y	5.0E+02	Electron capture detector
Am-241	412 y	1.9E+02	Calibration and smoke Detection
Am-241/Be	433 y	8.0E+05	Well logging
Ra-226	1600 y	3.7E+03	Nuclear Medicine
Pu-239	2.4E+04y	3.70E+03	Static Electricity Removal
Tc-99	68800y		Nuclear Medicine
Cl-36	3.E+05 y	4.00E+04	standards in instruments
I-129	1.6.E+7 y	4.00E+04	Sources as standards in instruments

It was assumed that Group 1 has no limit for disposal in the borehole disposal facility and hence excluded in the safety assessment. In Group 2 Se-75, Ru-106, Pm-147, Gd-153 and Cf-252 were excluded due to their similarity with Co-60 in half life, mobility and dose coefficient, and hence Co-60 stands as a surrogate. In Group 3, Cl-36 was not included also because Cl-36 was surrogated with I-129, due to its similarity with I-129. The radionuclides, therefore used in the assessment include Co-60, Ni-63, Co-57, Sr-90 Ir-192, Cd-109, I-129, Cs-137, Po-210, Ra-226, Pu-238, Am-241 and they serve as a surrogate to the rest of the radionuclides in Table 3.1. Some of these radionuclides have daughter products that can pose hazard to the public because of their long half lives and high activities. These daughter products were also included in the assessment. The daughters are Pb-210, Np-237, Th-229, U-235, Pa-231 and Ac-227 (see detail in Table 3.2).

Table 3.2 Radionuclides and their daughter products.



3.4.2 The Borehole Disposal Design

It was assumed that the design used was based on the borehole design developed under the AFRA project by ISAM Group, (IAEA 2004b and IAEA 2005). The design was also assumed to consist of series of engineered barriers as shown in chapter Two (fig. 2.2 to 2.4). The borehole has a diameter of 260mm and is drilled to a depth of over 65m. It is fitted with a high-density polyethylene (HDPE) casing. It has a thickness of 10mm and internal diameter of 140mm. The base of the disposal zone is assumed to be at least 65m from the ground surface. A 0.5m thick plug of backfill slurry is emplaced at the base of the borehole.

In radioactive waste disposal, specific consideration is given to the applicable geochemical phenomena in the long term safety analysis, including for instance, the possible interaction with the vitrified waste matrix or with the surrounding geological medium through a so-called plume effect.

In order to reduce these interactions, Portland Pozzolana Cement (PPC) is used, which is more neutral with respect to the waste matrix or underground environment, while keeping the necessary mechanical and sealing properties. Portland Pozzolana Cement (PPC) is used in disposal of long-lived radioactive wastes because it has a better resistance to Sulphate attack and hence it is preferably used in Sea Shore, Dam constructions and in the earth work concreting to neutralize corrosion effect of soil and water under the earth's crest.

The cement is manufactured by blending a mixture of Ordinary Portland Cement (OPC) and Pozzolana materials in proportions not less than 15% and not more than 35% by weight of cement (Hugo-Persson et al, 2005). A Pozzolana is siliceous materials that reacts with the cement and cement paste and change the composition of it. Pozzolana

lowers the pH of the cement which then minimizes the internal stresses that lead to micro-cracking of the concretes and grouts. It also helps in minimizing the impacts of paste-shrinkage and steel micro-reinforcement fibers.

With a Pozzolana CH is first formed and later it reacts with the cement paste to get the equilibrium required to get a pH of 11.

The waste package used for the purpose of this research was assumed to have a total of 30 waste packages disposed in the borehole. Each waste package configuration is thus in the order of one meter (1m).

3.4.3 Site Geography and vegetation.

Zaria is situated within the Northern Nigeria basement rocks complex. It lies between latitude $11^0$7'N and $11^0$24'N and longitudes $7^0$31'E and $7^0$50'E. Zaria has both dry and rainy season during the year. The month of October-April are usually dry and become wet during the months of May-September. The driest months are February-March while July-August are the wettest months (Bashiru, 1986).

Two metrological stations in Zaria provided the precipitation data used in the model. One of the stations is in Zaria Civil Aviation Training Centre and the other one is at Samara College of Agriculture, ABU. Zaria. Twenty years precipitation data (1984-2003) were collected as shown in Fig. 3.1 and Appendix B. The long term Annual rainfall average is 86.54mm. Maximum rainfall recorded was 105.3mm in 1998 and a minimum of 63.3mm was recorded in 1986.

The vegetation of Zaria is mainly grasses with few deciduous widely scattered trees which hardly reach a height of 20metres. The grasses are about 80cm high in some

places. Evergreen trees exist mainly along the few perennial streams and rivers. The dominant trees in the area are mainly mango trees with some few fire resistance trees.

The soil belongs to the generalized ferruginous tropical soils: clay (kaolinite) and some weathered minerals are the dominant fractions of the soils. As such the soil fertility is generally low (Davis, 1973). The low soil fertility is subjected to intensive subsistence farming. Cereals are the main types of crops grown in the area while cattle grazing are carried out on the grassland. Such cereals are mainly maize and sorghum. Millet, groundnut and beans are also grown but not in large quantity as maize and sorghum. Root tubers are the second major food grown in the area. They include yam, cocoyam, sweet potatoes and cassava. Cereals and tubers are the staple food of the local people.

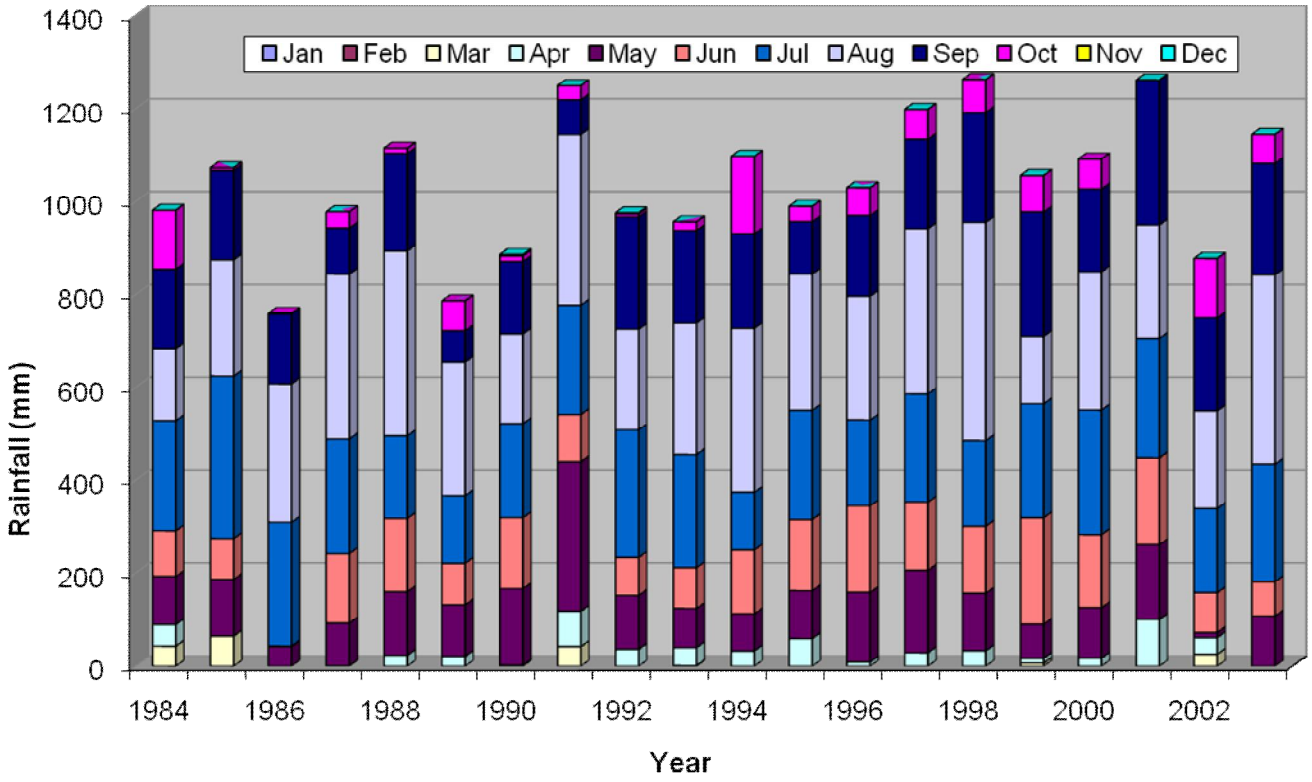


Fig. 3.1 Annual rainfall of Zaria for 20 years.

3.4.4 The Geology, and Hydrology

Zaria lies within Basement complex in the Northern part of Nigeria. The rock of the area are mostly Precambarian in age and have been subjected to several phases of deformation, the latest being the Pan African Oregeny (McCurry, 1975). Undifferentiated basement complex of migmatites, granites, gneisses and metasediment is overlaid by laterites (Muhammad et al., 1980).

In the basement complex, the main aquifer system includes the weathered and fractured rocks. However, other formations such as gravel layer may serve as underground water bearing layer (Zuma, 1999). The aquifer thickness varies from 1-28m with an average of 12m. The existing boreholes have depth to water table greater than 4-8m range and their depth to basement are greater than 17m (Oahmire, 2004).

The predominant layers running through the profile were; the top soil consisting of clay, sand and 'fadama' loam soil having an average thickness of 1m. Underlying this is the weathered basement rocks with thickness not exceeding 22m. The next is the fractured basement with slightly variable thickness and underneath is the fresh basement of infinite thickness. Weathered/fractured basement serves as principal aquifer in the study area with an average thickness of 13m as also reported by Oahmire (2004). Appendix C shows the well-logging and lithology of some borehole wells in some part of the study area.

Distribution Coefficient (K_d) and Solubility of Radionuclides: The K_d values are adopted from yu. et al, (2002). Table 3.2 shows the k_d values for sandy type materials since there are no constant set of K_d values for cementations materials (IAEA, 2004_b). The values for both K_d distributions and solubility were treated probabilistically using uniform distribution for simplicity. Table 3.2 also includes the radionuclides' solubility.

Table 3.3 Solubility Limits and Distribution Coefficient (yu. et al, 2002).

Radionuclide	Solubility(mg/l)		K_d - Sand(m^3/kg)	
	Min	Max	Min	Max
^{137}Cs	3.26E+02	3.26E+03	1.40E-01	4.20E-01
^{241}Am	2.77E-04	2.77E-01	9.50E-01	2.85E+00
^{237}Np	8.39e+00	8.39E+03	2.50E-03	7.50E-03
^{233}U	2.70E-03	2.70E+02	1.75E-02	5.25E-02
^{229}Th	1.57E-02	1.57 E+00	1.60E+00	4.80E+00
^{226}Ra	2.90E-03	2.90E-01	2.50E-01	7.50E-01
^{210}Pb	5.40E-05	1.35 E+00	1.35E-01	4.05E-01
^{239}Pu	2.71E-04	2.71E-01	2.75E-01	8.25E-01
^{235}U	2.70E-03	2.7E+02	1.75E-02	5.25E-02
^{231}Pa	2.63E+00	7.89E+04	2.75E-01	8.25E-01
^{227}Ac	2.01E-02	2.01E+03	2.25E-01	6.75E-01

Transfer Coefficient: Table 3.3 shows the values of the transfer factor used in the model. The values are from Kennedy and Strenge, (1992). Transfer factor is the fraction of the daily intake of a radionuclide that is transferred to one kilogram of animal products. Values of transfer coefficient from direct measurement are scarce. Therefore a wide range of published values from relevant references are considered as best representation of the parameter value. These works include results documented in the following reports by Coughtrey (1990), IAEA (1994), Kennedy and Strenge (1992) and Ng (1982). The distribution for the transfer factors is considered to be lognormal (BSC 2003), with a geometric standard deviation of 3 and a median values as shown in Table 3.4.

The Ingestion dose coefficient values are given in Table 3.5 These values are assumed to be constant that are measured in Sv/Bq.

Table 3.4 Transfer Factors Used in the Assessment(Kennedy and Strenge, 1992).

Radionuclide	Sheep	Poultry	Egg
	(d.kg^{-1})		
^{137}Cs	2.00E-02	4.00E+00	4.90E-01
^{241}Am	3.50E-06	2.00E-04	9.00E-03
^{237}Np	5.50E-05	4.00E-03	2.00E-03
^{233}U	2.00E-04	1.20E+00	9.90E-01
^{229}Th	6.00E-06	4.00E-03	2.00E-03
^{226}Ra	2.50E-04	3.00E-02	2.00E-05
^{210}Pb	5.00E-07	2.00E-01	8.00E-01
^{239}Pu	5.00E-07	1.50E-04	8.00E-03
^{235}U	2.00E-04	1.20E+00	9.90E-01
^{231}Pa	1.00E-05	4.00E-03	2.00E-03
^{227}Ac	2.50E-05	4.00E-03	2.00E-03

Table 3.5 Dose Conversion Factor.

Radionuclide	Dose Conversion Factor (Sv.Bq^{-1})
^{137}Cs	1.30E-08
^{241}Am	2.00E-07
^{237}Np	1.11E-07
^{233}U	5.10E-08
^{229}Th	6.13E-07
^{226}Ra	2.80E-07
^{210}Pb	1.89E-06
^{239}Pu	2.50E-07
^{235}U	4.73E-08
^{231}Pa	7.10E-07
^{227}Ac	1.21E-06

Table 3.5, 3.6 and 3.7 are values of consumption rate, dry-wet ratio of plants and soil-to-plant concentration ratio of the radionuclides respectively. These values were also taking from Kennedy and Strenge (1992).

Table 3.6 Consumption Rate $_{Plant}$

S/No.	Plant type	Consumption rate kg/yr
1	Vegetable	18
2	Root	4
3	Fruit	20
4	Grain	100

Table 3.7 Dry/wet Ratio$_{Plant}$ (Kennedy and Strenge, 1992).

S/No.	Plant type	Conversion factor (kg dry-weight/kg wet-weight)
1	Vegetable	0.2
2	Root	0.25
3	Fruit	0.18
4	Grain	0.91

Table 3.7 Soil – to- Plant concentration Ration CR_{Plant}. (Kennedy and Strenge, 1992).

S/No.	Radionuclide	Vegetable	Root	Fruit	Grain
1	^{66}Ni	2.8E -1	6.0E – 2	6.0E – 2	3.0E - 2
2.	^{90}Sr	1.6E + 0	8.1E – 1	1.7E – 1	1.3E – 1
3.	^{129}I	3.4E – 3	5.0E – 2	5.0E – 2	5.0E – 2
4.	^{137}Cs	1.3E – 3	4.9E – 2	2.2E – 2	2.6E
5	^{210}Pb	5.8E – 3	3.2E – 3	9.0E – 3	4.7E – 3
6	^{226}Ra	7.5E – 2	3.2E – 3	6.1E – 3	1.2E – 3
7.	^{227}AC	3.5E – 3	3.5E – 4	3.5E – 4	3.5E – 4
8.	^{229}Th	6.6E – 3	1.2E – 4	8.5E – 5	3.4E – 5
9.	^{231}Pa	2.5E – 3	2.5E – 4	2.5E – 4	2.5E
10.	^{233}U	1.7E – 3	1.4E – 2	4.0E – 3	1.3E – 3
11.	^{235}U	1.7E – 3	1.4E – 2	4.0E – 3	1.3E – 3
12	^{237}Np	1.3E – 2	9.4E – 3	1.0E – 2	2.7E – 3
13	^{239}PU	3.9E – 4	2.0E – 4	4.5E – 5	2.6E – 5
14	241Am	5.8E – 4	4.1E – 4	2.5E – 4	5.9E - 5

3.5 Model Development

When the site and land used conditions were investigated and data collected, a simplified approach to scenario generation and justification was followed. A common element in many scenario generations is the initial construction of a comprehensive FEPs list that could directly or indirectly influence the disposal system and the migration and fate of radionuclide within it. By adopting a systematic approach we can reduce the principal scenario uncertainties and define the important factor to take into account regarding the safety. The steps include:

1. *Identifying a comprehensive list of FEP*. The ISAM FEPs list was chosen to be used in this study. The ISAM FEPs list is a list of FEPs relevant to the assessment of long term safety of near surface disposal facilities, which attempts to be comprehensive within reasonable bounds. It consists of 141 FEPs presented here as in Appendix D. The list is classified into four major classes: Assessment Context(**level 0**), External Factors (**Level 1**), Disposal System Domain also called enviromental factor and radionuclide/contaminant Factors.

   Figure 3.2 illustrates the classification scheme used in the ISAM FEP list. At its centre, the classification scheme includes processes related to contaminant release, migration and exposures (radionuclide and contaminant factors, as **Level 3**). It is also necessary to consider the features of the disposal system (wastes, engineered and natural barriers and human behaviour) and events and processes, which may cause the system to evolve (environment factors, as **Level 2**). Beyond this, there are processes and events originating outside the disposal system, but which act upon it (external factors). These external factors (or

external FEPs, as **Level 1**) are often considered to be scenario generating FEPs. By changing their status, different scenarios can be generated.

In deciding the scope of an assessment, it is necessary to consider not only of physical factors that might be relevant but also the regulatory guidance and aims of the assessment. These may constrain the extent to which some FEPs are considered or the way in which they are treated in the assessment, e.g. regulatory time periods and the use of critical groups as representative of future human populations at risk. Therefore, a fourth layer is added – assessment context (**Level 0**).

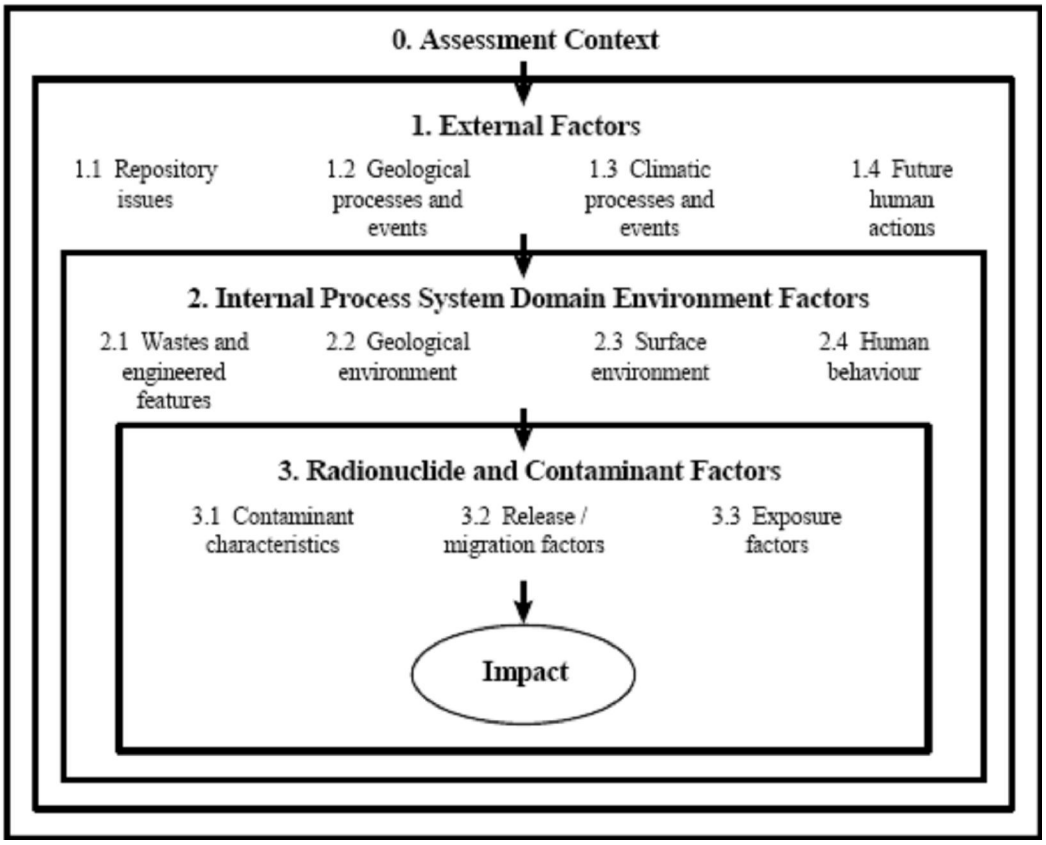


Figure.3.2 Illustration of the Classification Scheme Used in the ISAM FEPs List (derived from Nuclear Energy Agency, (2000)).

2. *Screening the comprehensive list and classification.* The following procedure was followed to screen the FEPs list identified. The FEPs that are relevant for the safety of the disposal system was then selected. In choosing the relevant FEPs, the screening process has been to eliminate four categories of FEPs from further consideration in this report:
    - FEPs that are not relevant for the current assessment.
    - FEPs that are not relevant because of the chosen assessment context.
    - FEPs that are not considered to be important.
    - FEPs that are not considered because there is no information about them, and for which it is unreasonable to expect information to be available in the foreseeable future.
3. *Building and justification of scenarios.* The relevant screened FEPs list was then used to develop scenarios. Several techniques have been used in the past to generate set of scenarios relevant to waste disposal (IAEA 2000a). The techniques relevant to near surface disposal as reviewed by ISAM Group include Expert Judgment, Fault Tree and Event-tree analysis. The study uses the expert judgment to develop the scenario.

3.5.1 Scenario Generations and Justification.

FEP List screening: After identifying the exposure scenarios (see 3.5.2) that would be considered, the FEP's list was then screened using the assessment context and system description for the factors that are important to the safety assessment. In the screening of the list a simple "yes" was used for the list to be included. 'No' was used for excluded FEPs but with explanation of the exclusion of the FEP list. The results of the screening process are recorded in Appendix E.

Looking at the FEP's list screened, level 0 (assessment context) are factors that influence the assessment and are all included as relevant. Levels 1 (***External Factors*** and sometimes called scenario generation FEPs) are repository issues, and geological processes and effects. Levels 1.1 are all applicable to the borehole, except 1.1.11 and 1.1.13, but most of levels 1.2(*Geological Processes and Effects*) were screen out with exception of 1.2.10. At levels 1.3 (*Climatic Processes and Effects*), only FEP's that are limited to climate changes (1.3.01and 1.3.02) and their influences on the total system (1.3.06, 1.3.07, 1.3.08 and 1.3.09) were included. Levels 1.4 (*Future Human Action*) were not applicable to the borehole except those related to inadvertent human intrusion (1.4.02, 1.4.04 and 1.4.05).

Level 2 (***Internal Factors***) represents the disposal system domain. It includes the waste and the engineered features, site and human behaviour characteristics. With the exclusion of 2.1.14 and 2.1.15, all the levels 2.1 FEP's were included. These two were excluded because of the insufficient activity of the inventory and does not also contain any exotic or unidentified material. Level 2.2 (*Geological Environment*) were considered in the concept but two FEPs (2.2.06 and 2.2.10) were considered irrelevant. 2.2.06 was irrelevant considering the depth of the disposal and 2.2.10 also because thermal processes within the near field is included and it is not expected that thermal activity originating within the geosphere will influence the disposal case. Level 2.3(*Surface Environment*) are all applicable except 2.3.05 that is associated with coastal features and 2.3.06 associated with marine features as well as 2.3.12 when the location of the site was considered. Level 2.4 are screened as relevant as was stated in the assessment context with exception of 2.4.06, and 2.4.11.

Levels 3 (***Radionuclide/Contaminants Factor***) were directly associated with characteristics, movement and possible exposure mode of the contaminants. Beside the

radiological impact (3.1.01), the chemical/organic toxin stability (3.1.02), In-organic solids/solutes (3.1.01), and organic and potential for organic forms (3.1.05) were irrelevant in level 3.1. Levels 3.2 and 3.3 were all screened relevant except 3.3.07 that was considered as irrelevant.

3.5.2 Exposure Scenario

Exposure scenarios are patterns of human activities that can affect the release of radioactivity from the contaminated zone and amount of exposure receive at the exposure location. It explains the possible ways in which the radioactive waste disposal will be leak out and be exposed to human with time. There are many potential exposure scenarios, such as subsistence farming, industrial working, recreation site, dwellers, land excavation and mining activities. The work considers only a subsistence farmer scenario. The scenario, it was assume that the waste will be placed in a saturated zone and that the stainless steel capsule will corrode with time and allows the movement of activity into the cement backfill.

At about 1000 years to 5000 years failure of the waste packed will allow access of water to the source. The water will dilute the waste and transport it through the saturated zone. The abstraction of contaminated water is then made (by a farmer or dweller) from a borehole drilled for domestic used (agriculture and household purposes). The agricultural purposes were assumed to be mainly drinking, irrigation and other house use like bathing.

3.5.3 Farmer Scenario

In choosing a scenario to consider in this research, a subsistence farmer scenario was chosen. The farmer scenario is a scenario that considers a farmer that constructs a house

on the contaminated site and uses it as a permanent resident in the vicinity of the disposal facility. He moves his family onto the site after institutional control period and raises crops and livestock for family consumption. He would unknowingly use contaminated water for drinking and farming and would grow his own food and was assumed to raise a large fraction of his own fruits and vegetables from a backyard garden that is located on contaminated soil for personal consumption. Further, the scenario assumes that such exposure would last a lifetime, and not just a few years. In addition, it assumes that the diets as well as food and water intake of future populations will be similar to those of today. People are considered protected if their lifetime exposure is less than an assigned limit. The reasoning is that in such a case all other people would be protected since their doses would be lower than that of the hypothetical subsistence farmer. His exposure is most likely to be a long term that generally involves exposure by more pathways.

Other scenarios like construction workers, scavengers, recreational activities, industrial workers and other commercial activities receive much smaller dose than the farmer because they spend less time on the disposal site. The exposure of scavengers or construction workers is unlikely to last longer than few months and is generally limited to working hours. Their exposure is therefore unlikely to exceed the lifetime dose for the farmer. There is also a possibility of building a factory or commercial building but the exposure the workers will receive is generally less than that of a subsistence farmer, because the exposure is limited to working hours and does not include contribution from ingestion of food grown on site.

Many projects have used the subsistence farmer scenario that includes the Waste Isolation Pilot Plant (WIPP), Sandia National Laboratories and the Hanford repository program among others (Makhijani, and Gopal, (2001), Napier, et al., (1988)).

3.5.4 Conceptual Model for Farmer Scenario

When the scenario is developed, it was used to develop conceptual model. As stated in section 3.5.1, there are many approaches to conceptual model development, but in the study, the Interaction Matrix Approach is employed, because it is among the most useful tool for illustrating the interaction between FEPs.

Mathematical model is used to translate the assumptions made in the conceptual model using set of algebraic, differential and/or integral equations with appropriate initials and boundary conditions in a specified domain. The equation is then solved using computer codes. Both the waste, the site and repository design data is fed into the computer codes to solve the mathematical models derived from the scenario generated. Solution of the mathematical models is usually achieved by implementing one or more computer codes using analytical and/or numerical techniques.

An interaction matrix (IM) approach is selected in the study, because it provides a convenient, easy way to represent the process system in a traceable manner (Wu, et. al. 2002). Figure 3.3 shows the interaction matrix (IM) for farmer scenario and the key interaction between the various disposal system components in the release and migration of the radio-nuclides through the system and the subsequent exposure to humans. The matrix is prepared based on the assessment context condition in the biosphere. The elements of the leading diagonal element (LDE) of the IM that were initially identified are the waste packet placed in cell (source) 1.1, engineering barrier (2.2), disposal zone (3.3), unsaturated zone (4.4), saturated zone (5.5) that transport the radionuclide to the well, soil (6.6), atmosphere (7.7), flora (8.8), fauna(9.9) and human receptor (10.10) characterized the agricultural products ingested either directly by the dwellers (root and leafy vegetables) or indirectly (grain) via animal products (cows, sheep, chicken and eggs) bearing in mind that the water for irrigation was abstracted

from the contaminated well near the borehole disposal facility (about 10m adjacent to borehole) and dose to exposure group (human) is the end-point of the farmer scenario..

The model assumes that a farmer intrude into the disposal site, build a house and sunk a well after the end of institutional control period (30 years from closure). It was also assume that water is abstracted from the well that is used for:

- Irrigation of food and animal feeds
- Drinking water for animals
- Drinking water by farmer
- Bathing by farmer.

The model also assumes that the same land is irrigated annually with contaminated water, which leads to radionuclide build-up in the irrigated soil. The build-up process is mitigated in the model by removal mechanism, radioactive decay, leaching to the deep soil and surface soil wind erosion (5,6) and (7,6).

Over the long period of time considered (i.e. > 10,000yrs) for the land in production, all radioactivities incorporated into crops will get recycled in the biosphere either in form of animal manure or non-edible part of crops (6,9). Thus removal of radioactivity in foodstuffs (6,8) is conservatively ignored in the model.

Deposition of contaminated atmospheric dust on the surface soil is another possible radioactive source (6,7). However this mechanism is considered to be balanced out by re-suspension from surface soil (7,6). Thus these 2 mechanisms are not included. Because of the continues addition and removal of radionuclides equilibrium conditions eventually occur and radionuclide concentration in the surface soil will no longer change with time.

The mechanism of radionuclide transfer to plant (flora) are through root uptake, direct deposition on leaves from irrigation water and deposition of re-suspended soil particles

(8,4), (8,6) and (8,7). Five types of crops are considered: leafy vegetables, other vegetables, fruits, grain and forage crops for domestic animals.

Three environment transport pathways that contribute to radionuclide uptake in Animal (fauna) are included in the model: contaminated crops, drinking water and soil ingestion, (9,8) (9,5) and (9,6). Radionuclide uptake by inhalation is not included because of its lower contribution compared to ingestion (Wu, et. al 2002).

While four types of animal product (Meat, poultry, milk and eggs) were considered, ten ingestion pathways were considered in the farmer scenario. They include: drinking of contaminated well water, in advent soil ingestion, four types of foodstuff and four types of animal product.

The model calculates the radiation dose due to ingestion intake of the radionuclides. The 50-year total effective dose equivalent (TEDE) was calculated for this pathway. The inputs to the model are radionuclide concentration in well water (10,5) and out puts from the soil, plants and animals (10,6), (10,8) and (10,9).

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
1	**Source** *(waste packet)*	*Advection Dispersion Diffusion Gas migration (only once capsule is breached)*								
2	*Groundwater flow (only once capsule is breached)*	**Engineered Barrier** *(degradation, sorption, decay)*	*Advection Dispersion Diffusion Gas migration*							
3		*Groundwater flow (only once disposal container is breached)*	**Disposal Zone** *(degradation, sorption, decay)*							
4				**Unsaturated Zone**	*Recharge*					
5					**Saturated Zone** *(advection, dispersion, diffusion, sorption, decay)*	*Irrigation*		*Root uptake (through Irrigation)*	*Ingestion*	*Ingestion (through water supply)*
6	Leaching			*Percolation*	*Decay, leaching*	**Soil** *(Surface Soil)*	*Suspension*	*Root uptake*	*Soil ingestion*	*External irradiation Soil Ingestion*
7						*Precipitation, erosion, Deposition*	**Atmosphere**	*Particulate Deposition*	*Inhalation*	*Inhalation*
8						*Death and decay*	Transpiration	**Flora** *(Crops)*	*Ingestion of forage*	*Ingestion*
9						*Excretion Bioturbation*			**Fauna** (Animal products)	*Ingestion*
10					*Abstraction*	*Ploughing*		*Cultivation Harvesting*	*Rearing*	**Humans** (Dose to Exposure Groups)

Figure 3.3 Interaction Matrix for Farmer Scenario.

3.6.5 Mathematical Model

When the waste container starts to degrade, the radionuclide leaks out to the surrounding environment. The mathematical representation of the release of activity from the steel container through the grout in the container to the aquifer was governed by Eqn. (3.8) to Eqn. (3.9). when the radionuclide is out of the container, it travels through the saturated zone to the abstraction borehole (or well). The borehole water concentration was derived by using an analytical one-dimensional transport equation. The equation was given in Eqn. (3.8).

The groundwater mingles with the disposed waste, leaching its radiological constituents to contaminate the water-table. The contaminated water mixed with an aquifer which supply a drinking water well about 10m adjacent to the disposal borehole.

As stated in the scenario, the receptor assumed, was a local resident farmer who spend much of his time on the site, eat locally produced crops and animal products and drinks water from the well. The dose that the farmer received from the disposed waste was calculated from the total effective dose equivalent (TEDE), considering various exposure pathways (ingestion of water, plant (cereal and vegetables), mutton consumption, poultry meat and egg). The TEDE for the scenario was calculated as:

$$TEDE = \sum (SDCF) * C_w \qquad 3.1$$

Where SDCF= scenario dose conversion factor and C_w = the radionuclide concentration in water for all the radionuclide.

The SDCF is the sum of the three pathways dose conversion factors (PDCF).

$$SDCF = \sum_{i=1}^{n} 3(PDCF)_i \qquad 3.2$$

Where the three pathways dose conversion factors are for drinking water, mutton ingestion and poultry ingestion including eggs.

$$PDCF_{(mutton)} = (DCF) * (TF) * (WI)_{(sheep)} * (IR_{(receptor)}) \qquad 3.3$$

Where WI = water intake rate,

IR = mutton ingestion rate by receptor.

DCF = Dose conversion factor and TF = transfer factor.

$$PDCF_{(poultry)} = (DCF) * (TF) * (WI)_{(poultry)} * (IR_{(receptor)}) \qquad 3.4$$

$$PDCF_{(egg)} = (DCF) * (TF) * (WI)_{(egg)} * (IR_{(receptor)}) \qquad 3.5$$

$$PDCF_{(drinking\ water)} = (DCF) * (WI)_{(receptor)} \qquad 3.6$$

And

$$PDCF_{(plant)} = DCF * (CR_{Food}) * SML * CR_{Veg} * DWR_{Veg} * FLD_{Veg} \qquad 3.7$$

Where (CR_{Food})= food concentration ratio, SML = soil Mass Loading, CR_{Veg}= consuming Rate of vegetables, DWR_{Veg}= dry wet ratio and FLD_{Veg}= fraction local diet of plant.

The equations were solved by computer software to give the temporal and spatial dependence of the radionuclide concentrations and dose to humans. GoldSim 9.60 software was used in computing the concentrations and the receptor's doses. GoldSim is

powerful software that is used worldwide for carrying out probabilistic simulations of complex systems to support management and decision-making in engineering, science, and business. It is particularly, good for waste management application. It has been used to develop models for a wide range of safety assessment, including previous assessment of Borehole facility design by ISAM Group (IAEA, 2005). Many hundreds of users around the world (including nearly 200 academic institutions in 40 countries) are using the GoldSim software (Golder Associates, 2008). It is in fact considered as a premier tool for carrying out safety assessment of proposed and existing radioactive waste management site.

GoldSim is a flexible Window-based computer program. It is highly graphical and completely object oriented, that is you can create, document and present models by creating and manipulating graphical objects (referred to as elements), representing data and relationship between the data. It provides a wide variety of built-in objects from which you can construct your model. Appendix F shows how Zaria model was built using the GoldSim Software elements. The model is organized into several containers based on conceptual distinctions as can be seen in fig F-1. The 'simulation setting' container contains all the setting made in the model. The 'materials' container carries most of the data used like kd values, solubilities, soil properties, etc. as in fig. F-16. The 'inventory' contains the radiological inventories, the 'Disposal' shows the disposal system construction and so on.

Fig F-3 shows the content of 'Disposal' container. It contains 'cell pathway', 'buried Drums' and 'pipe pathway' elements with another container carrying the site geometry. The cell pathway is representing the disposal facility cap and the pipe contains a porous medium, and contaminants entering at the upstream end are transported along with

water. The pipe makes a lateral transport in the saturated zone. This aquifer transport takes advantage of GoldSim plume function, which allows for implied lateral dispersion of contamination as well or borehole. A 'sink GW' cell is at the outflow of the pipe. It provides a dose assessment calculation with drinking water concentration.

The calculation of the total effective dose equivalent (TEDE) for the resident farmer including each exposure pathway and each radionuclide contained in the 'Dose Assessment' container as in fig. F-8. The calculation was carried out on probabilistic mode. The result shows 100 (but equally probable) realizations, sampling from the stochastic inputs. The time-series of each pathways dose conversion factor (PDCF) calculations made and TEDE was contained in the 'Results' container and Fig F-17 shows what it contain.

3.6.6 Analysis of results

The result from the computer calculations were then analysed and compared against the assessment criteria to allow the adequacy of the safety assessment to be assessed. If the safety assessment is considered to be adequate the assessment will be considered accepted. But if it is considered to be inadequate the components of the safety assessment will then be reviewed and modified if appropriate(Fig 2.6). Iteration between the steps in the approach is expected until when the assessment considered accepted.

CHAPTER FOUR

RESULT AND DISSCUSSION

Fig. 4.1 shows the time history of the activity of the fifteen radionuclides under consideration inside the waste container. It can be seen that the curve of ^{90}Sr, ^{239}Pu, ^{137}Cs, and ^{63}Ni are dropping rapidly due to their short half-life. But the radionuclides with longer half-lives have linear horizontal curves.

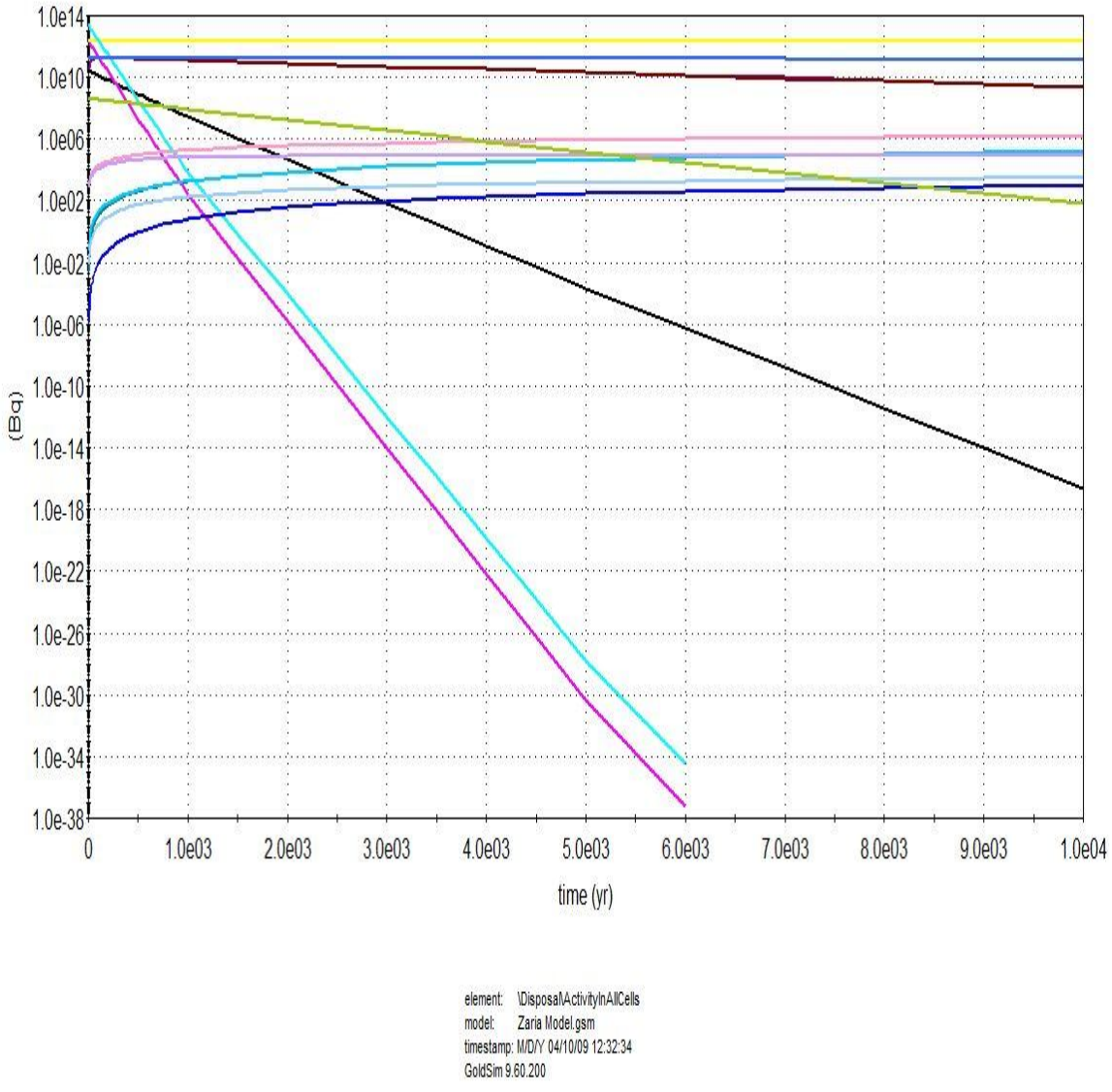


Figure. 4.1 Radionuclide Activity in the Stainless Steel Container.

Fig. 4.2 shows the time history of the concentration of the radionuclides from the disposal facility to the saturated zone. Only seven radionuclides (^{237}Np, ^{233}U, ^{235}U, ^{229}Th, ^{321}Pa, ^{227}Ac and ^{210}Pb) show breakthrough within the 10,000 years simulation period. The engineering barrier (stainless steel and concrete matrix) delays and attenuate the flux of radionuclides due to sorption. Because of the low distribution coefficient

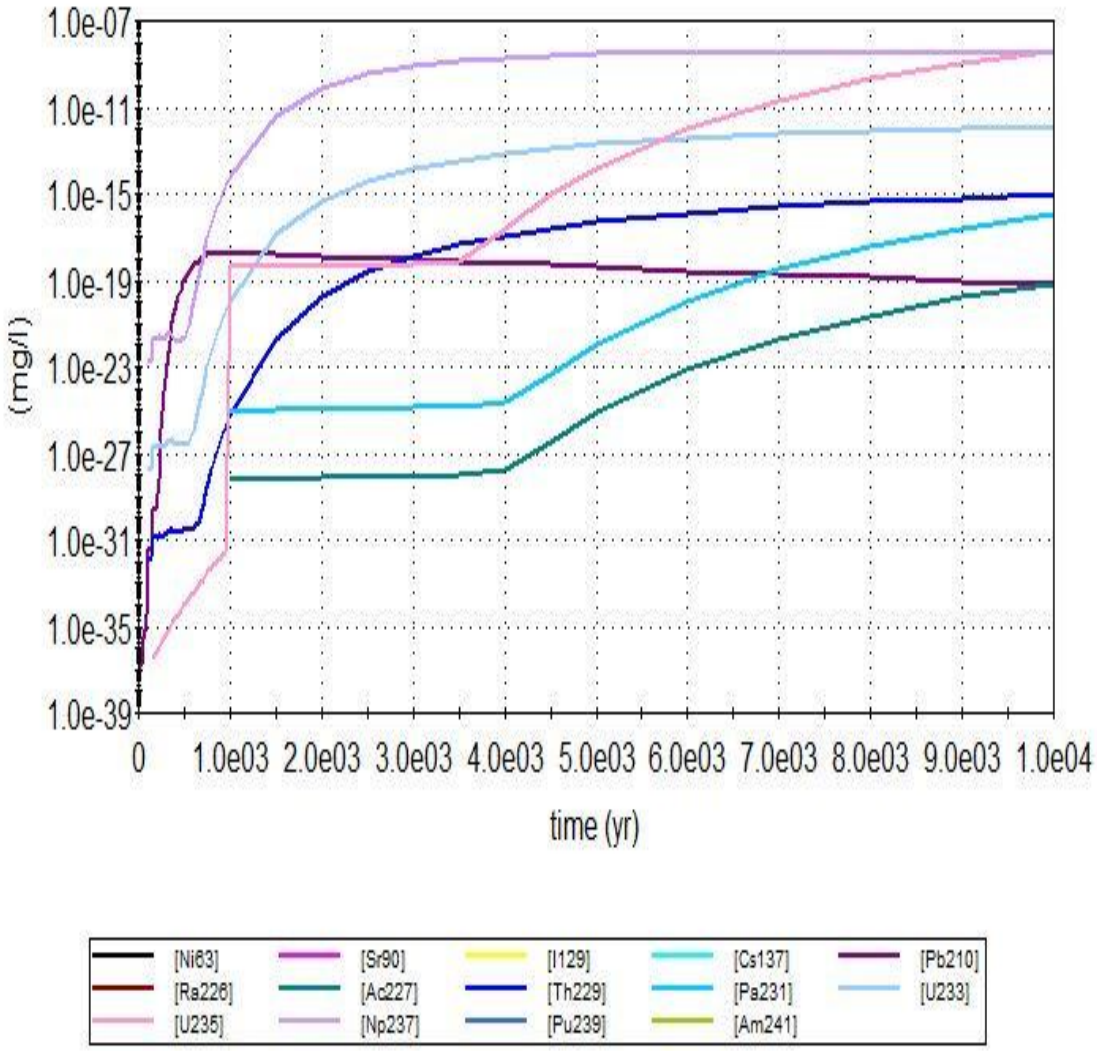


Figure. 4.2 Radionuclide Concentrations in the Saturated Zone.

(K_d) and/or relatively short half-lives of the remaining radionuclides (^{241}Am, ^{90}Sr, ^{129}I, ^{226}Ra, ^{63}Ni and ^{239}Pu), their concentration does not reach the saturated zone in any traceable quantity that can be seen in the time history. The radionuclides have half-lives less than 100 years, hence their activities decay to insignificant level prior to the failure of the stainless steel capsule and their subsequent release to the environment.

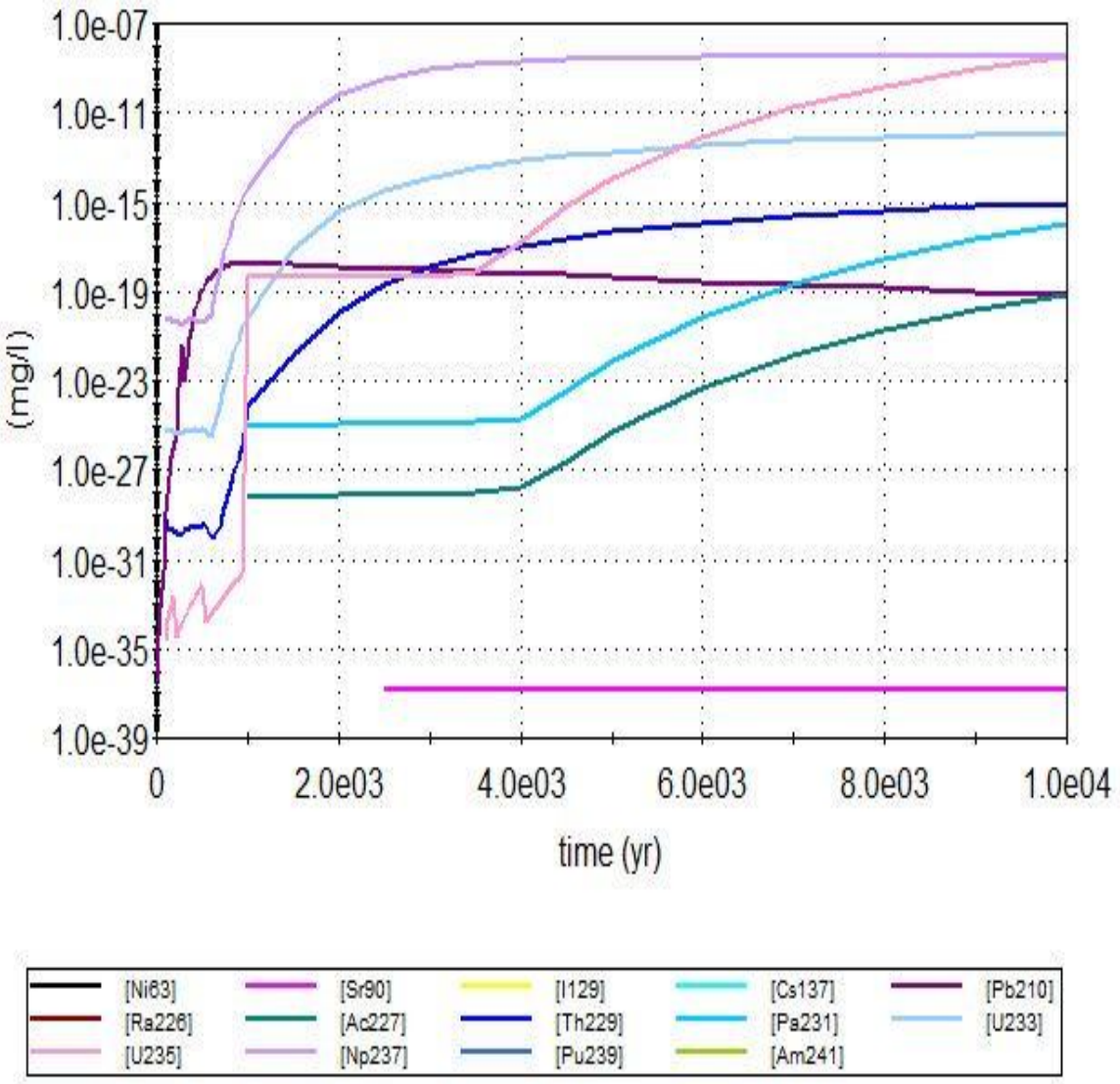


Figure. 4.3 Concentration of Radionuclides in Abstraction Well.

The concentration of the well water was shown in Fig. 5.3 and it can be seen that the saturated zone does not significantly retard the key radionuclides. The peak concentration in saturated zone and the concentration in the well water are broadly the same. This is because of the relatively rapid transit time of water along the fracture assumed and the low distribution coefficient of these radionuclides in saturated zone.

4.1 Annual Individual Dose from Use of Well Water

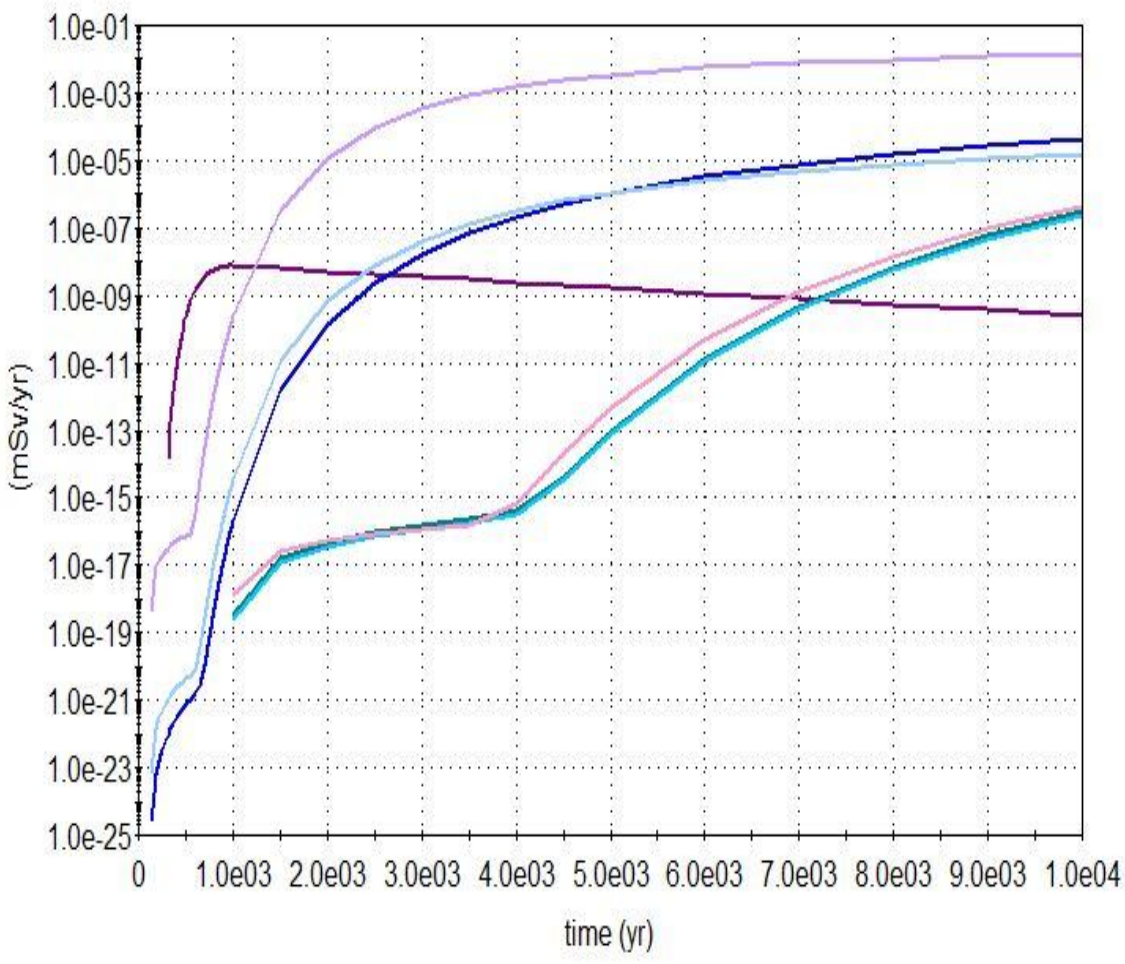


Figure. 4.4 Total Effective Dose Equivalent (TEDE) for Soil Ingestion.

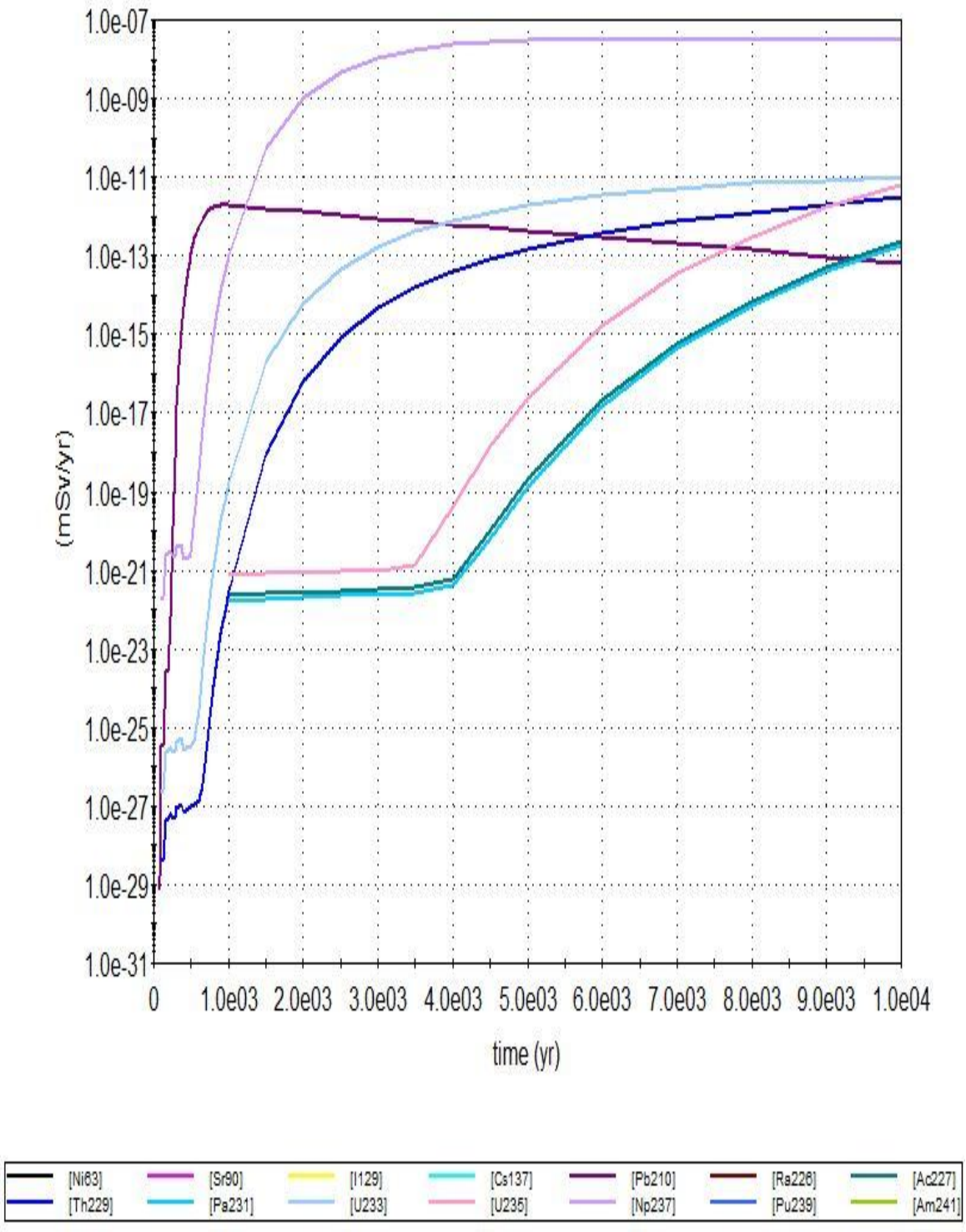


Figure. 4.5 Total Effective Dose Equivalent (TEDE) for Ingestion of Water.

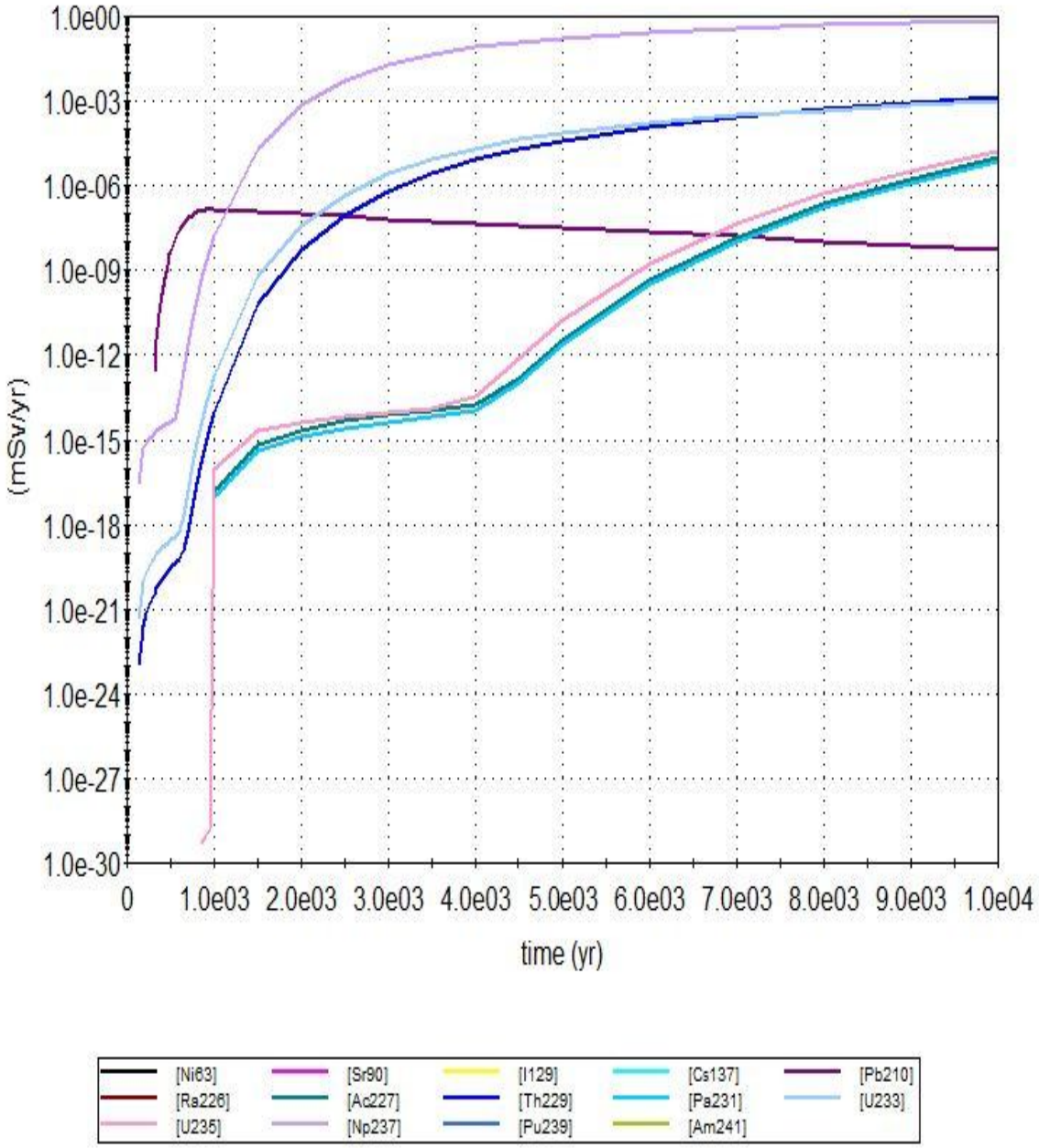


Figure. 4.6 Dose (TEDE) from the Ingestion of Plant.

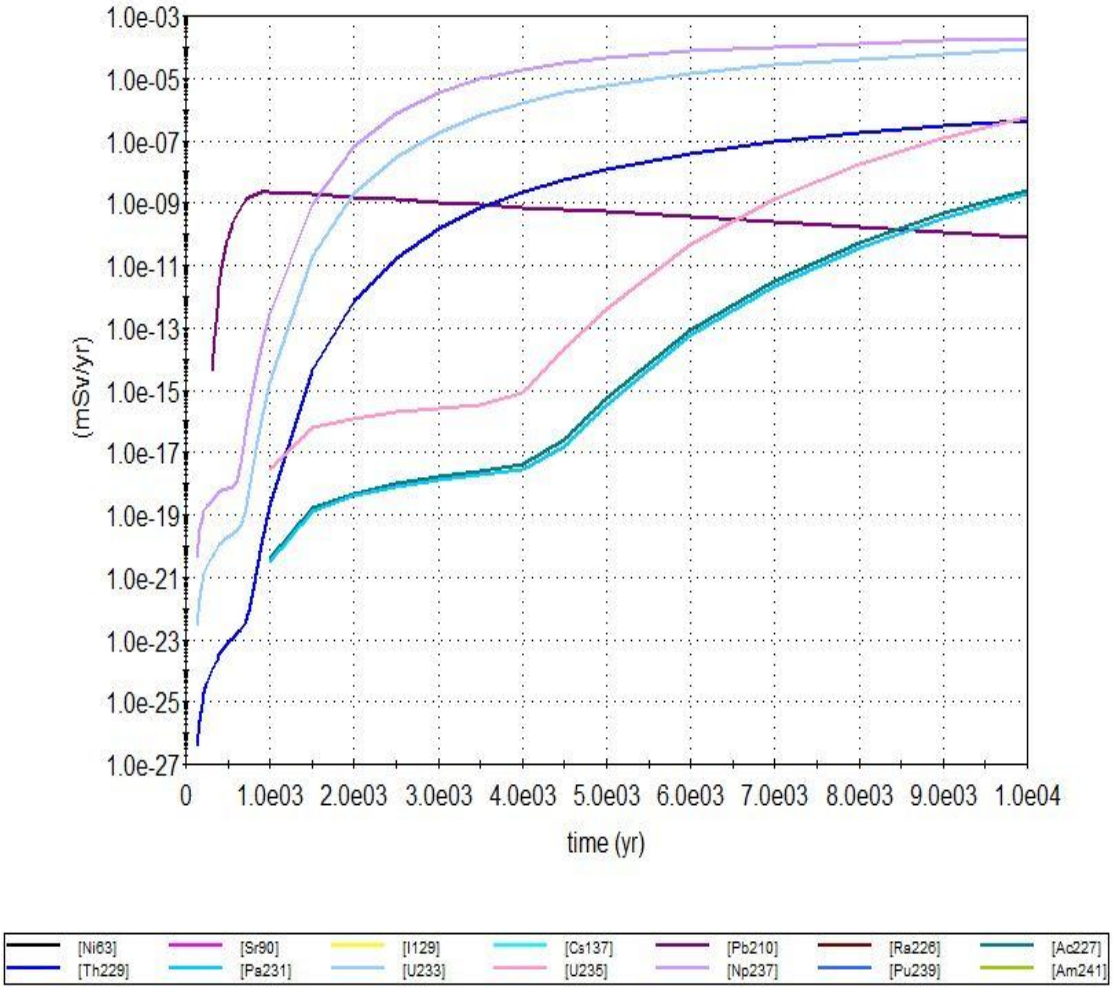


Figure. 4.7 Dose from the Ingestion of Animal.

Fig.4.4 to 4.7 shows the annual individual dose from use of the contaminated well water. Table 4.1 shows the summary of the results shown from fig. 4.1 to fig. 4.7.The dose for drinking well water, ingestion of soil, plant, and animal were calculated. The result presented in Fig 4.4 shows the contribution of the dose due to drinking water ingestion. Dose due to the ingestion of soil was shown in Fig. 4.5, while Fig. 4.6 displayed the contribution of the sum of doses of various plants ingested (crops, fruits, vegetables and roots tubers). The result presented in Fig.4.7 shows the sum of doses due to animal ingestion (meat, egg and milk ingestions). In all the above time histories and

the summary of the result in table 4.1, for various ingestions by the farmer, the long term contribution of ^{237}Np is the highest followed by ^{233}U, while ^{210}Pb has the least at 10,000 years.

Table 4.1. Summary of the results of various pathways at 10000years after closure.

		Inventory	conc. Of Radionuclide in: (Bq)			TEDE Value for ingestion of…. (mSv/yr)				
Radionuclide	**Half-life**	(Bq)	container	Sat. zone	Abst. well	soil	water	Plant	Animal	All pathway
^{237}Np	2.14E+6y	0	80633	3.50E-09	3.51E-09	0.013348	2.94E-08	0.74777	0.000187	0.761304849
^{229}Th	7300y	0	1102.7	9.68E-16	9.34E-16	4.07E-05	3.02E-12	0.001434	4.64E-07	0.00147548
^{233}U	1.592E+05y	0	3.23E+03	1.28E-12	1.26E-12	1.55E-05	1.02E-11	9.57E-04	8.25E-05	0.001054869
^{235}U	7.04E+08y	0	1.58E+06	3.77E-09	3.36E-09	4.14E-07	6.30E-12	1.61E-05	5.53E-07	1.70712E-05
^{227}Ac	21.77y	0	1.63E+05	7.29E-20	6.37E-20	3.21E-07	2.30E-13	9.77E-06	2.56E-09	1.0095E-05
^{231}Pa	3.28E+4y	0	1.64E+05	9.68E-16	1.02E-16	2.41E-07	1.83E-13	6.99E-06	1.87E-09	7.22756E-06
^{210}Pb	22.6y	0	2.54E+09	6.57E-20	6.81E-20	2.64E-10	6.63E-14	5.16E-09	8.08E-11	5.50742E-09
^{137}Cs	30.1 y	5.00E+05	0	0	0	0	0	0	0	0
^{239}Pu	2.4E+04y	3.70E+03	1.39E+11	0.00E+00	0	0	0	0	0	0
^{90}Sr	29 y	5.00E+04	0	0	1.54E-37	0	0	0	0	0
^{63}Ni	100 y	5.00E+02	2.56E-17	0	0	0	0	0	0	0
^{241}Am	412 y	8.00E+05	68.458	0	0	0	0	0	0	0
^{129}I	15700000y	4.00E+04	2.00E+12	0	0	0	0	0	0	0
^{226}Ra	1600 y	3.70E+03	2.51E+09	0	0	0	0	0	0	0

Table 4.2 Values of all pathway Doses by radionuclides.

Radionuclide	*Peak value of TEDE (mSv/yr)*
^{63}Ni	7.61305E-01
^{239}Th	1.47544E-03
^{233}U	1.05487E-03
^{235}U	1.70716E-05
^{227}Ac	1.00950E-05
^{231}Pa	7.22754E-06
^{210}Pb	5.50746E-09

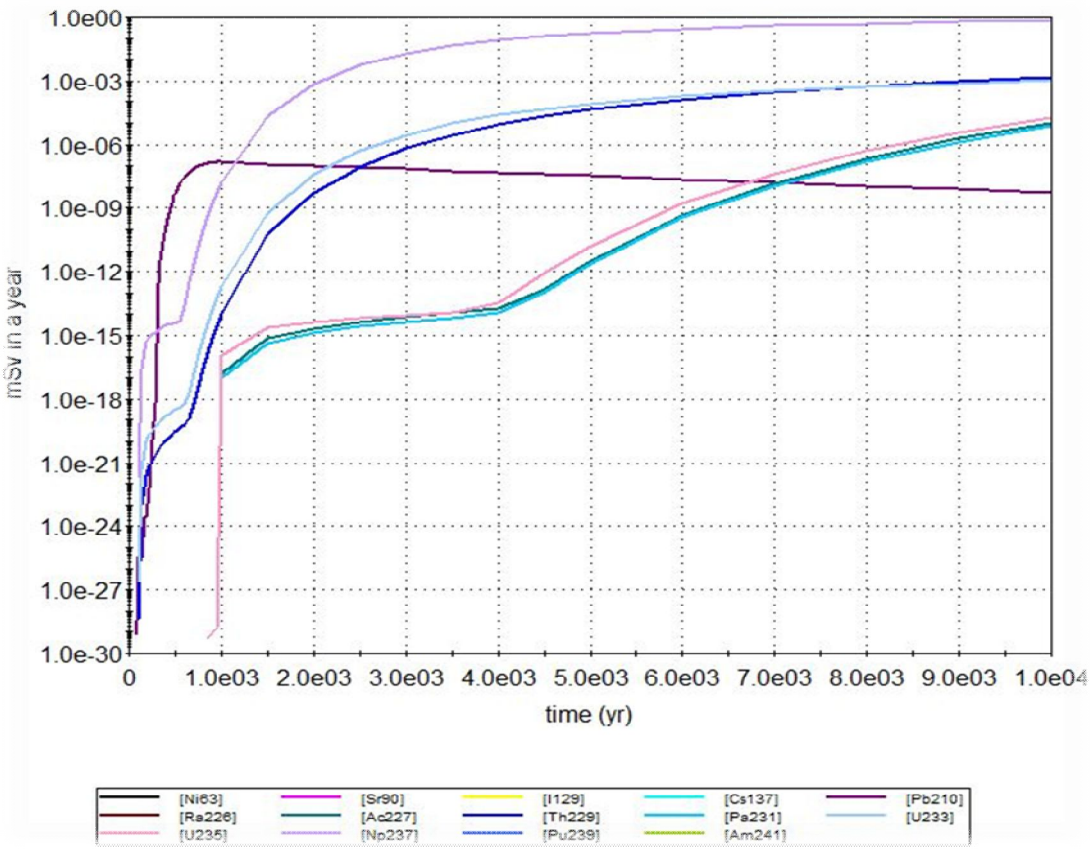


Figure 4.8 All Pathway Doses by Radionuclides

Table 4.2 and Fig. 4.8 shows the mean total dose per radionuclide in all the pathways (drinking water, ingestion of soil, animals and plants) per radionuclide disposed, assuming intrusion occurs at the loss of institutional control (30years). The main contributors to the total dose are ^{237}Np, ^{229}Th, ^{233}U, ^{235}U, ^{227}Ac, ^{231}Pa, and ^{210}Pb. The highest contribution to the total dose is from ^{237}Np (0.761mSv/yr), which is the decay product of ^{241}Am. The second highest contributor is also from the daughter of Am-241. In fact the first, the second and the third highest contributors are from the daughters of ^{241}Am (^{237}Np, ^{229}Th and ^{233}U) that contribute to the total effective dose equivalent for the farmer scenario. The other three radionuclides (235U, ^{229}Th, and ^{231}Pa) that follows the ^{241}Am are daughters of another radionuclide, ^{239}Pu. The last contributor, ^{210}Pb, is also daughter of ^{226}Ra nuclide.

Fig.4.9 shows the mean dose contribution of these daughters. The dose contributed by ^{237}Np is greater than the dose constraint. Fig.4.11 shows the mean of the sum of the daughters. At 10000 years the mean calculated was 0.763mSv/yr. This amount to 99.99% of the total peak dose summed over all radionuclides. This result shows the need to reduce the inventory of ^{241}Am due to the long-lived radionuclides of its daughters (i.e. ^{237}Np, ^{229}Th and ^{233}U) which tend to pose hazard. The reduction should be to some orders of magnitudes that would ensure acceptable doses from radionuclides. This result is very important in establishing the dose limit for radionuclides, in order to avoid high dose values.

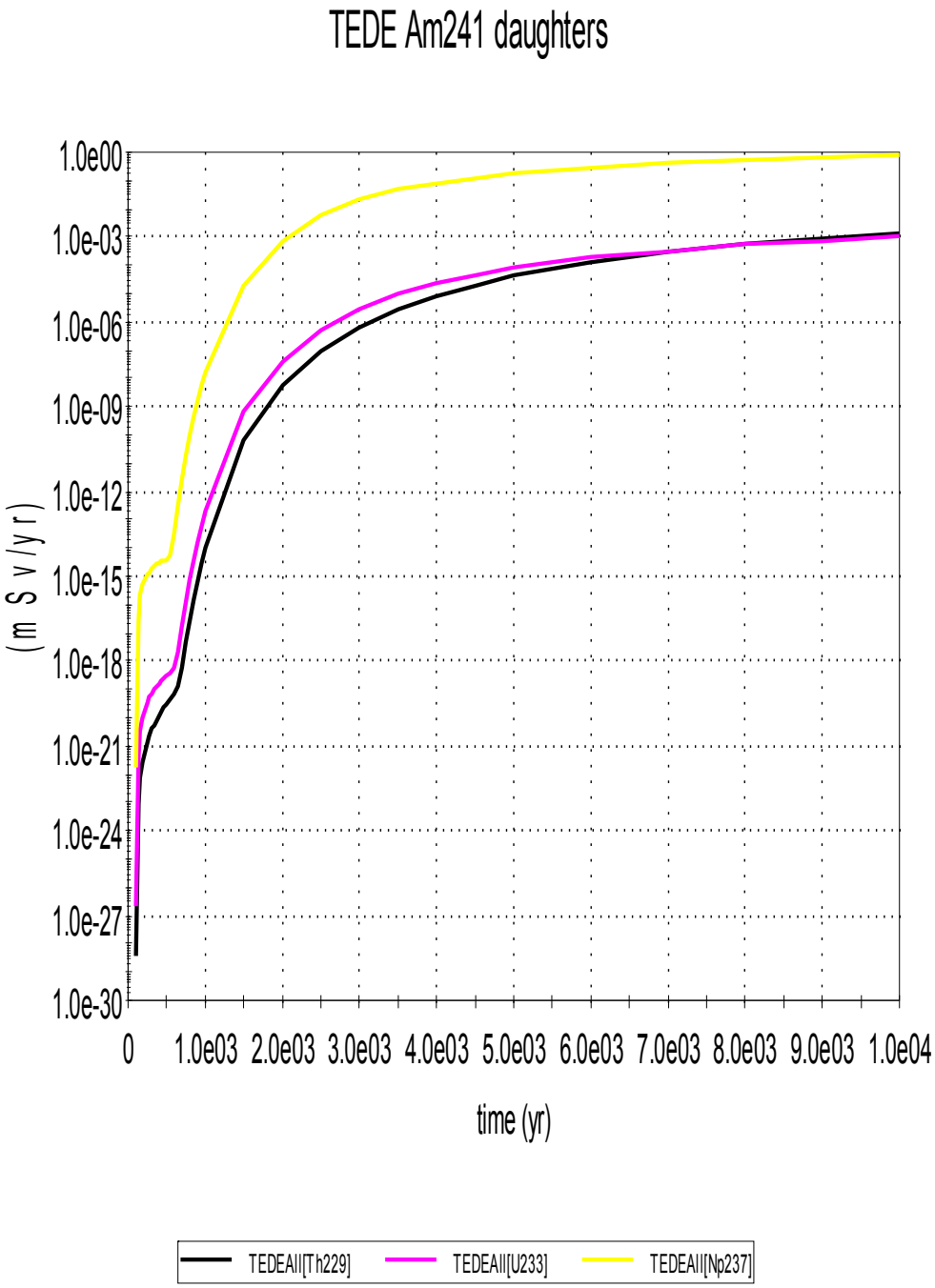


Figure. 4.9 Doses for Am-241 Daughters.

Based on the above, different values of ^{241}Am activity were used in the inventory of the waste. The program was run each time the inventory changed and the calculated values of All-pathway TEDE were recorded as in Table 4.2 below. A graph of ^{241}Am Activity

Table 4.3. Values of all pathway Doses for different values of Am-241 activities.

^{241}Am inventory (Bq)	All-pathway TEDE (mSv/yr)
80	0.004608
800	0.00468
8000	0.0054
80000	0.0126
100000	0.0146
200000	0.0246
400000	0.0446
600000	0.0646
800000	0.0846
1000000	0.1046
2000000	0.2046
4000000	0.4046
6000000	0.6046
8000000	0.8046

against All-pathways TEDE was plotted as in fig. 4.11. The graph shows a linear relationship between the inventory and the impact (TEDE). This is then used to find the reference activity level for ^{241}Am. That is the maximum activity to be disposed in a borehole or else the TEDE value will be greater than the dose constrain (0.3mSv/yr.). From the graph the activity level is in excess of 2,950,000Bq (2.95MBq).

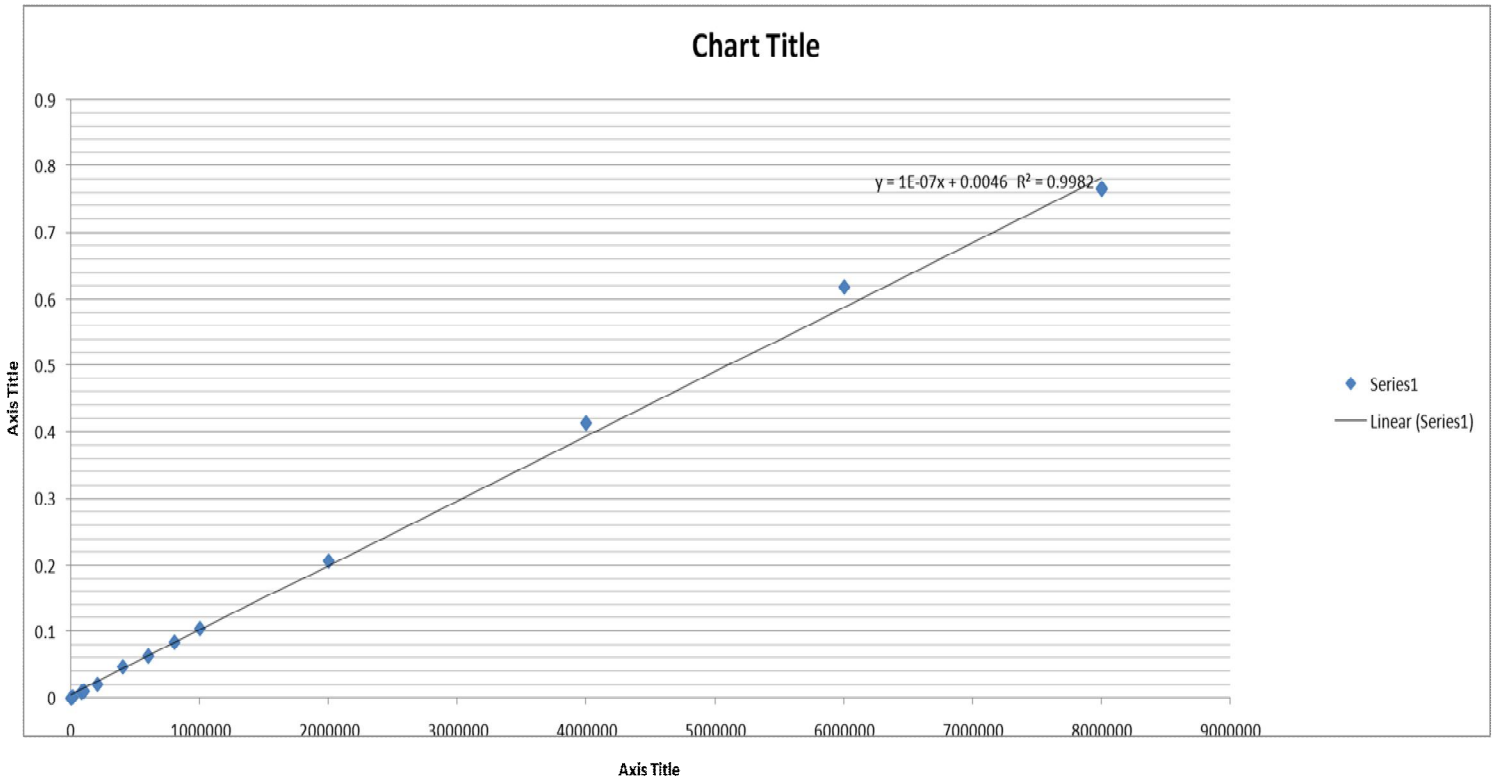


Figure.4.10 A graph of All-Pathway TEDE (mSv/yr) and ^{241}Am Activity (Bq)

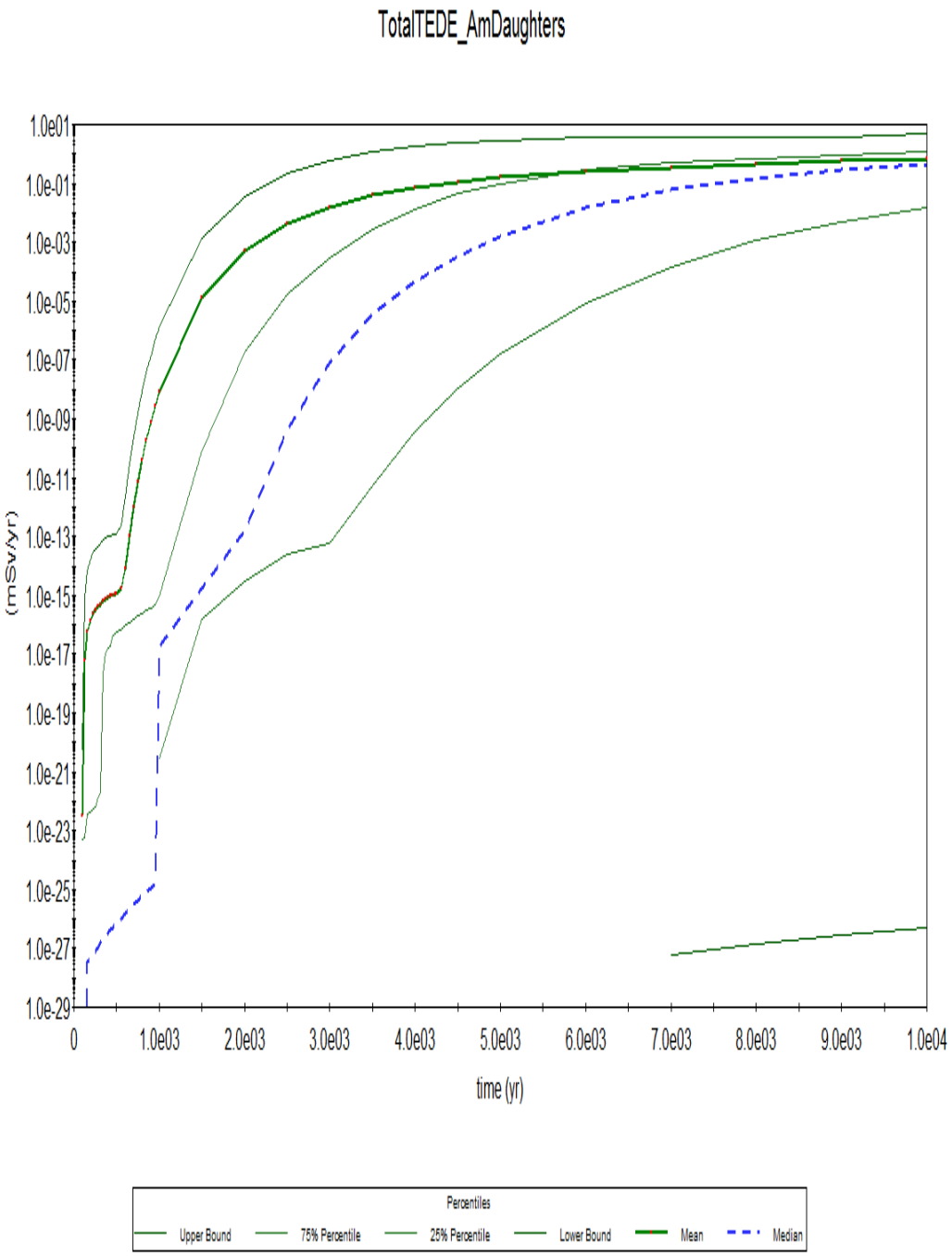


Figure. 4.11 Mean Dose of the Total TEDE of AM-241 Daughters.

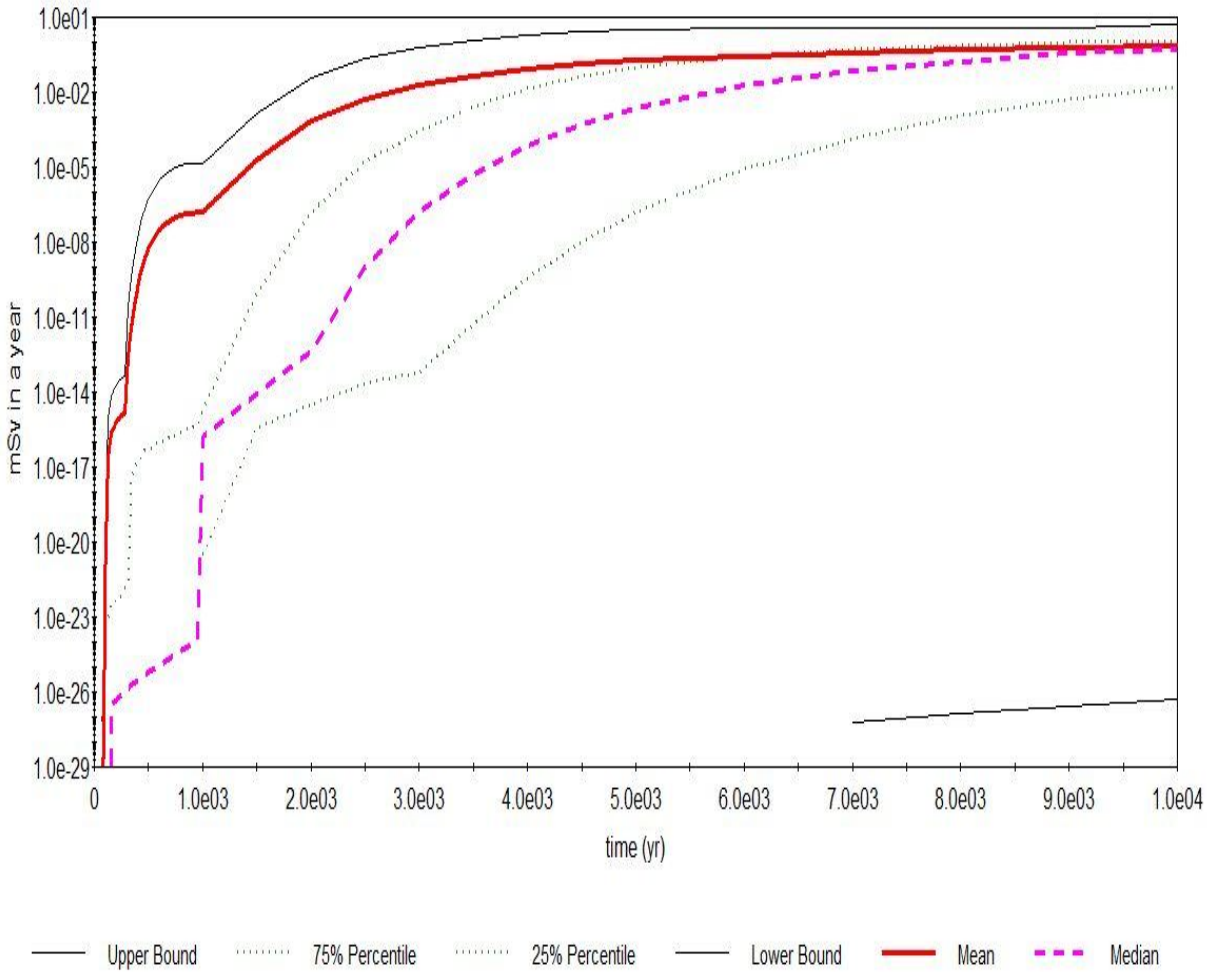


Figure.4.12 All Pathway Maximum TEDE for the Farmer Scenario.

The dose distribution for all the pathways at 10000 years has a mean of 0.763869mSv/yr, a median of 0.484637mSv/yr, a 75th percentile of 1.16282mSv/yr and a 25th percentile of 0.01603mSv/yr.

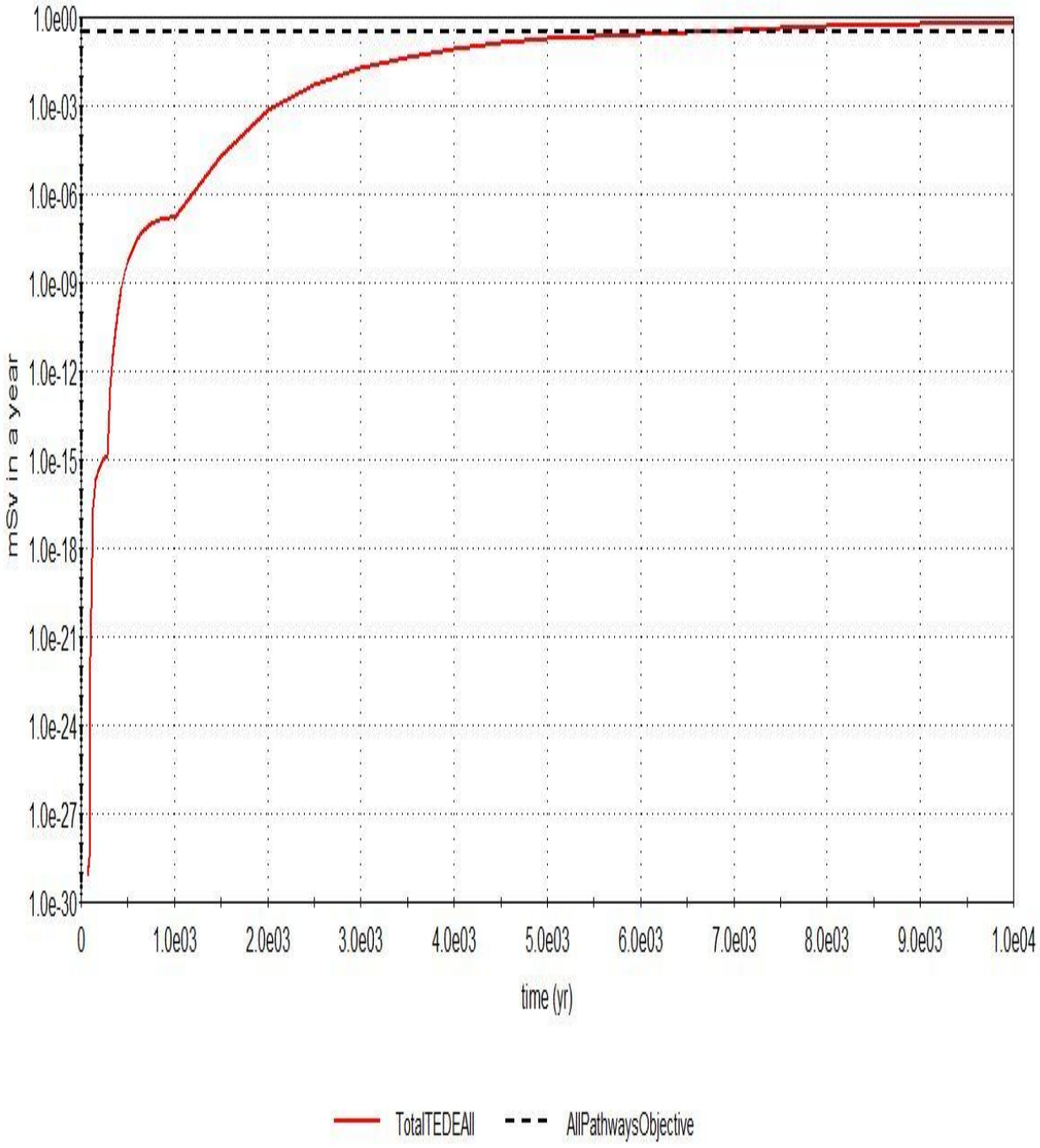


Figure. 4.13 Estimated Total TEDE via all Pathways, Summed over Species

4.2 UNCERTAINTY ANALYSIS

When analysing the result of this work, it should be noted that several kind of uncertainties are associated. According to the sources from which such uncertainties arise they can be divided into three groups (E.P.A. 1992):

4.2.1 Scenario Uncertainty

Scenario uncertainty arises from limited knowledge of the evolution of slow processes such as chemical interaction between the engineered barrier materials, groundwater and transport of radionuclides in the geosphere; the timing and frequency of events that may affect the stability of the geological environment; and future human activities.

This type of uncertainty is normally treated by carrying out safety assessment calculations for a number of scenarios representing possible future state of the site. The general list of events and processes was reduced according to site description and assessment context, during the scenario generation some events with a very low probability (e.g. earth quark) are not considered in this study. During formation of the scenario, therefore, the scenario selected is considered to cover a wide range of possible events and pathways for the purpose of an initial assessment.

Even though only one scenario was considered in the assessment due to time and resource constraints, confidence is bestowed by the fact that this scenario provides a reasonable, scientifically and historically defensible framework that is robust to a large variety of future uncertainties and the scenario represents the upper bound of exposure and the extreme of the actual doses in the entire population (see section 3.5.3).

4.2.2 Model uncertainty

Model uncertainty is uncertainty in the conceptual, mathematical and computer models used to simulate the behaviour and evolution of the disposal system (e.g. owing to the inability of models to represent the system completely), approximations used in solving the models equation and coding errors. Modelling errors can also be due to simplification of models from the real situation, for example, approximating a three-dimensional aquifer with a two-dimensional mathematical model. A variety of approaches can be used to qualitatively characterize the uncertainty associated with model constructs. One approach is the use of different modelling formulations (including the preferred and plausible alternatives) and considers the range of outputs to be representatives of the uncertainty range. The uncertainty can be investigated in a preliminary manner by comparing the result from two independent set of calculation performed, with different conceptual, mathematical and/or computer models. This strategy is the most useful when no clear best approach can be identified due to the lack of supporting data or when situations being assessed require extrapolations beyond the conditions which the model were originally designed(EPA,1986).

The method used in developing this model was similar to the method used by Gallegos et al (2004). The model developed was conservative relative to the existing site information. We uses model that consistently over predict releases in relation to what the actual release might be. The reason behind this is that, if it can be demonstrated that the model complies with the regulations, then it follows that the actual site should also comply.

GoldSim computer model is chosen as the computer model for solving the mathematical model developed. The computer model was chosen due to it wide application in probabilistic simulation of complex systems and decision making as mention in section

3.6.5. The software uses simulation framework where the simulations are repeated for a large number of times. Each simulation is an equally likely realization of the system. 100 simulations are used in each of the parameter uncertainty. The results of these realizations are then assembled into probability into probability distributions of outcomes. The total effective dose equivalent (TEDE) is also derived as a probability distribution and the mean of the distribution is compared against the dose constraint (0.3mSv/yr) to show compliance.

In the initial result the value of the TEDE is found to be 0.763mSv/yr which is greater than the dose constraint. The assessment is iterated by reducing ^{241}Am inventory for the TEDE to show compliance with the dose constraint.

4.2.3 Data/Parameter Uncertainty*:*

In this section we are concerned with the primary contributions to the parameter uncertainty and can be classified as variability and lack of knowledge (inaccurate, unrepresentative or limited data). Many of the parameters used in this assessment are uncertain; for example, there are insufficient data about geological and hydrological conditions, ingestion of water and other human exposure data. Therefore many data are taken from literature. The impact of measurement error on parameter uncertainty is often felt to be small relative to other source of uncertainty and easily quantified. Parameter uncertainty can be treated using Monte Carlo approach for key parameters. In fact uncertainties associated with the conceptual and mathematical models and their associated parameters and parameter values can be assessed by the use of probabilistic computer tools which allow the output of results in probabilistic format (e.g. mean values and associated confidence intervals, and the re-running of deterministic tools with different conceptual and mathematical models and/or parameter values. This is one of the reasons why GoldSim software is used, because it gives result in both

probabilistic and deterministic format. The work uses the software in the probabilistic mode and different probability distributions were used depending on the type of parameter values we have. For annual rainfall, normal distribution is used with estimated mean of 86.54mmy-^{1}, standard deviation of 12.2mmy-^{1}, minimum 63.3mm y-^{1} and maximum 105.3mm y-^{1}. Uniform distribution is used for distribution coefficient (k_d values) and solubility limits, while transfer factors are assumed to be log-normally distributed with median values as shown in Table 3.3 and a geometric standard deviation of 3. Figures 4.14 – 4.16 show stochastic graphs describing the assessment parameters as probability distributions as used in the work.

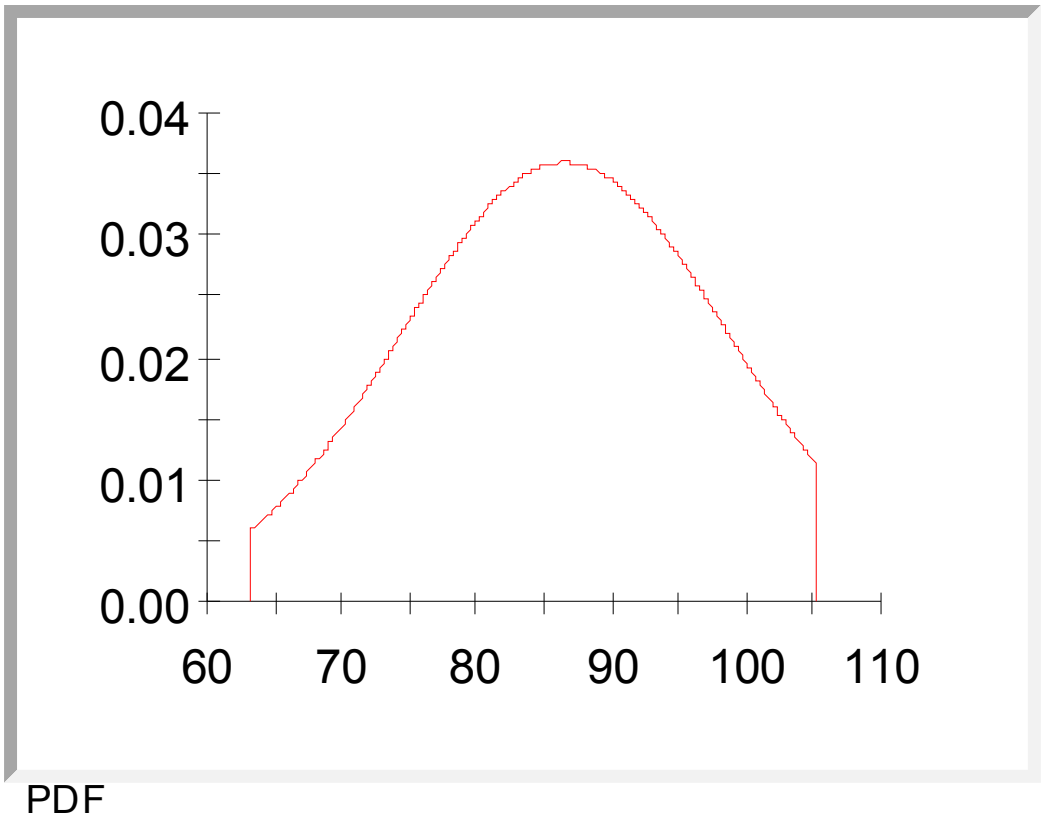


Figure 4.14. Annual Rainfall values using normal distribution.

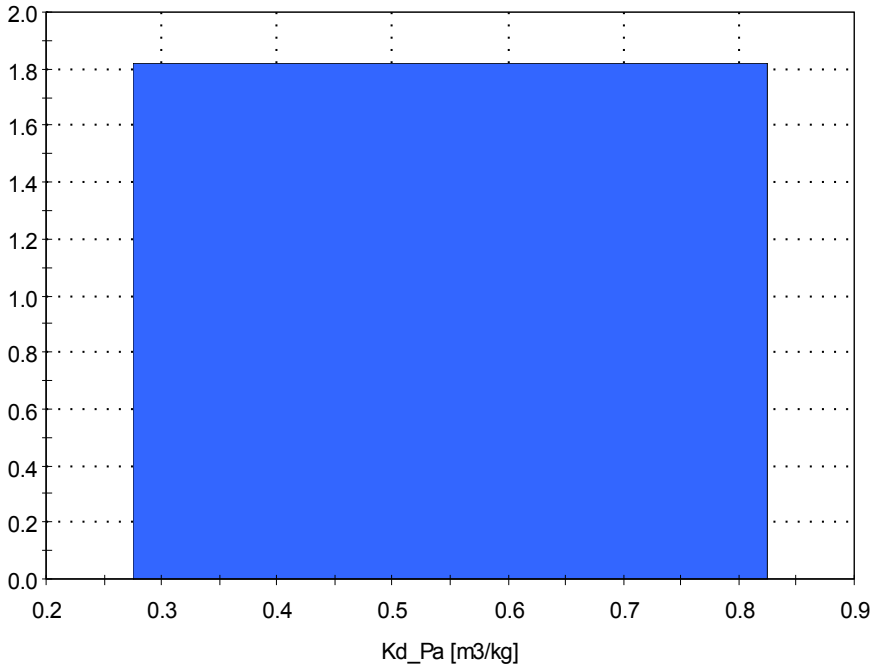


Figure 4.15. ^{231}Pa k_d values using uniform distribution.

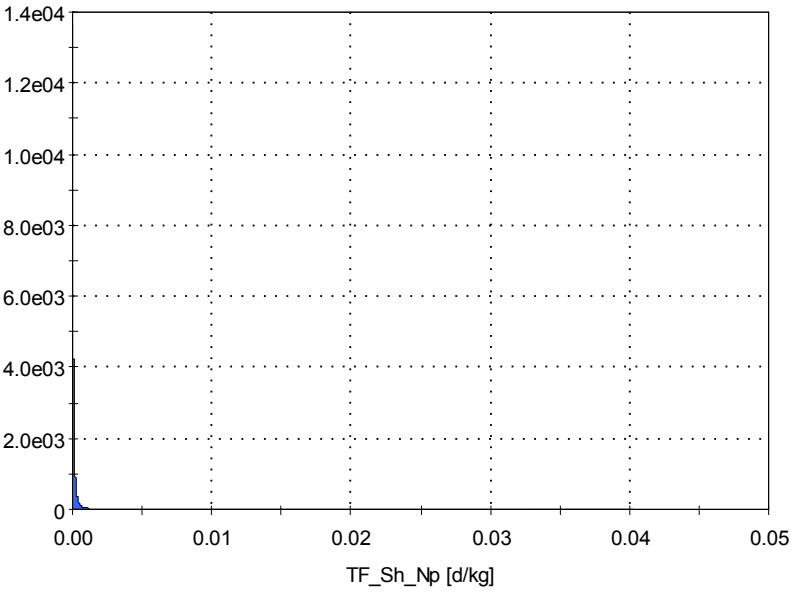


Figure 4.16. ^{237}Np transfer factor values using log-normal distribution.

4.2.4 Sensitivity Analysis

Sensitivity analysis is a process of changing one variable, while leaving others constant and determining the effect on the output. It is a quantitative measure of the effect input parameter have upon the calculated result (Maheras and Kotecki, 1990; Seitz et al., 1990). It is important to ask "what if" questions. For example you may need to ask: what if the inventories of the radioactive waste increases. Since you know that the future is uncertain the radionuclide inventory can increase rapidly.

Sensitivity analysis to changes in waste inventories that appears at the abstraction well after 10,000years is conducted for specific input parameters. The procedure involves fixing each radionuclide quantity, one at a time, at its credible lower-bound and then its upper-bound (holding all others at their medians), and then computing the outcomes for each combination of values.

The model was run multiple times systematically sampling each of the radionuclides over a specified range (80 - 8.0E+14), while holding all other variables constant. Table 4.2, 4.3 and 4.4 show the result of ^{241}Am, ^{226}Ra and ^{239}Pu daughters TEDE respectively for different inventories of ^{241}Am, ^{226}Ra and ^{239}Pu. At first their contribution to the total dose is insignificant and hence not very important. But as their inventories are becoming larger they make very important contribution to the total dose. For inventory values of 3.0E+6Bq, 6.0E+14Bq and 2.0E+13Bq for ^{226}Ra and ^{239}Pu respectively, the dose each radionuclide contributed is greater than the dose constraint. Other sensitivity analysis graphs for other parameters can be found in Appendix G.

Table 4.4 Values of ^{226}Ra daughter TEDE.

^{226}Ra inventory (Bq)	^{226}Ra daughter TEDE (mSv/yr)
80	3.67E-14
800	3.67E-13
80000	3.67E-11
8000000	3.67E-09
8E+08	3.67E-07
8E+10	3.67E-05
8E+12	3.67E-03
8.00E+14	3.65E-01

Table 4.5 Values of ^{239}Pu daughters TEDE (mSv/yr).

^{239}Pu inventory (Bq)	^{239}Pu daughters TEDE (mSv/yr)
80	1.155E-12
800	1.155E-11
80000	1.155E-09
8000000	1.155E-07
8E+08	1.155E-05
8E+10	0.0011552
8E+12	0.11552
8.00E+14	11.435

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Safety assessment of borehole disposal facility of disused sealed sources was developed with the aim of solving the problem of most of the developing countries has on radioactive waste. It is foreseen that the technology developed for the borehole disposal concept could be used and safely implemented by any country possessing small volume of high specific radioactive waste (Nel and Potier, 2005). The concept provides direct and cost effective access to suitable geology, using readily available construction material and technologies. It requires limited land area and has low probability of human intrusion due to the small footprint of the borehole.

Concentrations of radionuclides are calculated for soil, crops and animal products. Exposure pathways included are ingestion of water, fruits, vegetables, grains, animal products and soil. The input parameters used to calculate these concentrations and receptor exposure are based on site specific information or analogue data when possible and are sampled as distributions to propagate uncertainty and variation in the parameter values. Annual individual doses to average doses to a resident farmer using contaminated abstracted waste have been presented, assuming unit release rate in the water of 14 different radionuclides. Result has been presented for the sum over all exposure pathways. It should be noted that the drinking water doses do not dominate in the total dose for the radionuclides considered. According to the calculations made, more significant doses arise from consumption of various food stuffs and other pathways.

The assessment also shows that the concept place no limit on the short-lived radionuclides ($T_{1/2}$ ≥30 years) inventory that could be disposed of in this way. But for long-lived radionuclides, the concept can only accommodate not more than two units of MBq of ^{241}Am waste, 200 TBq of ^{226}Ra and seven unit of TBq of ^{239}Pu. It could therefore be concluded, from the safety assessment, that the borehole disposal facility will provide a safe solution for the disposal of the waste if suitable combination of inventory and engineering barrier is made in the environment.

5.2 RECOMMENDATIONS

This safety assessment shows that the area under study is worth studying in more detail. This is the first iteration of the assessment and can be served as a basis for future iterations.

The assessment was also based on limited early geological investigations found in literature. There is therefore need for further safety assessment with all the relevant site data and conceptual design information. The amount of uncertainty will change in the light of new knowledge. New data on the site could decrease uncertainties and give more realistic picture of the disposal case.

Independent investigations are also desirable so that their results would be compared to recognized misunderstanding, gaps and flaws in analysis, and many outright errors.

It is also recommended that more than one repository should be sited if the inventory of ^{241}Am, ^{226}Ra and/or ^{239}Pu exceed the dose limit. Each borehole should be placed sufficiently far apart so that interactions among the boreholes will be insignificant.

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APPENDICES

Appendix A:

Principles of Radwaste Management

Principle 1: Protection of human health: Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health. An acceptable level of protection therefore needs to be provided. Particular attention needs to be paid to control the various ways by which human might be exposed to radiation, and to ensure that such exposure is within established requirements.

Principle 2: Protection of the environment: Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment. This should be conducted in such a way to limit, to the extent feasible, the effects on the future availability or utilization of natural resources (e.g. land, forest, surface waters, ground waters, raw materials), over extended period of time. Since humans are among the most radiation-sensitive organisms, measures taken to protect individual humans from radiation hazards are in general considered adequate to protect other species, although these measures may not necessarily protect individual members of the species possible future exploration of natural resources should be taken into consideration when siting and designing repositories, because this could potentially result in adverse effect on the environment capability of a repositories. Radwaste management activities may result in non-radiological environment impacts, such as chemical pollution or alteration of natural habitats. These impacts need to be considered also.

Principle 3: 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. A country has a duty to act

responsibly not to impose effects on human health and the environment in other countries more detrimental than those which have been judged acceptable within its own borders.

Principle 4: 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. It is not possible to ensure total containment and isolation of radioactive waste over extended time scale, the intent is that there will be no significant impacts on human health when radionuclides enter the environment.

Principle 5: Burdens on future generations: Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations. The responsibility of the present generation includes developing the technology, constructing and operating the facilities and providing a funding system and sufficient control for the management of radwaste. This includes providing the means and the technology for disposal.

Management of radwaste should, to the extent possible, not rely on long term institutional arrangements as a necessary safety feature, although future generation may decide for example to monitor radwaste repositories. The identity, location and inventory of a waste disposal facility should be appropriately recorded.

Principle 6: 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. Countries in which radionuclides are being produced or used should develop a national legal framework, taking into account overall strategies and providing laws, guidelines and regulations for radwaste management. The responsibilities of each party or organization involved in radwaste management should be clearly allocated for all waste management activities that take

place in a country. Since radwaste management can span time-scales involving a number of human generations, appropriate consideration of present and likely future operations should be taken into account. Sufficiently long lasting administration, including continuity of responsibilities and funding requirement should also exist.

Principle 7: Control of radioactive waste generation: Generation of radioactive waste shall be kept to the minimum practicable. The generation of radwaste, both in activity and volume shall be kept to the minimum practicable by appropriate design measures and operating practices. The preferred focus of radioactive waste management should generally be on containment of radionuclides rather than dilution and dispersion in the environment.

Principle 8: Radioactive waste generation and management interdependencies: Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account. The basic steps of radwaste management are pre-treatment, treatment, condition, storage and disposal. There are interdependencies among and between steps in waste management. Since the steps of radwaste management occur at different times, there are, in practice, many situations where decisions must be made before all radwaste management activities are established.

Principle 9: Safety of facilities: The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime. Siting, design, construction, operation and decommissioning of a facility or closure of a repository should be carried out giving safety matters priority in such a way that it seeks to prevent accidents and to limit consequences if accidents should occur. Public issues should be addressed throughout these steps.

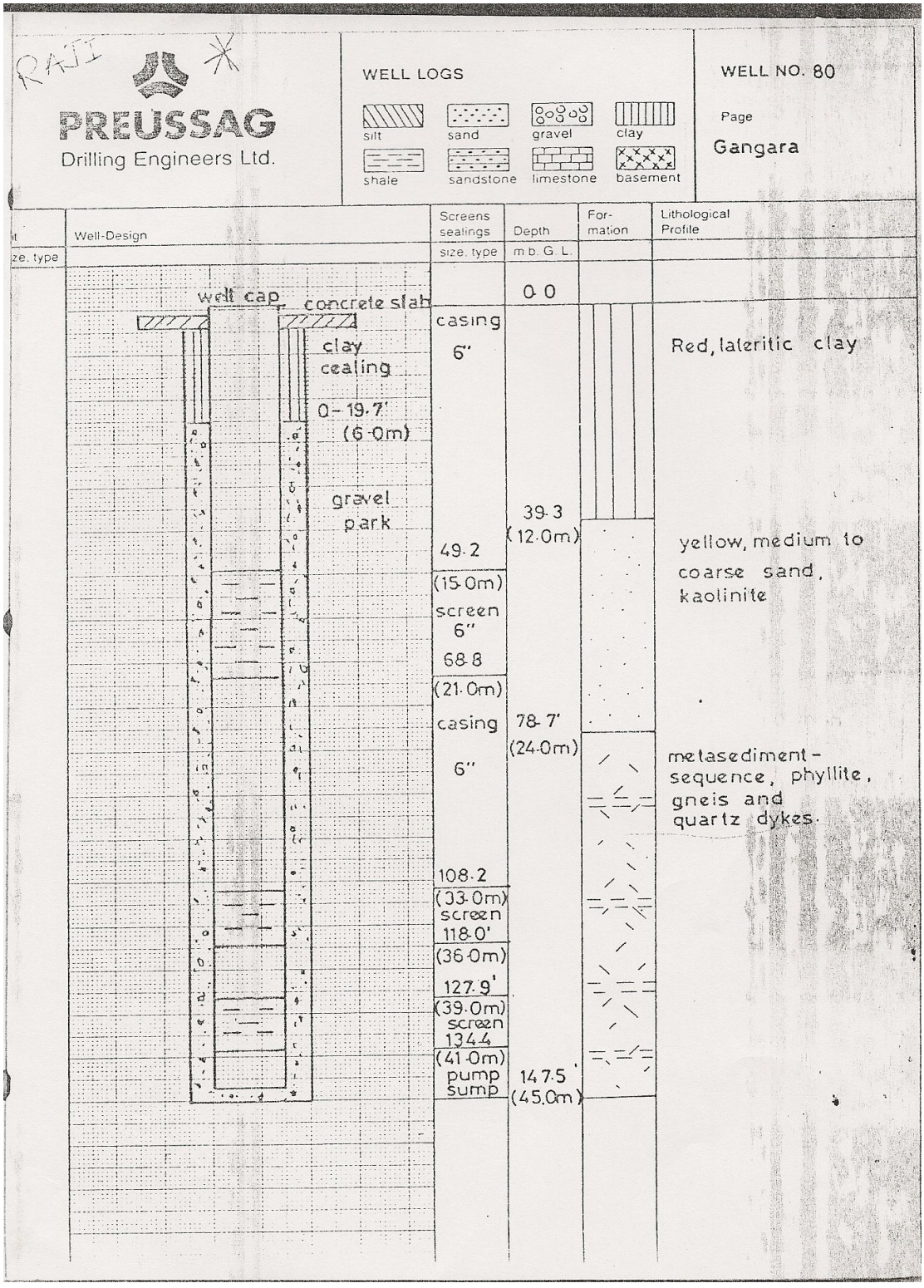
Appendix B

Long term Annual rainfall

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	Average
Jan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar	43.2	64.3	0	1	0	0	0	42.2	0	1.3	0	0	0	0	0	6.9	0	0	26	0	9.245
Apr	45.7	0	0	0	23.8	21.5	2.3	75.5	36.6	38.9	33.1	59.1	8.9	29.4	33.4	10.5	17.8	99.8	35	0	28.565
May	104.2	122.4	42.4	91.1	136	110.1	164.1	323.4	115.3	83.6	78.8	103	149.6	176.9	123.3	72	107.6	160.4	10.9	107.3	119.12
Jun	97.6	87.2	1	149.1	157.5	89.3	152.6	100.3	81.4	88	137.1	153	186.3	146.8	144	229.5	157.1	189	85.9	74.5	125.36
Jul	237.4	350.5	265.6	247.4	177.8	146.4	202.7	235.9	274.8	244.3	125.5	235.5	184.8	232.8	184.3	245.7	268.9	255.7	181.2	254.3	227.575
Aug	155.1	250.8	298.9	356.1	398.7	286.1	192.9	366.5	216.7	281.9	352.4	294.3	267	355.7	470.4	144.7	298.4	244.9	210.2	407.2	292.445
Sep	172	190.9	149.7	98.3	209.3	68.1	156.9	75.9	242.4	199.7	203.7	112	173.5	192.3	236.8	268.2	177.7	312.6	200.1	238.2	183.915
Oct	126.2	5.8	1.7	35	11.4	64.9	12	30.7	6.2	18.8	166.1	32.9	59.9	64.9	71.4	78	63.3	0	128.7	62.5	52.02
Nov	0	0	0	0	0	0	0	0	2.4	0	0	0	0	0	0	0	0	0	0	0	0.12
Dec	0	0	0	0	0	0	2.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0.135
Average	81.78	89.33	63.28	81.5	92.875	65.533	73.85	104.2	81.32	79.708	91.39	82.48	85.83	99.9	105.3	87.96	90.9	105.2	73.17	95.33	86.5417

Appendix C.

Lithology of some part of the research area.



RAJI

PREUSSAG
Drilling Engineers Ltd.

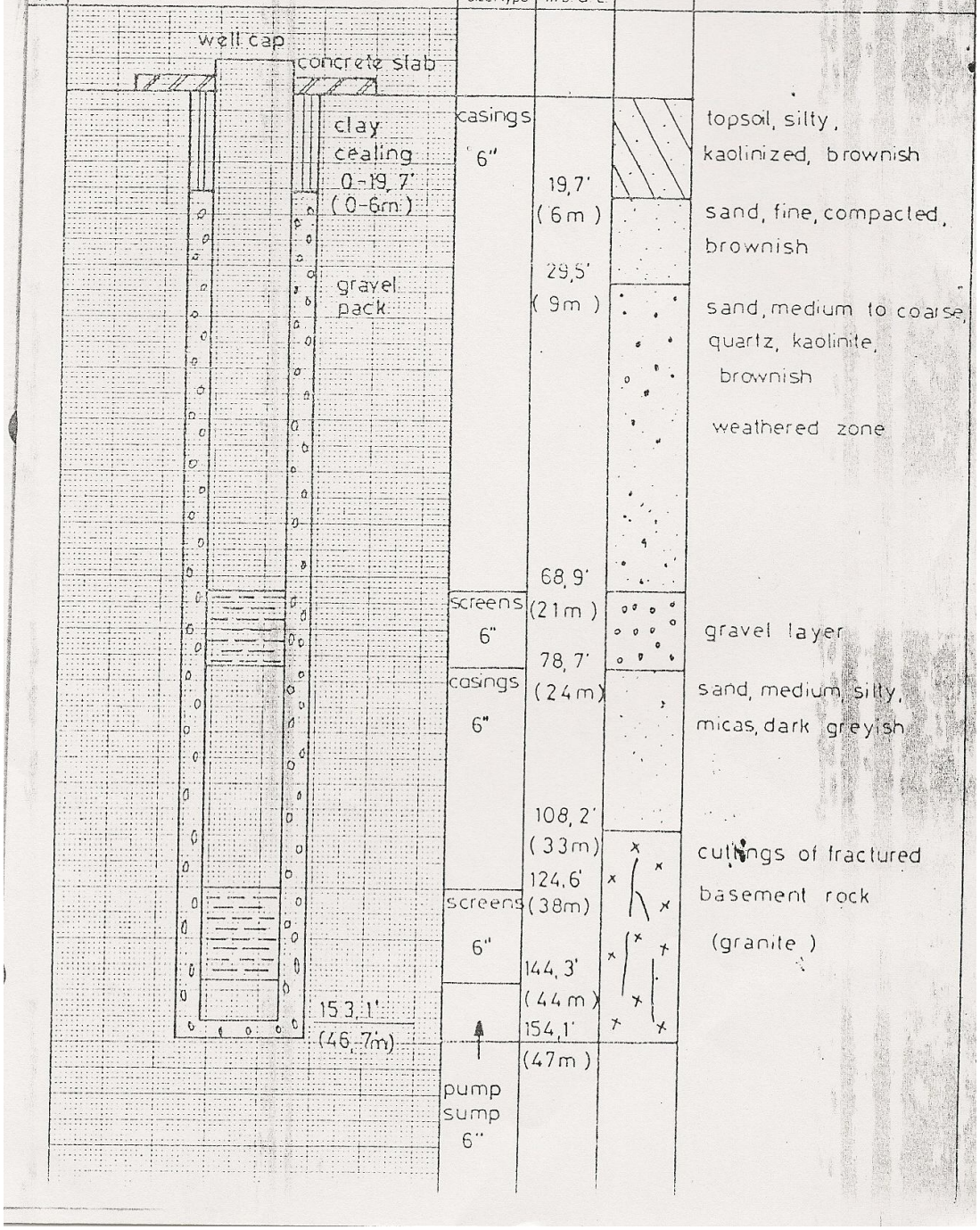
WELL LOGS

silt | sand | gravel | clay
mica schist | fractured basement | weathered basement | basement

WELL NO. ZA 96

Page

BIYE



RAJI

PREUSSAG
Drilling Engineers Ltd

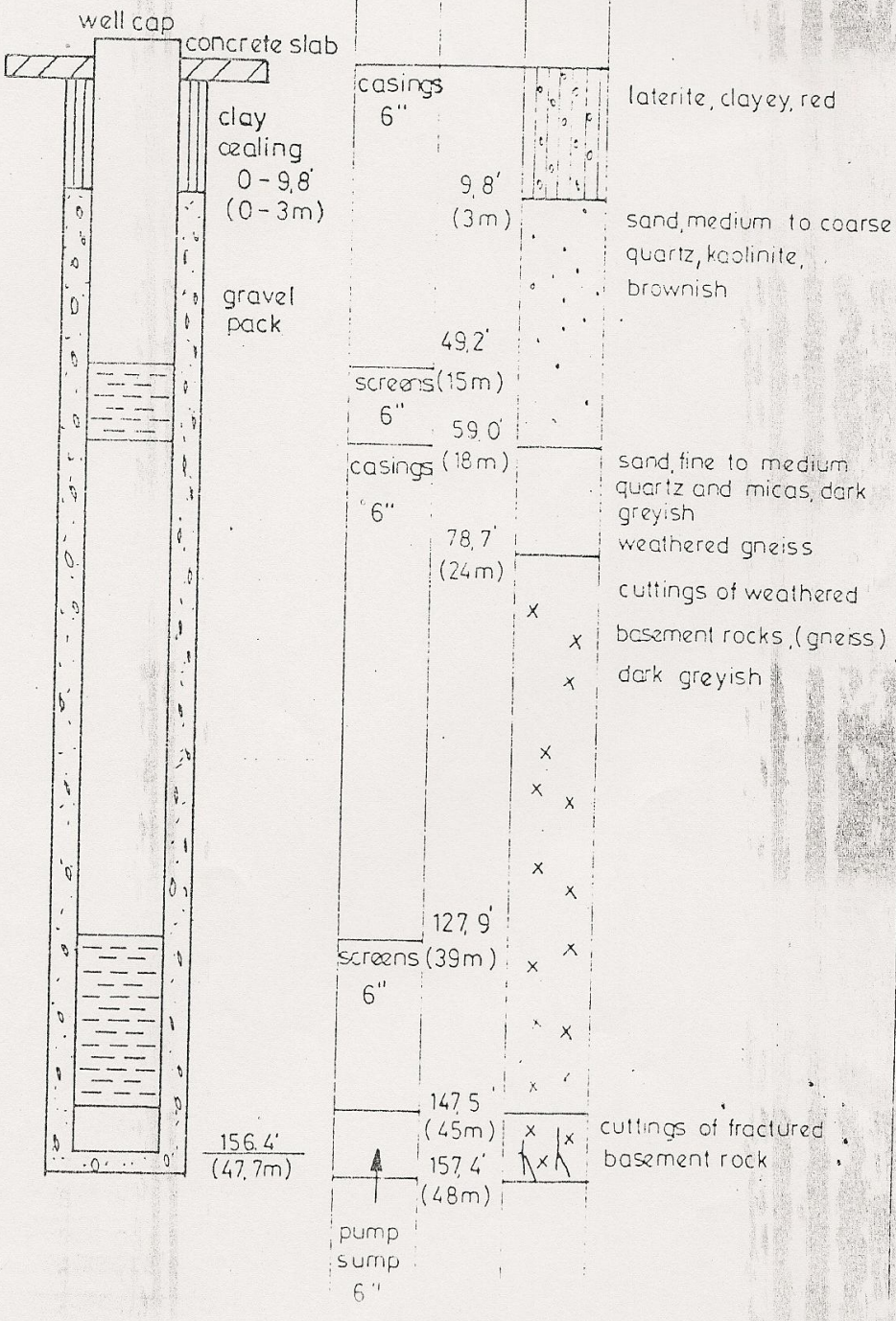
WELL LOGS

mica shists | fractured basement | weathered basement

WELL NO. 106

Page

Zabi



RAJI

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Drilling Engineers Ltd.

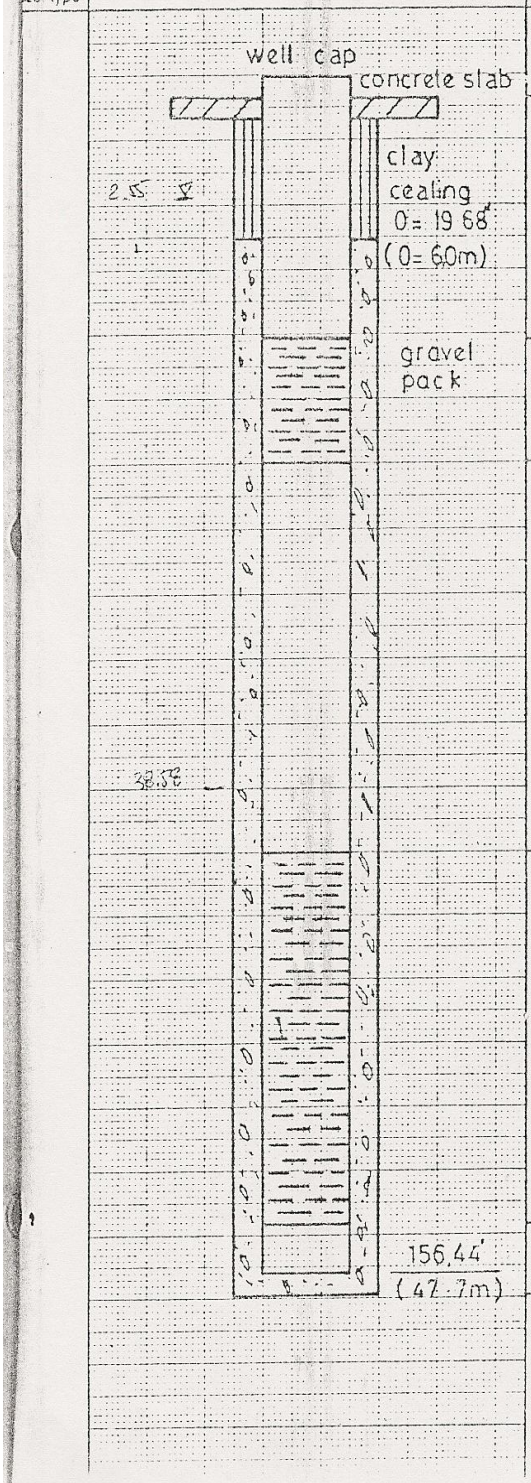
WELL LOGS

silt | sand | gravel | clay
mica shists | fractured basement | weathered basement | basement

WELL NO. 111

Page

Kallon Kura Bomo



RAJI

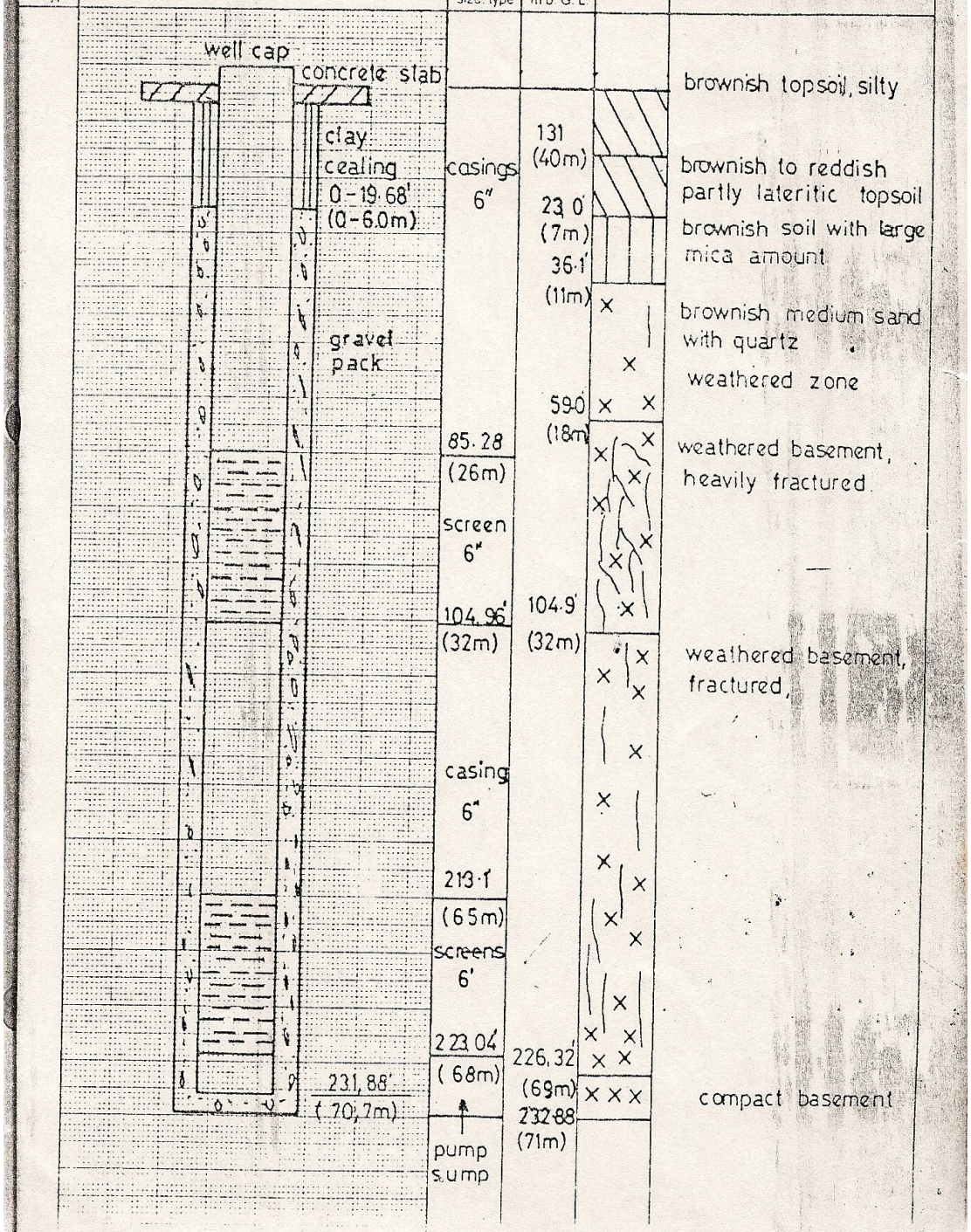
PREUSSAG
Drilling Engineers Ltd.

APPENDIX C
WELL LOGS

silt | sand | gravel | clay
mica shists | fractured basement | weathered basmement | casement

WELL NO. 110

Page
BOMO



Appendix D

The International FEP List (Version 1.0) in Classification Scheme Order.

0	**ASSESSMENT CONTEXT**
0.01	Assessment endpoints
0.02	Timescales of concern
0.03	Spatial domain of concern
0.04	Repository assumptions
0.05	Future human action assumptions
0.06	Future human behaviour (target group) assumptions
0.07	Dose response assumptions
0.08	Assessment purpose
0.09	Regulatory requirements and exclusions
0.10	Model and data issues
1	**EXTERNAL FACTORS**
1.1	**Repository Issues**
1.1.01	Site investigation
1.1.02	Design, repository
1.1.03	Construction, repository

1.1.04	Emplacement of wastes and backfilling
1.1.05	Closure, repository
1.1.06	Records and markers, repository
1.1.07	Waste allocation
1.1.08	Quality control
1.1.09	Schedule and planning
1.1.10	Administrative control, repository site
1.1.11	Monitoring of repository
1.1.12	Accidents and unplanned events
1.1.13	Retrievability
1.2	**Geological Processes and Effects**
1.2.01	Orogeny and related tectonic processes at plate boundaries
1.2.02	Anorogenic and within-plate tectonic processes (Deformation, elastic, plastic and brittle)
1.2.03	Seismicity
1.2.04	Volcanic and magmatic activity
1.2.05	Metamorphism
1.2.06	Hydrothermal activity
1.2.07	Erosion and sedimentation
1.2.08	Diagenesis and pedogenesis
1.2.09	Salt diapirism and dissolution
1.2.10	Hydrological/hydrogeological response to geological changes

1.3	**Climatic Processes and Effects**
1.3.01	Climate change, global
1.3.02	Climate change, regional and local
1.3.03	Sea level change
1.3.04	Periglacial effects
1.3.05	Glacial and ice sheet effects, local
1.3.06	Warm climate effects (tropical and desert)
1.3.07	Hydrological/hydrogeological response to climate changes
1.3.08	Ecological response to climate changes
1.3.09	Human response to climate changes
1.3.10	Other geomorphological changes
1.4	**Future Human Actions**
1.4.01	Human influences on climate
1.4.02	Motivation and knowledge issues (inadvertent/deliberate human actions)
1.4.03	Drilling activities (human intrusion)
1.4.04	Mining and other underground activities (human intrusion)
1.4.05	Un-intrusive site investigation
1.4.06	Surface excavations
1.4.07	Pollution
1.4.08	Site Development

1.4.09		Archaeology
1.4.10		Water management (wells, reservoirs, dams)
1.4.11		Social and institutional developments
1.4.12		Technological developments
1.4.13		Remedial actions
1.4.14		Explosions and crashes
2		**DISPOSAL SYSTEM DOMAIN: ENVIRONMENTAL FACTORS**
2.1		**Wastes and Engineered Features**
2.1.01		Inventory, radionuclide and other material
2.1.02		Waste form materials, characteristics and degradation processes
2.1.03		Container materials, characteristics and degradation processes
2.1.04		Buffer/backfill materials, characteristics and degradation processes
2.1.05		Engineered barriers system, characteristics and degradation processes
2.1.06		Other engineered features materials, characteristics and degradation processes
2.1.07		Mechanical processes and conditions (in wastes and EBS)
2.1.08		Hydraulic/hydrogeological processes and conditions (in wastes and EBS)
2.1.09		Chemical/geochemical processes and conditions (in wastes and EBS)
2.1.10		Biological/biochemical processes and conditions (in wastes and EBS)
2.1.11		Thermal processes and conditions (in wastes and EBS)
2.1.12		Gas sources and effects (in wastes and EBS)

2.1.13	Radiation effects (in wastes and EBS)
2.1.14	Nuclear criticality
2.1.15	Extraneous materials
2.2	**Geological Environment**
2.2.01	Disturbed zone, host lithology
2.2.02	Host lithology
2.2.03	Lithological units, other
2.2.04	Discontinuities, large scale (in geosphere)
2.2.05	Contaminant transport path characteristics (in geosphere)
2.2.06	Mechanical processes and conditions (in geosphere)
2.2.07	Hydraulic/hydrogeological processes and conditions (in geosphere)
2.2.08	Chemical/geochemical processes and conditions (in geosphere)
2.2.09	Biological/biochemical processes and conditions (in geosphere)
2.2.10	Thermal processes and conditions (in geosphere)
2.2.11	Gas sources and effects (in geosphere)
2.2.12	Undetected features (in geosphere)
2.2.13	Geological resources
2.3	**Surface Environment**
2.3.01	Topography and morphology
2.3.02	Soil and sediment
2.3.03	Aquifers and water-bearing features, near surface

2.3.04	Lakes, rivers, streams and springs
2.3.05	Coastal features
2.3.06	Marine features
2.3.07	Atmosphere
2.3.08	Vegetation
2.3.09	Animal populations
2.3.10	Meteorology
2.3.11	Hydrological regime and water balance (near-surface)
2.3.12	Erosion and deposition
2.3.13	Ecological/biological/microbial systems
2.3.14	Animal/plant intrusion leading to vault/trench disruption
2.4	**Human Behaviour**
2.4.01	Human characteristics (physiology, metabolism)
2.4.02	Adults, children, infants and other variations
2.4.03	Diet and fluid intake
2.4.04	Habits (non-diet-related behaviour)
2.4.05	Community characteristics
2.4.06	Food and water processing and preparation
2.4.07	Dwellings
2.4.08	Wild and natural land and water use
2.4.09	Rural and agricultural land and water use (incl. fisheries)
2.4.10	Urban and industrial land and water use
2.4.11	Leisure and other uses of environment

3	**RADIONUCLIDE/CONTAMINANT FACTORS**
3.1	**Contaminant Characteristics**
3.1.01	Radioactive decay and in-growth
3.1.02	Chemical/organic toxin stability
3.1.03	Inorganic solids/solutes
3.1.04	Volatiles and potential for volatility
3.1.05	Organics and potential for organic forms
3.1.06	Noble gases
3.2	**Contaminant Release/Migration Factors**
3.2.01	Dissolution, precipitation and crystallisation, contaminant
3.2.02	Speciation and solubility, contaminant
3.2.03	Sorption/desorption processes, contaminant
3.2.04	Colloids, contaminant interactions and transport with
3.2.05	Chemical/complexing agents, effects on contaminant speciation/transport
3.2.06	Microbial/biological/plant-mediated processes, contaminant
3.2.07	Water-mediated transport of contaminants
3.2.08	Solid-mediated transport of contaminants
3.2.09	Gas-mediated transport of contaminants
3.2.10	Atmospheric transport of contaminants

3.2.11	Animal, plant and microbe mediated transport of contaminants
3.2.12	Human-action-mediated transport of contaminants
3.2.13	Foodchains, uptake of contaminants in
3.3	**Exposure Factors**
3.3.01	Drinking water, foodstuffs and drugs, contaminant concentrations in
3.3.02	Environmental media, contaminant concentrations in
3.3.03	Non-food products, contaminant concentrations in
3.3.04	Exposure modes
3.3.05	Dosimetry
3.3.06	Radiological toxicity/effects
3.3.07	Non-radiological toxicity/effects
3.3.08	Radon and radon daughter exposure

Appendix E

ISAM FEP List Screened for the Borehole Case

NO	*SCENARIO NAME*	*DESCRIPTION*	*JUSTIFICATION FOR EXCLUDING*
0	***ASSESSMENT CONTEXT***		
0.01	*Impacts of concern*	*yes.*	
0.02	*Timescales of concern*	*yes.*	
0.03	*Spatial domain of concern*	*yes.*	
0.04	*Repository assumptions*	*yes.*	
0.05	*Future human action assumptions*	*yes.*	
0.06	*Future human behaviour (target group) assumptions*	*yes.*	
0.07	*Dose response assumptions-*	*yes.*	
0.08	*Aims of the assessment- yes.*	*yes.*	
0.09	*Regulatory requirements and exclusions-*	*yes.*	
0.10	*Model and data issues-*	*yes.*	
1	**EXTERNAL FACTORS**		
1.1	***Repository Issues***		
1.1.01	*Site investigation –*	*Yes,*	
1.1.02	*Excavation/construction –*	*Yes,*	
1.1.03	*Emplacement of wastes and backfilling –*	*Yes,*	
1.1.04	*Closure e.g. capping –*	*Yes.*	
1.1.05	*Records and markers, repository*	*Yes.*	
1.1.06	*Waste allocation*	*Yes*	*fixed as LLW.*
1.1.07	*Repository design –*	*Yes.*	
1.1.08	*Quality control*	*Yes,*	*e.g. could have poor quality concrete which effects performance of the facility.*
1.1.09	*Schedule and planning –*	*Yes,*	*need to consider 30 year operational period.*
1.1.10	*Administrative control, repository site –*	*Yes,*	*but only for 30 years*
1.1.11	*Monitoring of repository –*	*no,*	*no impact on performance.*
1.1.12	*Accidents and unplanned events –*	*Yes,*	*but not considered in this scenrio.*
1.1.13	*Retrievability –,*	*No,*	*assumed not to be required.*
1.2	***Geological Processes and Effects***		
1.2.01	*Tectonic movements and orogeny*	*No,*	*given the location of*

			the site, especially over10,000years or even 1 million years.
1.2.02	*Deformation, elastic, plastic or brittle*	*no,*	*as 1.2.01*
1.2.03	*Seismicity*	*no,*	*seismicity will not have a direct effect unless there is an active fault running through the borehole. Effect of seismic event can be considered in 1.2.10 if required*
1.2.04	*Volcanic and magmatic activity –*	*no,*	*as 1.201.*
1.2.05	*Metamorphism –*	*no,*	*as 1.201.*
1.2.06	*Hydrothermal activity*	*no,*	*as 1.201.*
1.2.07	*Erosion and sedimentation*	*no,*	*geomorphological evidence suggests that area is very stable.*
1.2.08	*Diagenesis –*	*no,*	*not relevant.*
1.2.09	*Salt diapirism and dissolution –*	*no,*	*not relevant.*
1.2.10	*Hydrological/hydrogeological response to geological changes –*	*yes,*	*could have seismically driven groundwater flow.*
1.3	***Climatic Processes and Effects***		
1.3.01	*Climate change, global –*	*yes.*	
1.3.02	*Climate change, regional and local*	*yes.*	
1.3.03	*Sea level change –*	*no,*	*too far from sea.*
1.3.04	*Periglacial effects –*	*no,*	*not even with climate change.*
1.3.05	*Glacial and ice sheet effects, local –*	*no,*	*see 1.3.04*
1.3.06	*Warm climate effects (tropical and desert) –*	*yes.*	
1.3.07	*Hydrological/hydrogeological response to climate changes –*	*yes.*	
1.3.08	*Ecological response to climate changes –*	*yes*	*see 1.3.02 and 1.3.07*
1.3.09	*Human response to climate changes*	*no*	*given the assessment context that there is no change in human activities. This test case is not sensitive to population changes since individual doses are considered. Discussion as to whether the "no"*

			should be "yes" especially given that have got ecological change. No fundamental change in habits, but perhaps allow changes in magnitude. Overall decide to change to YES, but only in so far as it changes the amounts of food ingested. No fundamental change in habit.
1.3.10	*Other geomorphological changes*	*no,*	*the region is stable from the past record.*
1.4	***Future Human Actions***		
1.4.01	*Human influences on climate*	*no,*	*given the limited impact of climate change at the site.*
1.4.02	*Motivation and knowledge issues (inadvertent/deliberate human actions)*	*yes.*	
1.4.03	*Un-intrusive site investigation*	*No,*	*not relevant for the borehole concept.*
1.4.04	*Drilling activities (human intrusion)*	*No,*	*for farmer scenario other than drilling the well in the first place.*
1.4.05	*Mining and other underground activities (human intrusion)*	*yes.*	
1.4.06	*Surface environment, human activities*	*no,*	*below the depth of normal intrusion.*
1.4.06. 01	*Surface Excavations*	*no,*	*below the depth of normal intrusion.*
1.4.06. 02	*Pollution*	*no*	*significant impact envisaged.*
1.4.06. 03	*Site Development*	*no,*	*below the depth of normal intrusion.*
1.4.06. 04	*Archaeology*	*no,*	*below the depth of normal intrusion.*
1.4.07	*Water management (wells, reservoirs, dams) –*	*yes.*	
1.4.08	*Social and institutional developments –*	*yes.*	
1.4.09	*Technological developments –*	*no,*	*need to distinguish social and institutional*

			developments from technological developments on the basis of the assessment context.
1.4.10	*Remedial actions*	*no,*	*cautious to assume no remediation.*
1.4.11	*Explosions and crashes*	*no,*	*very low probability.*
1.5	***Other***		
1.5.01	*Meteorite impact*	*no,*	*very low probability, non-radiological consequences significantly greater. No difference between meteorite impact on store and disposal facility.*
1.5.02	*Miscellaneous and FEPs of uncertain relevance*	*no,*	*nothing thought of at present.*
2	***DISPOSAL SYSTEM DOMAIN: ENVIRONMENTAL FACTORS***		
2.1	***Wastes and Engineered Features***		
2.1.01	*Inventory, radionuclide and other material –*	*yes.*	
2.1.02	*Waste form materials and characteristics –*	*yes.*	
2.1.03	*Container materials and characteristics –*	*yes.*	
2.1.04	*Buffer/backfill materials and characteristics –*	*yes.*	
2.1.05	*Engineered barriers system e.g. caps*	*yes.*	
2.1.06	*Other engineered features materials and characteristics*	*yes.*	*specific in the system description.*
2.1.07	*Mechanical processes and conditions (in wastes and EBS)*	*yes.*	
2.1.08	*Hydraulic/hydrogeological processes and conditions (in wastes and EBS)–*	*yes.*	
2.1.09	*Chemical/geochemical processes and conditions (in wastes and EBS)*	*yes.*	
2.1.10	*Biological/biochemical processes and conditions (in wastes and EBS)*	*yes.*	
2.1.11	*Thermal processes and conditions (in wastes and EBS)*	*yes,*	*due to diurnal temperate variation.*
2.1.12	*Gas sources and effects (in wastes and EBS)*	*yes*	

2.1.13	*Radiation effects (in wastes and EBS)*	*yes,*	*sufficiently high – will need to do some hand calculations to check.*
2.1.14	*Nuclear criticality*	*no,*	*no sufficient activity.*
2.1.15	*Extraneous materials*	*No,*	*need to explain this FEP in the generic list. No, given the current stage of the assessment.*
2.2	***Geological Environment***		
2.2.01	*Excavation disturbed zone, host lithology*	*yes.*	
2.2.02	*Unsaturated lithology*	*yes.*	
2.2.03	*Saturated lithology*	*yes.*	
2.2.04	*Discontinuities, large scale (in geosphere)*	*yes.*	
2.2.05	*Contaminant transport path characteristics (in geosphere)*	*yes.*	
2.2.06	*Mechanical processes and conditions (in geosphere)*	*no,*	*not relevant for near surface borehole.*
2.2.07	*Hydraulic/hydrogeological processes and conditions (in geosphere)*	*yes.*	
2.2.08	*Chemical/geochemical processes and conditions (in geosphere)*	*yes.*	
2.2.09	*Biological/biochemical processes and conditions (in geosphere)*	*yes.*	
2.2.10	*Thermal processes and conditions (in geosphere)*	*no*	*not considered to be relevant for the geosphere (note that we are considering it in the nearfield).*
2.2.11	*Gas sources and effects (in geosphere)*	*yes,*	*because radon gas impact may be considered.*
2.2.12	*Undetected features (in geosphere)*	*yes,*	*could have undetected faults and fractures.*
2.2.13	*Geological resources*	*no*	*for farmer scenario.*
2.3	***Surface Environment***		
2.3.01	*Topography and morphology*	*yes.*	
2.3.02	*Soil and sediment*	*yes*	
2.3.03	*Aquifers and water-bearing features, near surface*	*yes.*	
2.3.04	*Lakes, rivers, streams and springs*	*No,*	*assume doses will be lower than water borehole.*
2.3.05	*Coastal features*	*no,*	*see site context.*

2.3.06	*Marine features*	*no,*	*see site context.*
2.3.07	*Atmosphere*	*yes.*	
2.3.08	*Vegetation*	*yes.*	
2.3.09	*Animal populations*	*yes.*	
2.3.10	*Meteorology*	*yes.*	
2.3.11	*Hydrological regime and water balance (near-surface)*	*yes.*	
2.3.12	*Erosion and deposition*	*yes*	*but note no net erosion/deposition but allow for resuspension and deposition.*
2.3.13	*Ecological/biological/microbial systems*	*yes*	
2.3.14	*Animal/plant intrusion*	*yes*	
2.4	***Human Behaviour***		
2.4.01	*Human characteristics (physiology, metabolism)*	*yes*	
2.4.02	*Adults, children, infants and other variations*	*yes*	
2.4.03	*Diet and fluid intake*	*yes*	
2.4.04	*Habits (non-diet-related behaviour)*	*yes*	
2.4.05	*Community characteristics*	*Yes*	
2.4.06	*Food and water processing and preparation*	*Yes*	
2.4.07	*Dwellings*	*Yes*	
2.4.08	*Wild and natural land and water use*	*yes*	
2.4.09	*Rural and agricultural land and water use (incl. Fisheries)*	*yes*	
2.4.10	*Urban and industrial land and water use*	*yes*	
2.4.11	*Leisure and other uses of environment*	*maybe yes*	*(bounded by site dweller scenario)*
3	***RADIONUCLIDE/CONTAMINANT FACTORS***		
3.1	***Contaminant Characteristics***		
3.1.01	*Radioactive decay and in-growth*	*yes*	
3.1.02	*Chemical/organic toxin stability*	*no,*	*given the scope of the research (only interested in radioactive contaminants)*
3.1.03	*Inorganic solids/solutes –*	*no,*	*3.1.02*
3.1.04	*Volatiles and potential for volatility*	*yes,*	*considering radon.*
3.1.05	*Organics and potential for organic forms*	*no,*	*3.1.02*
3.1.06	*Noble gases*	*yes,*	*3.1.04*

3.2	***Contaminant Release/Migration Factors***		
3.2.01	*Dissolution, precipitation and crystallisation, contaminant*	*yes*	
3.2.02	*Speciation and solubility, contaminant*	*yes*	
3.2.03	*Sorption/desorption processes, contaminant*	*yes*	
3.2.04	*Colloids, contaminant interactions and transport*	*maybe,*	*decided not to consider it as an explicit process in mathematical models, could consider via K_d sampling – ensure low K_d value for Pu for lower limit. It is recognized that colloids can exist.*
3.2.05	chemical/complexing agents, effects on contaminant speciation/transport	–yes	
3.2.06	*Microbial/biological/plant-mediated processes, contaminant*	*yes*	
3.2.07	*Transport of contaminants through water pathway*	*yes*	
3.2.08	*Transport of contaminants through solid releases*	*yes*	
3.2.09	*Transport of contaminants through gas releases*	*yes*	
3.2.10	*Atmospheric transport of contaminants*	*yes*	
3.2.11	*Animal, plant and microbe mediated transport of contaminants*	*yes*	
3.2.12	*Human-action-mediated transport of contaminants*	*yes*	
3.2.13	*Foodchains, uptake of contaminants in*	*yes*	
3.3	***Exposure Factors***		
3.3.01	*Drinking water, foodstuffs and drugs, contaminant concentrations in*	*yes,*	*it was thought that the FEP needed to be clarified.*
3.3.02	*Environmental media, contaminant concentrations in*	*yes*	
3.3.03	*Non-food products, contaminant concentrations in*	*maybe*	
3.3.04	*Exposure modes*	*yes*	
3.3.05	*Dosimetry*	*yes*	
3.3.06	*Radiological toxicity/effects –*	*yes*	

3.3.07	*Non-radiological toxicity/effects –*	*no,*	*not considering on the basis of the assessment context*
3.3.08	*Radon and radon daughter exposure*	*yes*	

Appendix F:

ZARIA MODEL

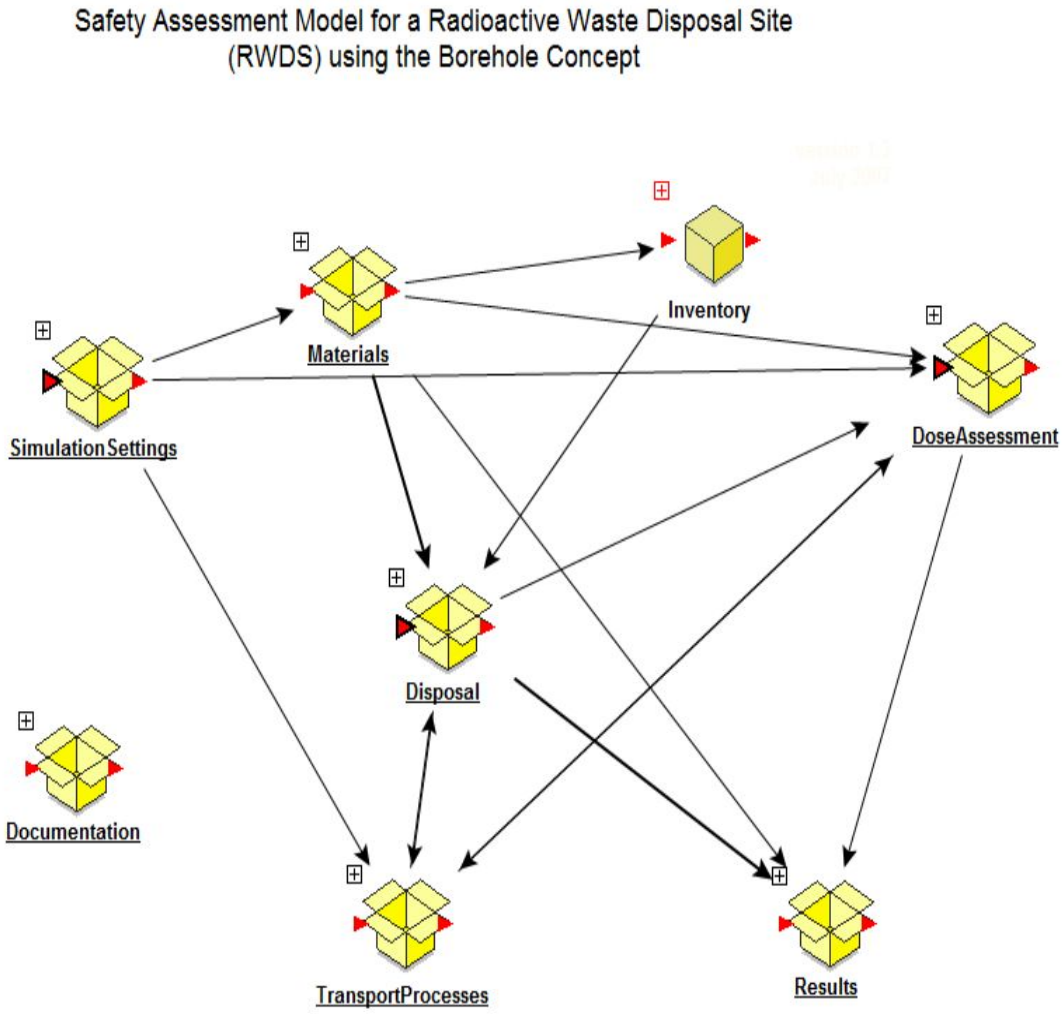


Figure. F-1 Safety assessment Model for the disposal facility.

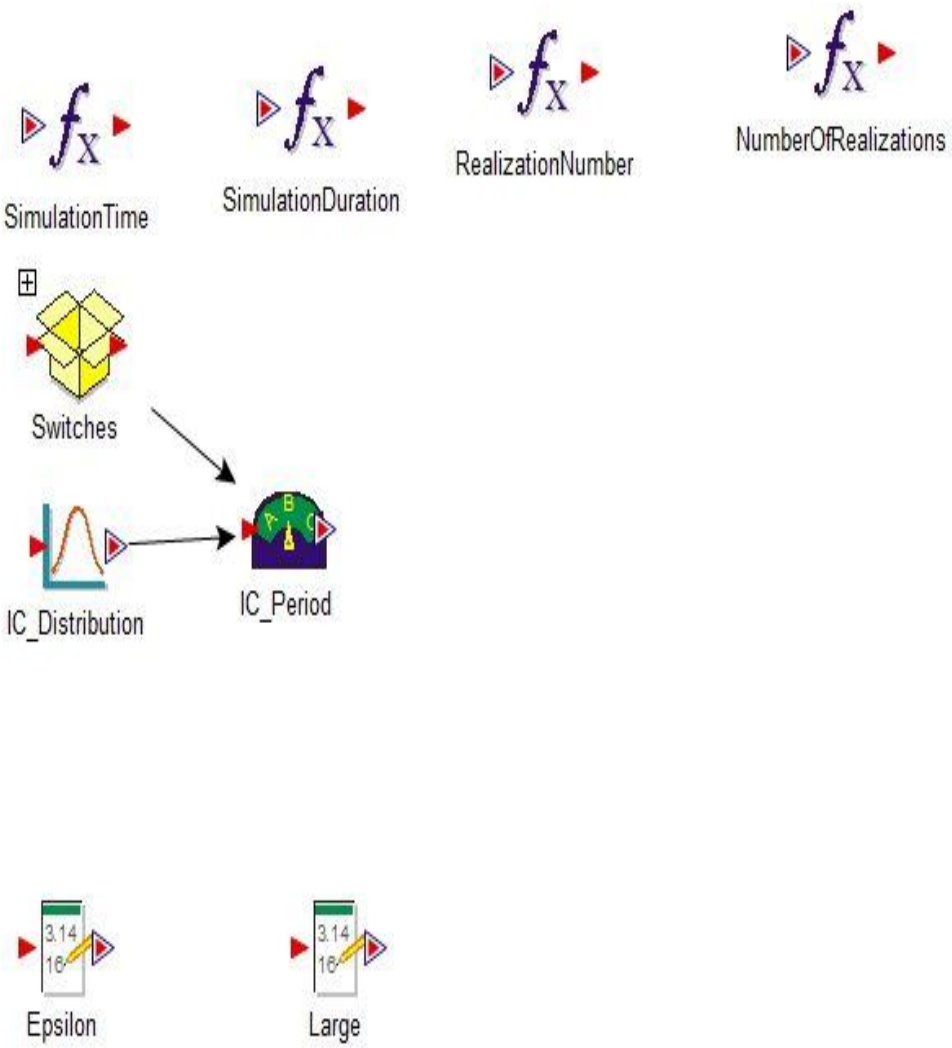


Figure. F-2. **Simulation Settings control.**

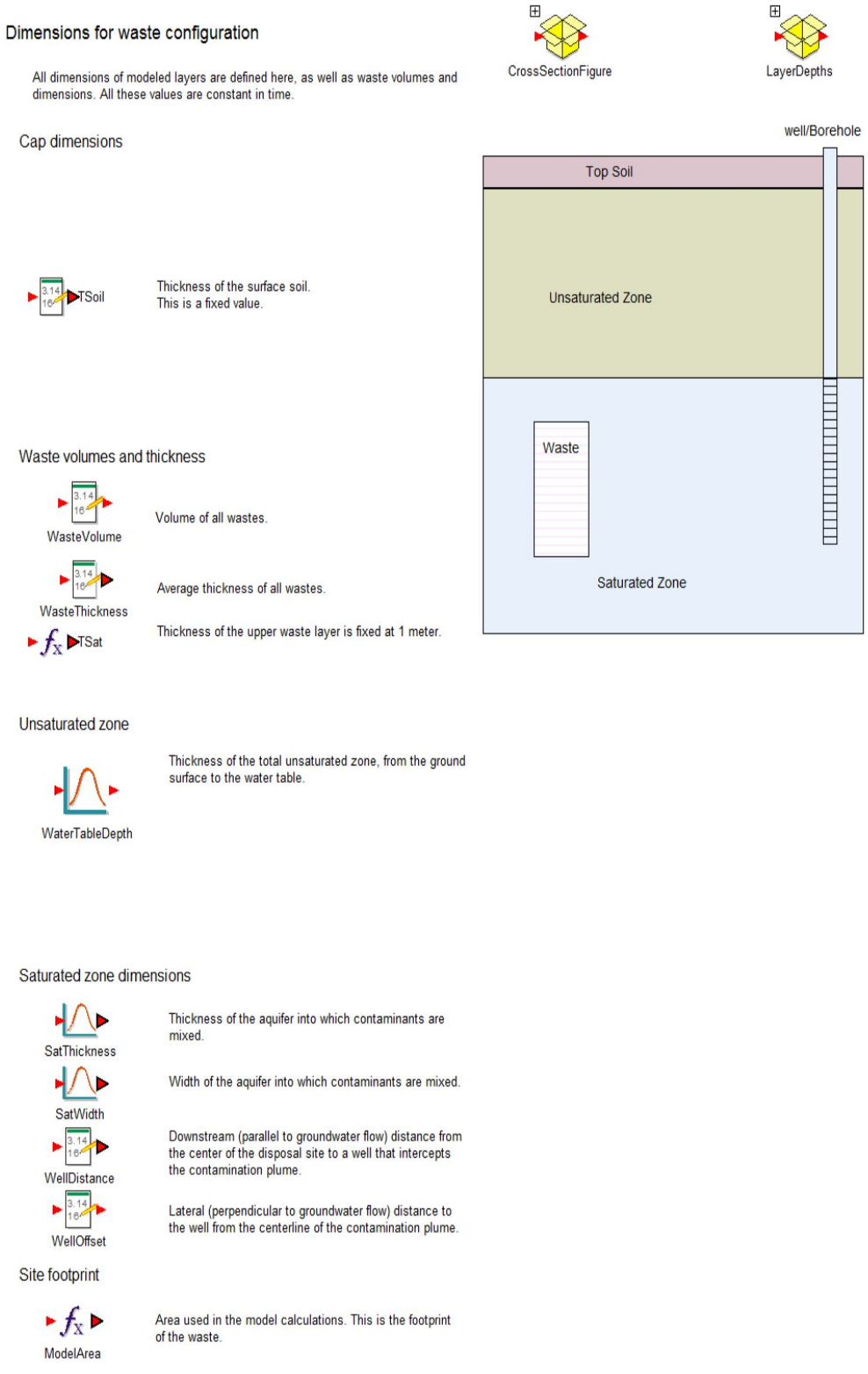


Figure. F-3 the disposal system construction.

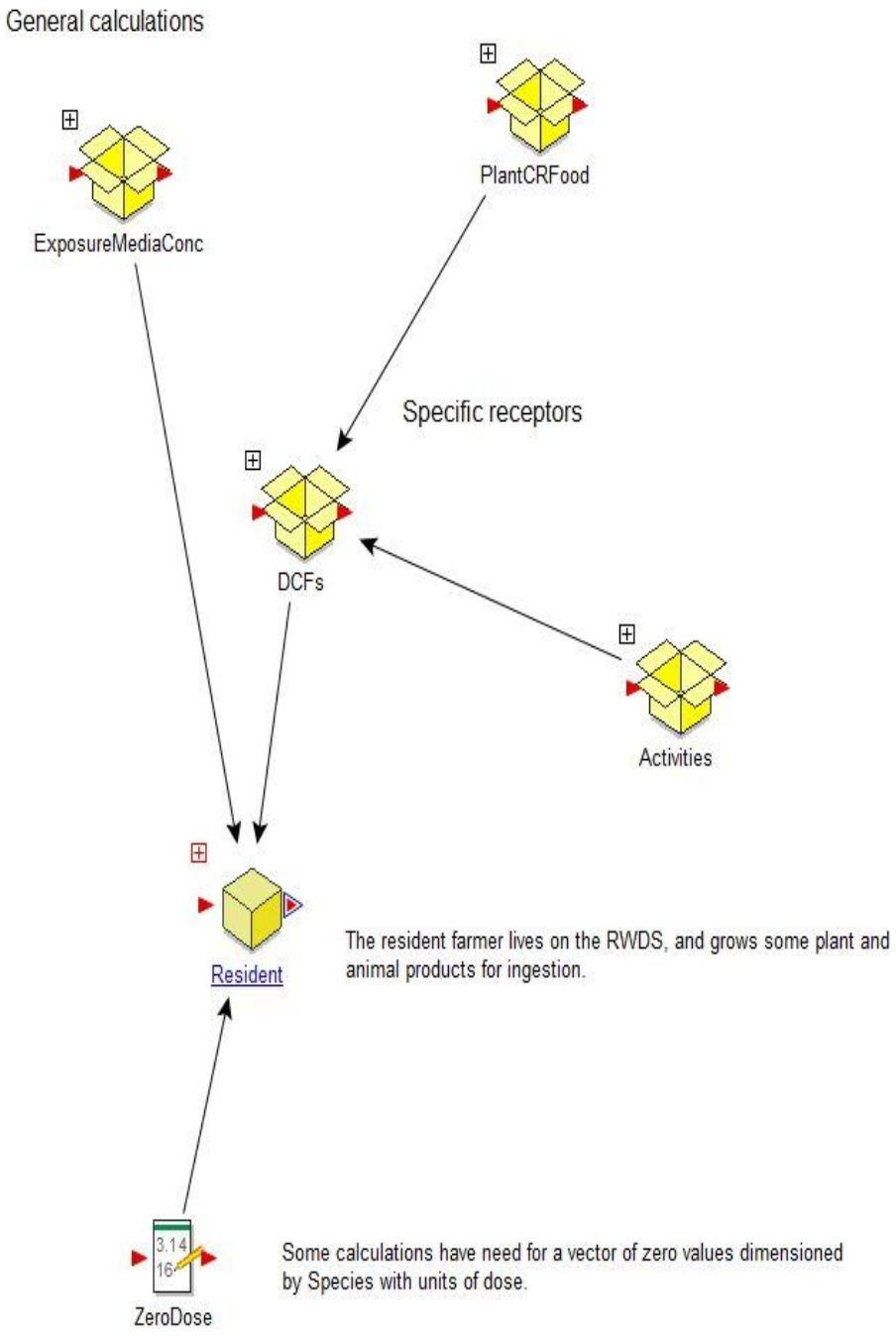


Figure. F-4 Dose assessment Container.

Exposure medium concentrations

The Resident is exposed to local surface soils and well water. The soil concentrations are dependent on the area throughout which the surface soils are homogenized.

Surface soils at the RWDS



This is turned into a mass concentration by dividing by the soil bulk density:



Well water



Aqueous concentration of radionuclides in well water.

Figure. F-5 Exposure Medium Concentration.

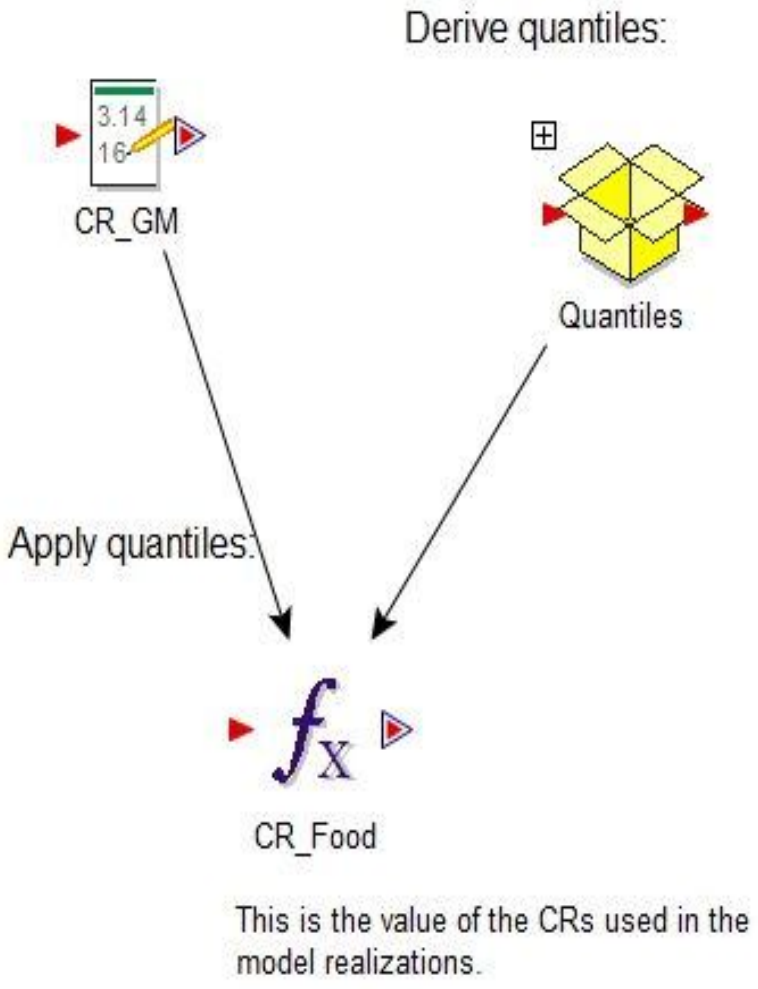


Figure. F-6. Concentration Ration for Plant Ingestion.

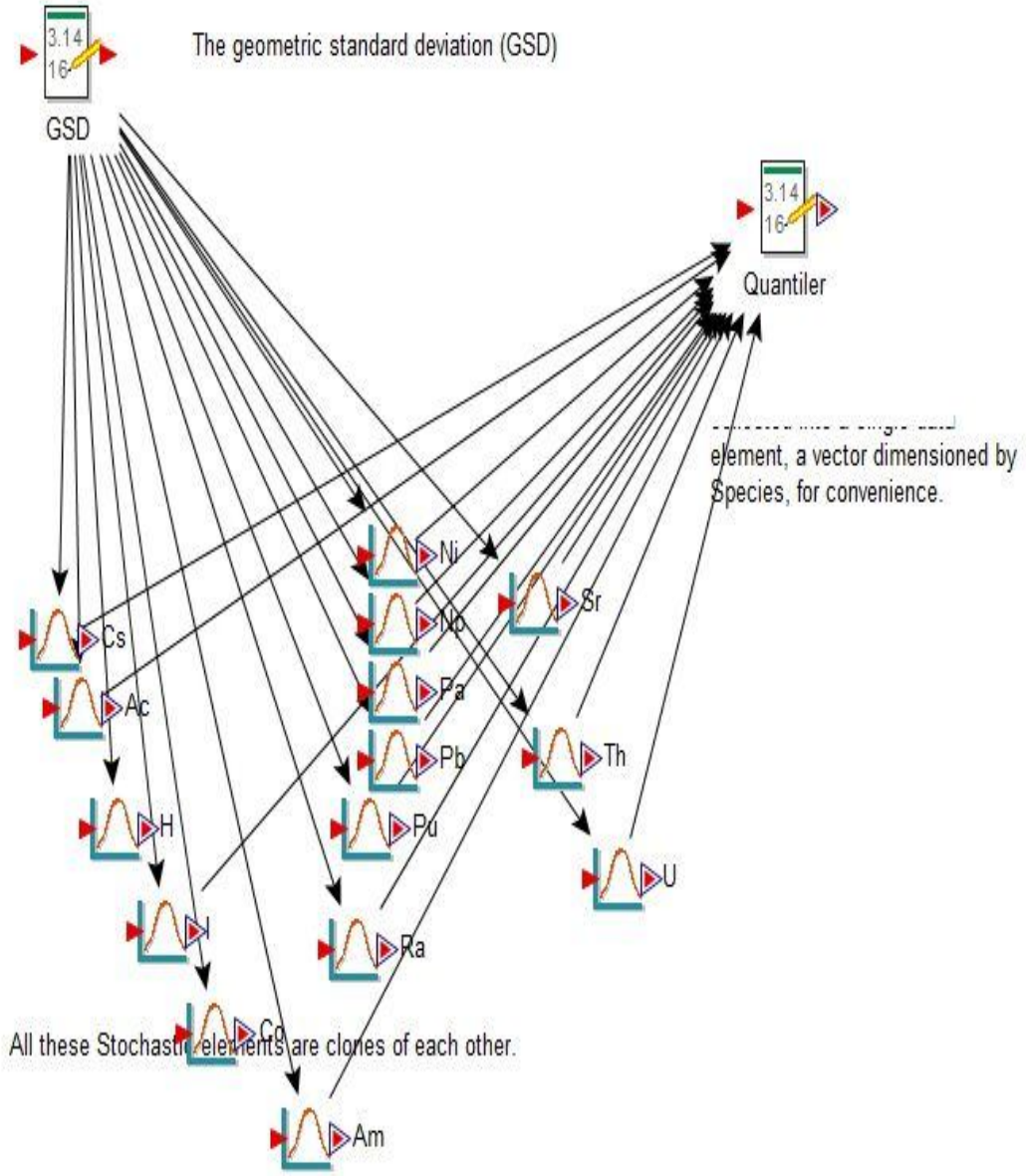


Figure. F-7. Quantile generations for the Plant CRs

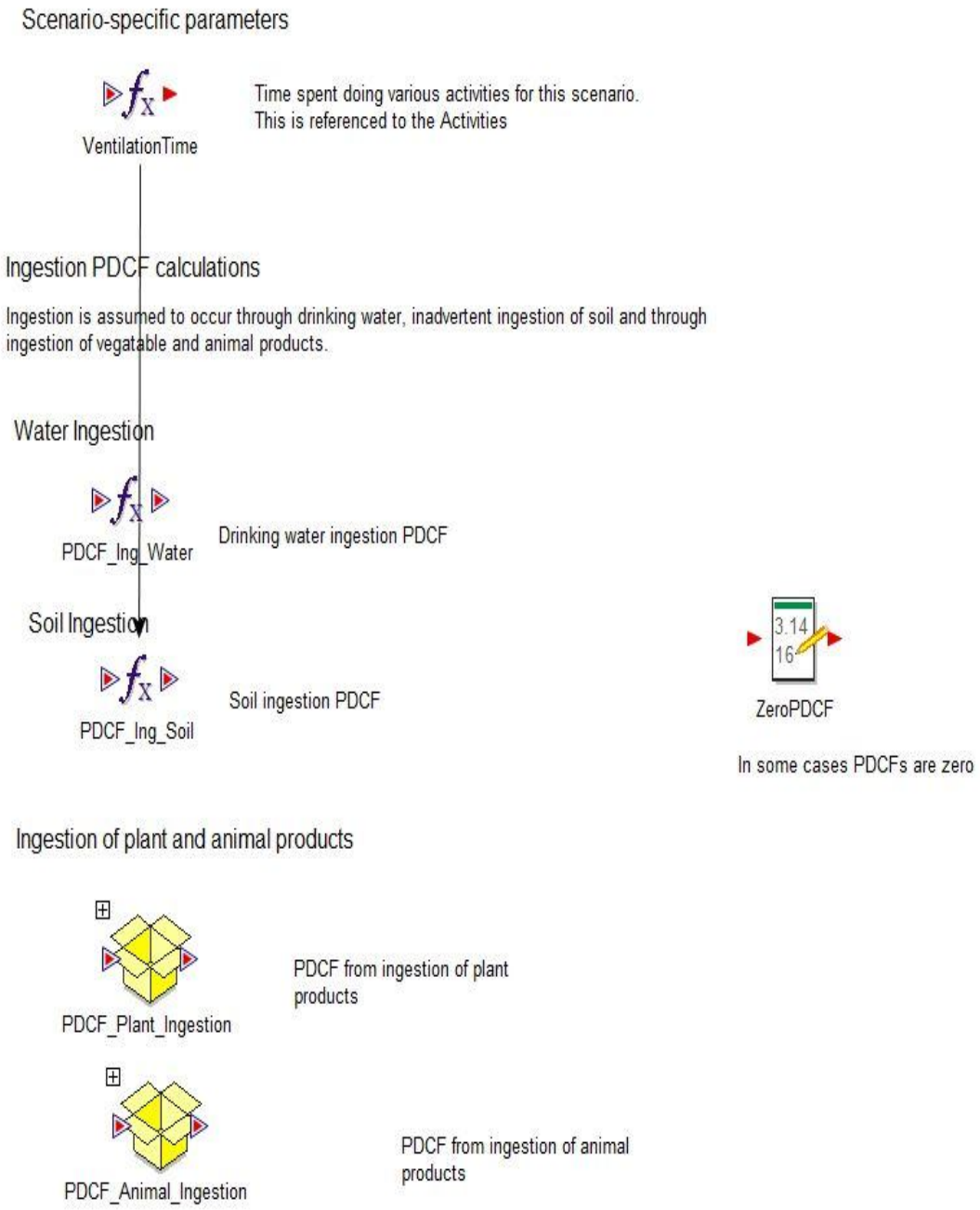


Figure. F-8. Calculation of Pathways Dose Conversion Factors

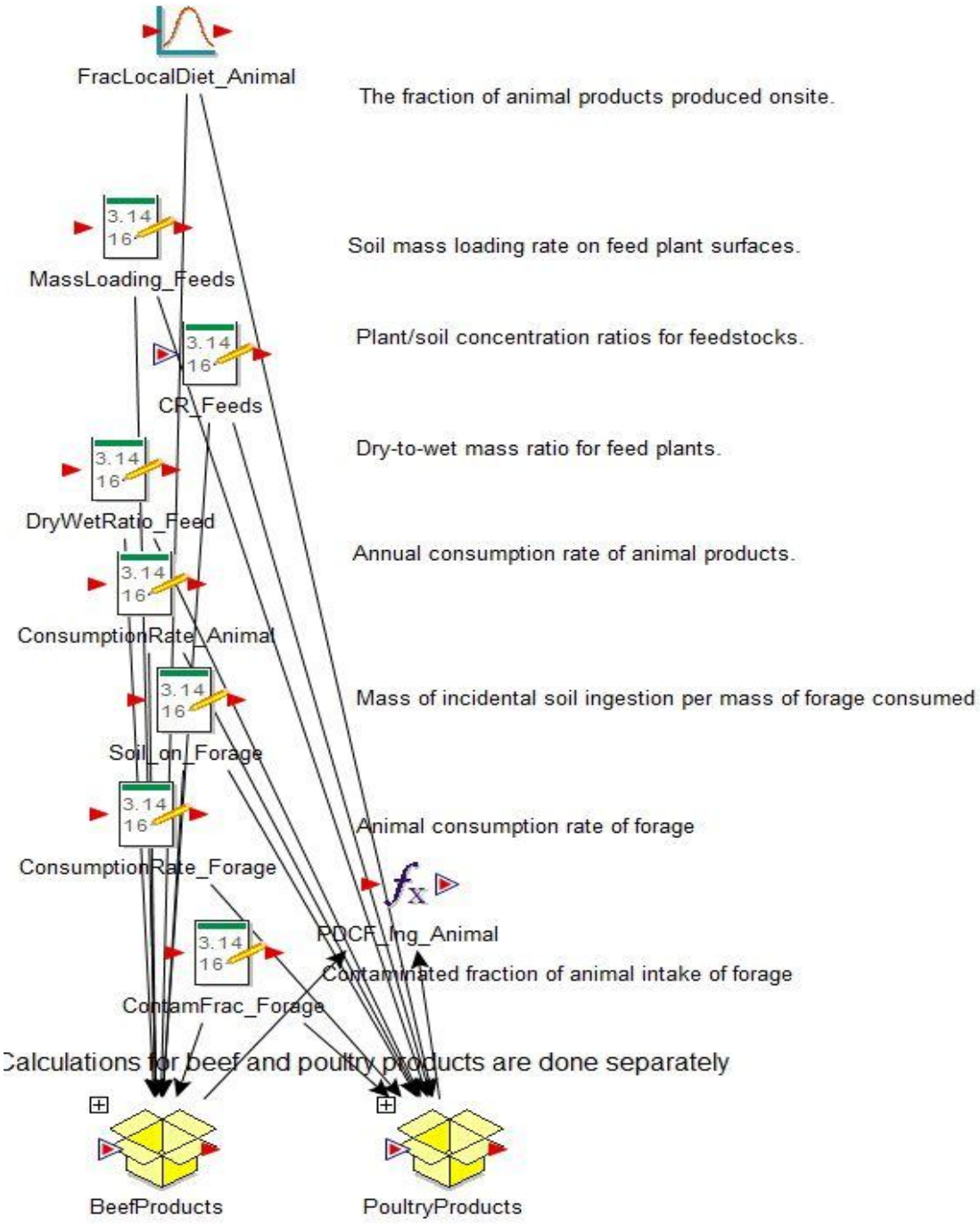


Figure. F-9. PCDF for Ingestion of Animal product.

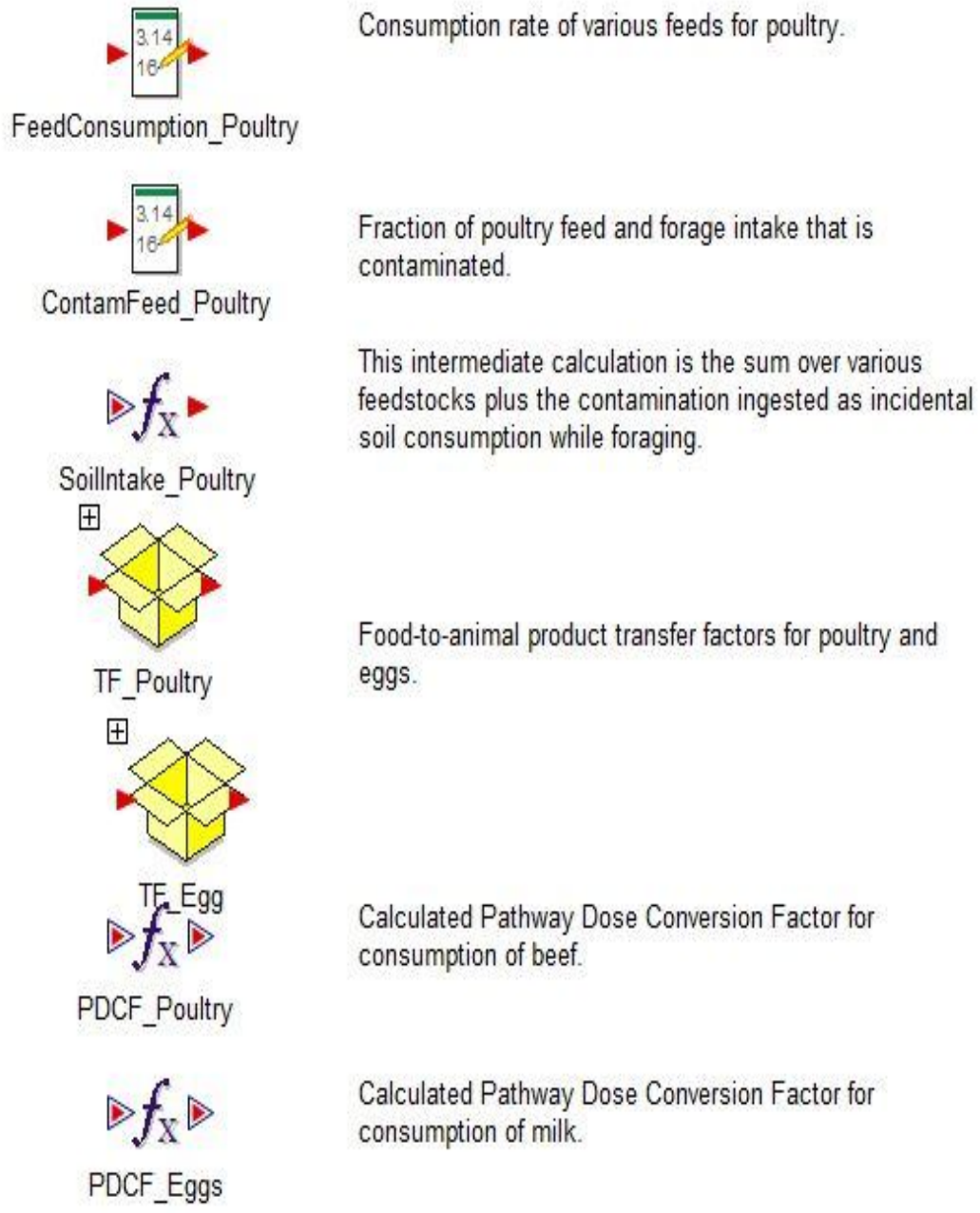


Figure F-10. PDCF for Poultry products

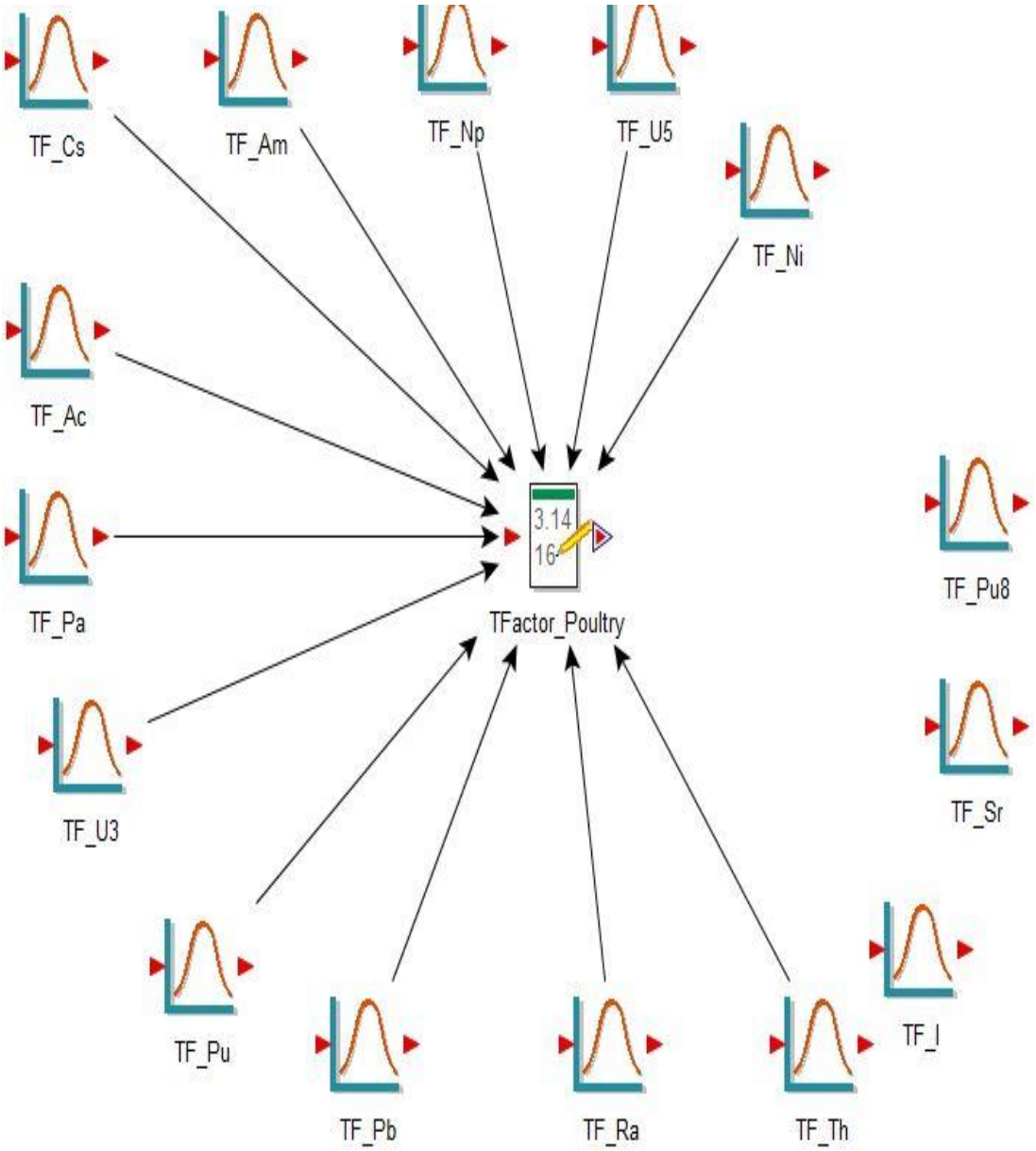


Figure F-11. Transfer Factor for Poultry

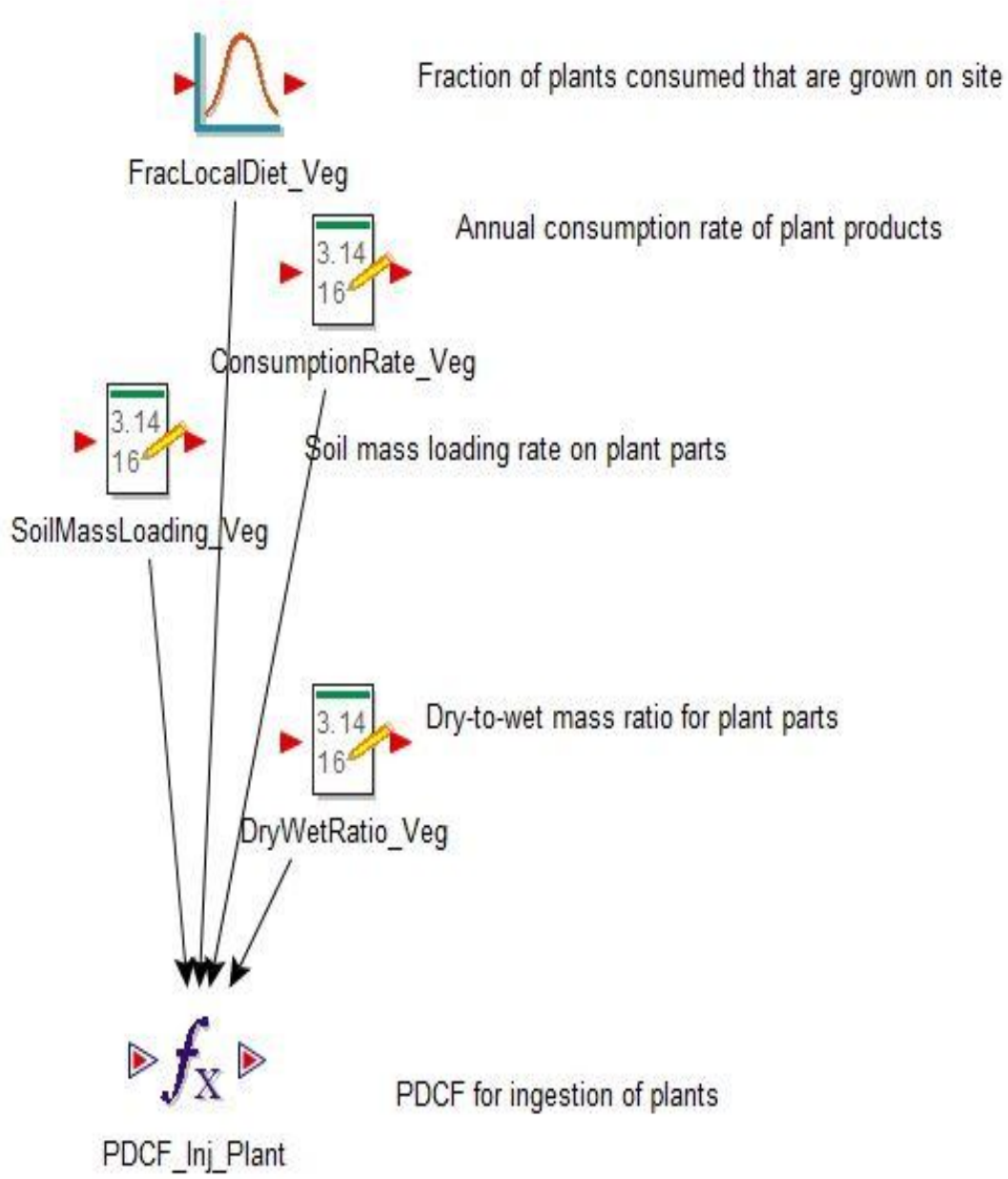
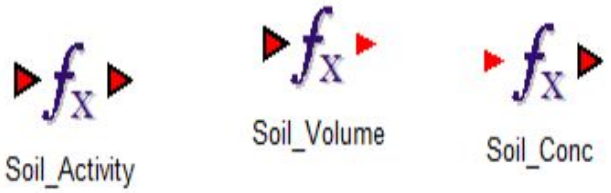


Figure F-12. PDCF for Plant ingestion.

Exposure medium concentrations

The Resident is exposed to local surface soils and well water. The soil concentrations are dependent on the area throughout which the surface soils are homogenized.

Surface soils at the RWDS



This is turned into a mass concentration by dividing by the soil bulk density:



Well water



Aqueous concentration of radionuclides in well water.

Figure F-13. Exposure medium concentrations

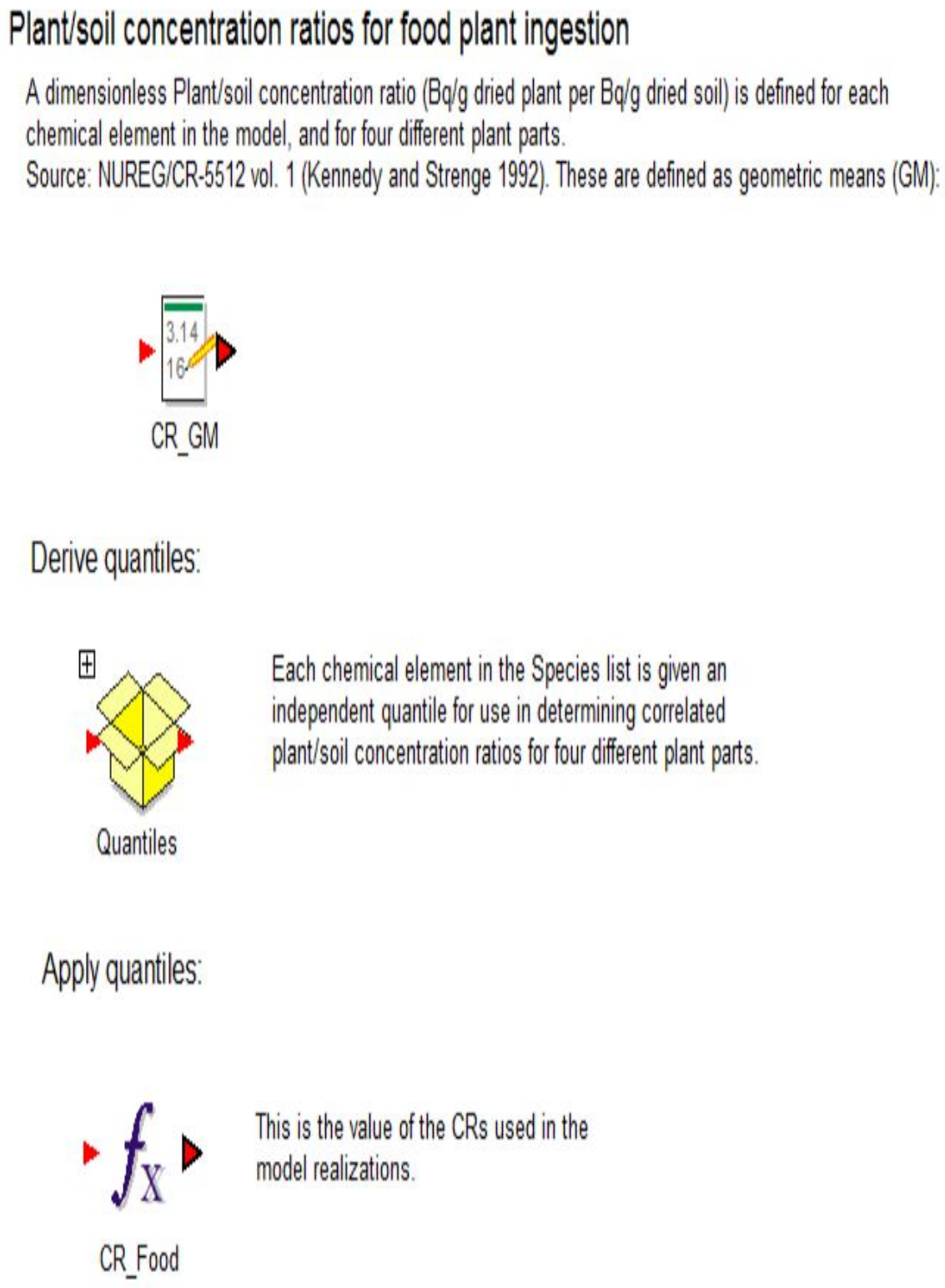
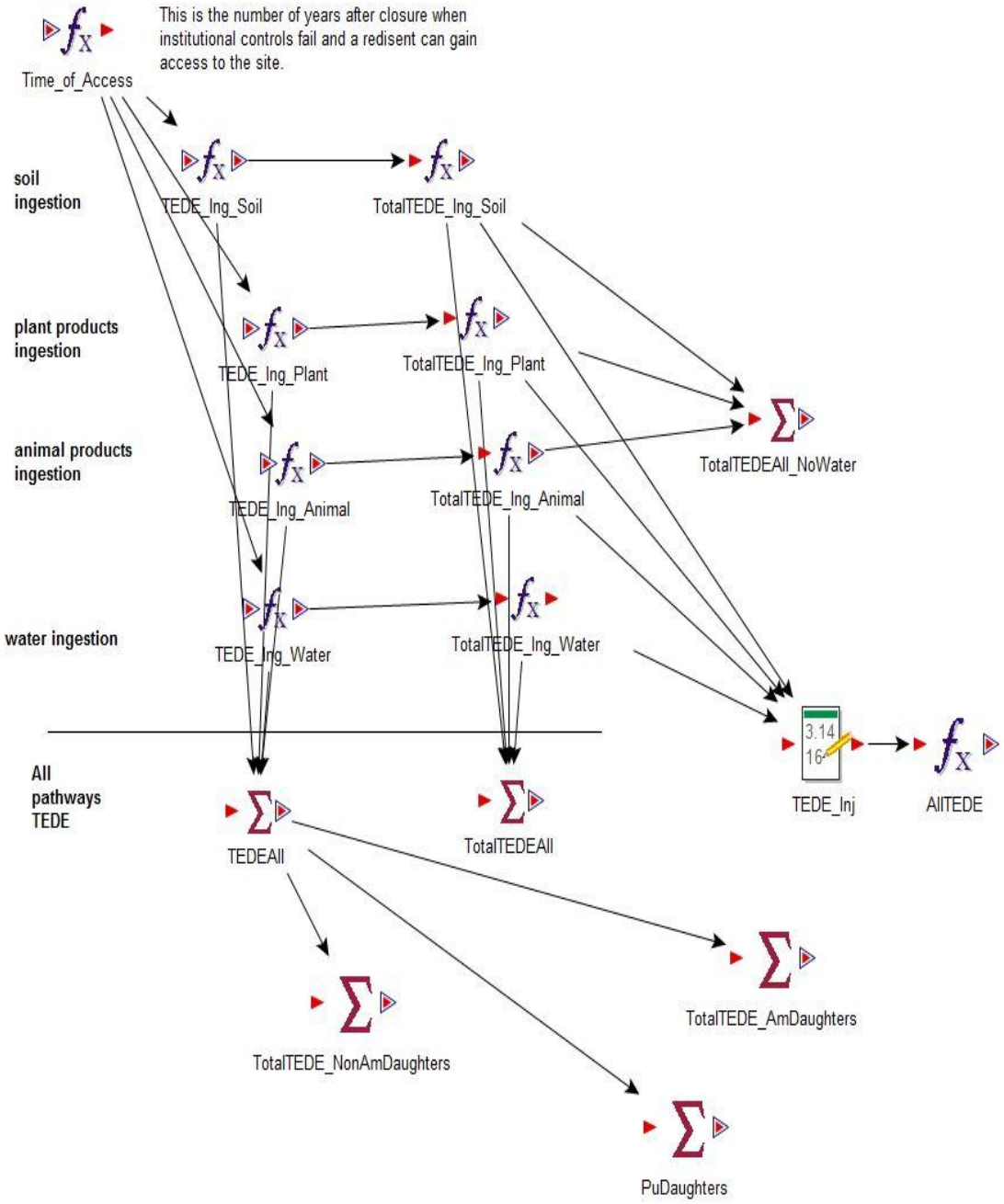


Figure F-14. Plant/soil concentration Ratio.

Assumptions for this calculation are outlined in the note pane for this container.



Inventory



Figure F-15 TEDE for resident farmer and waste inventory

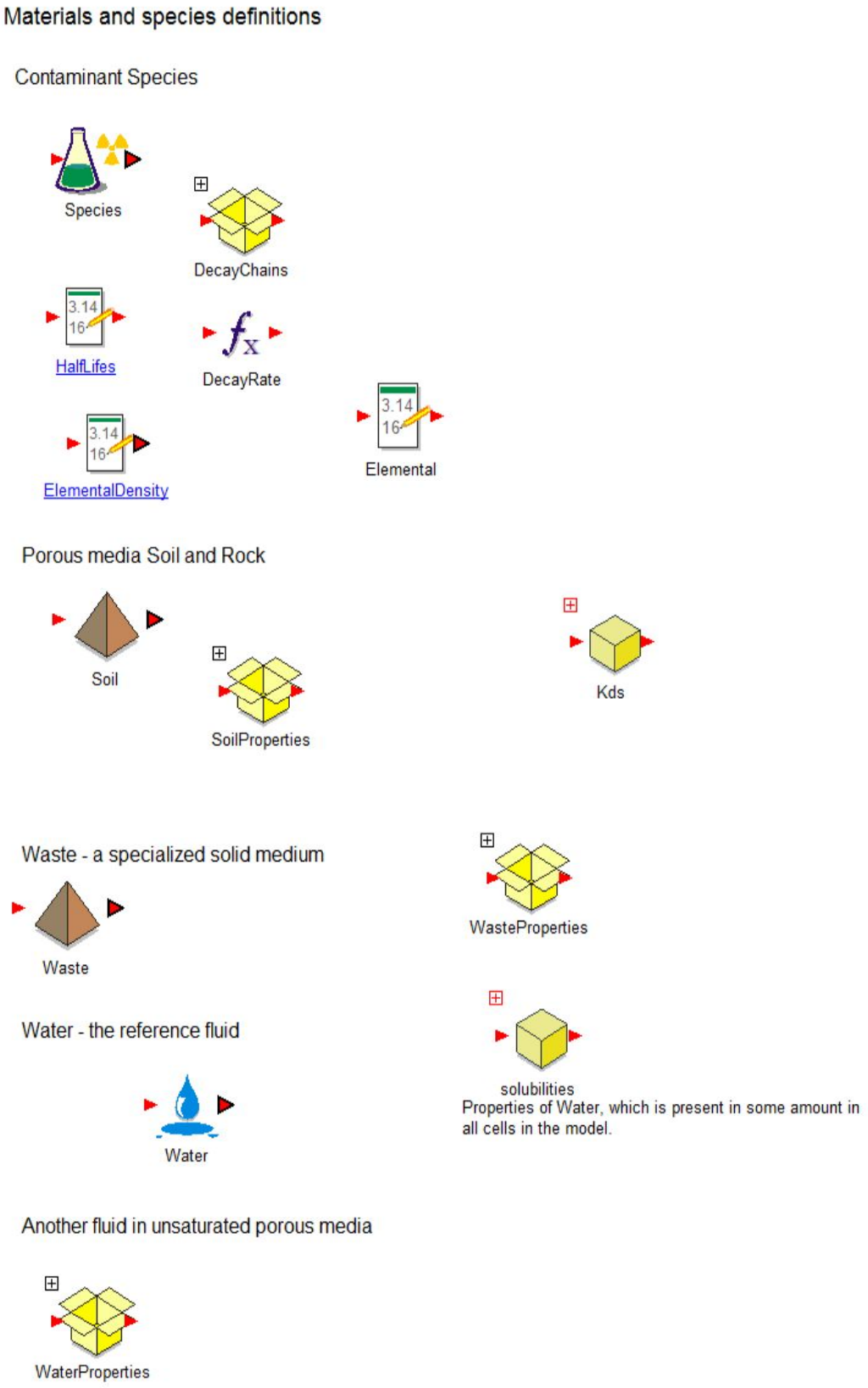


Figure F-16 Materials and species definitions

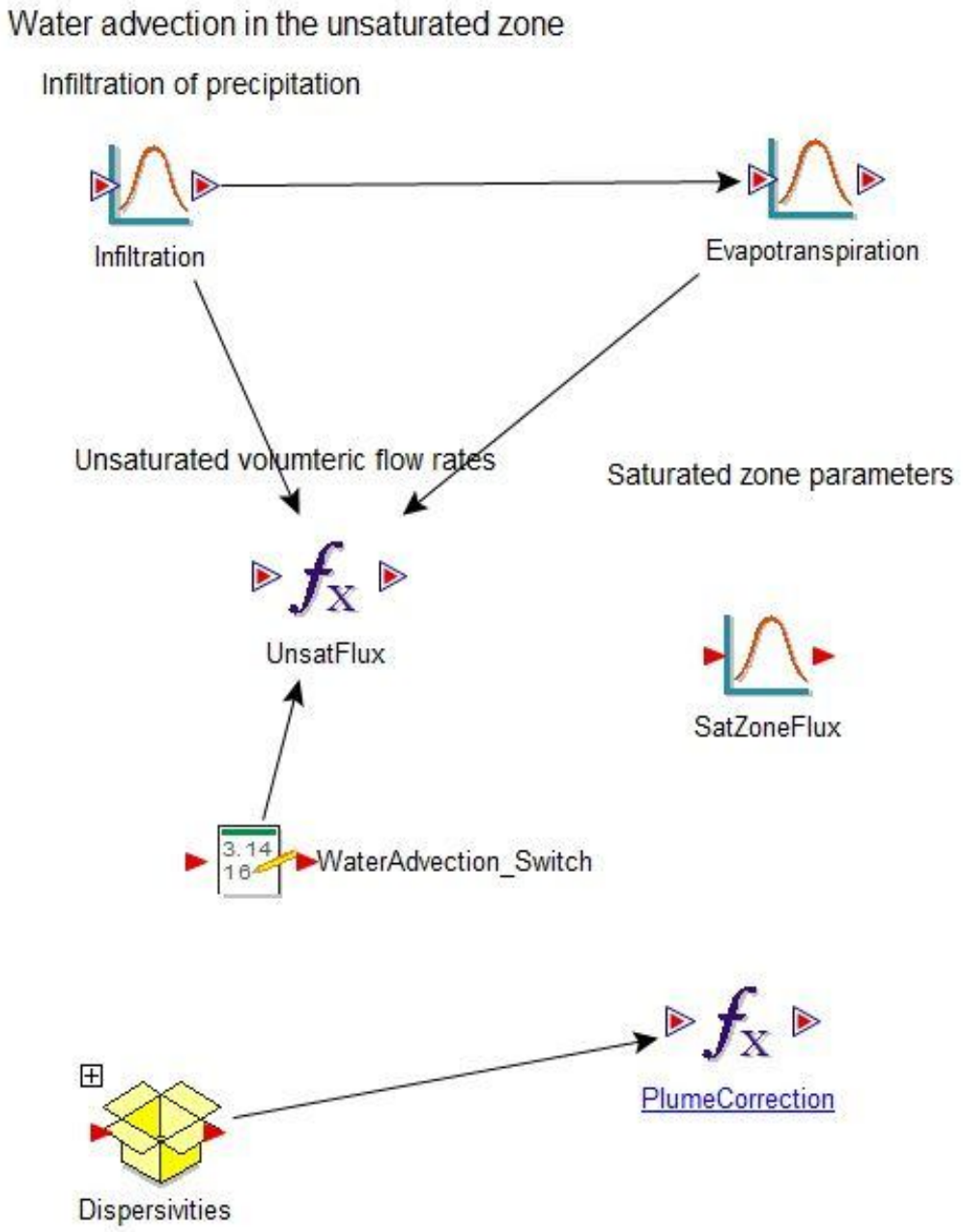


Figure F-17 Water Transport

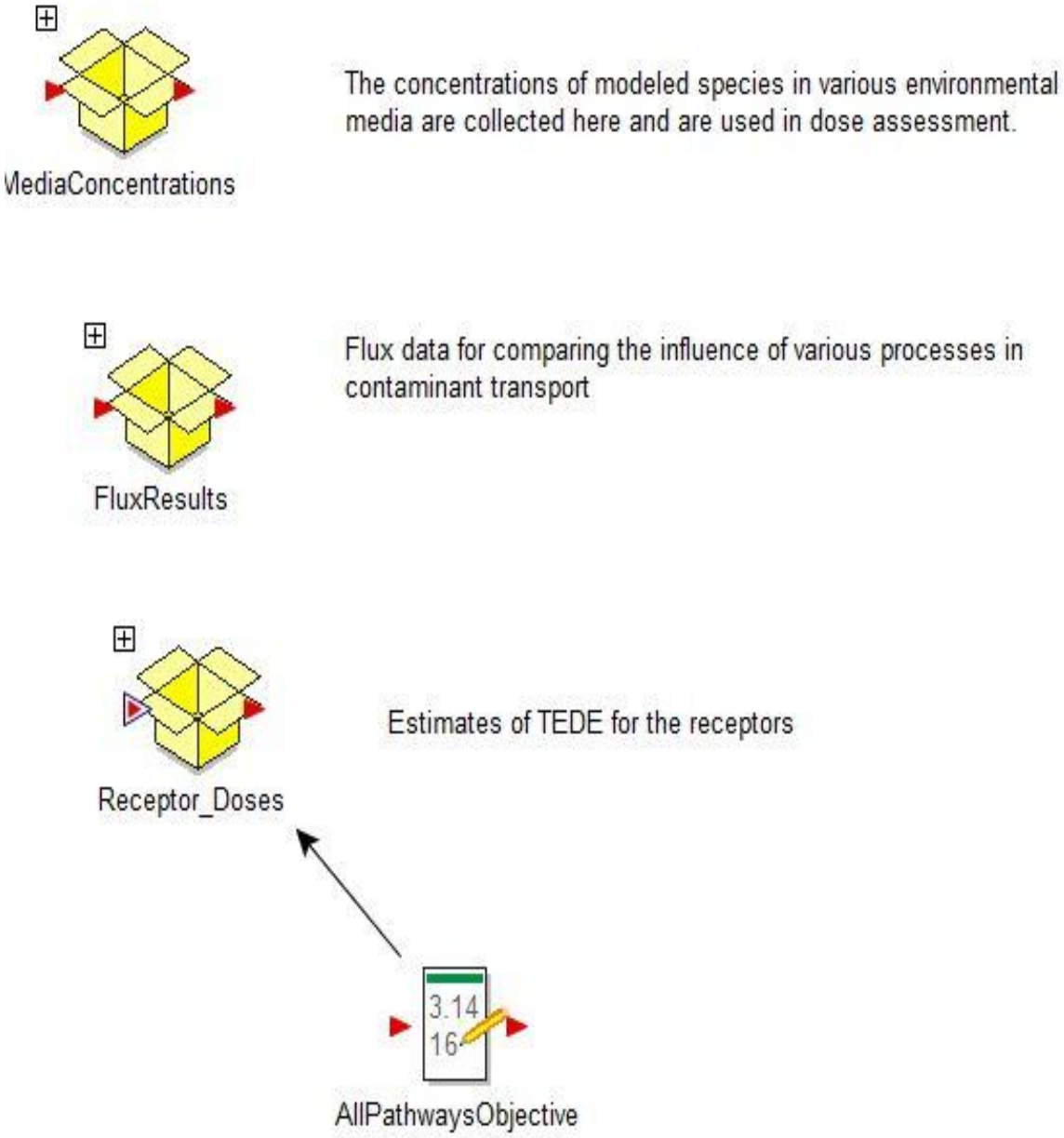
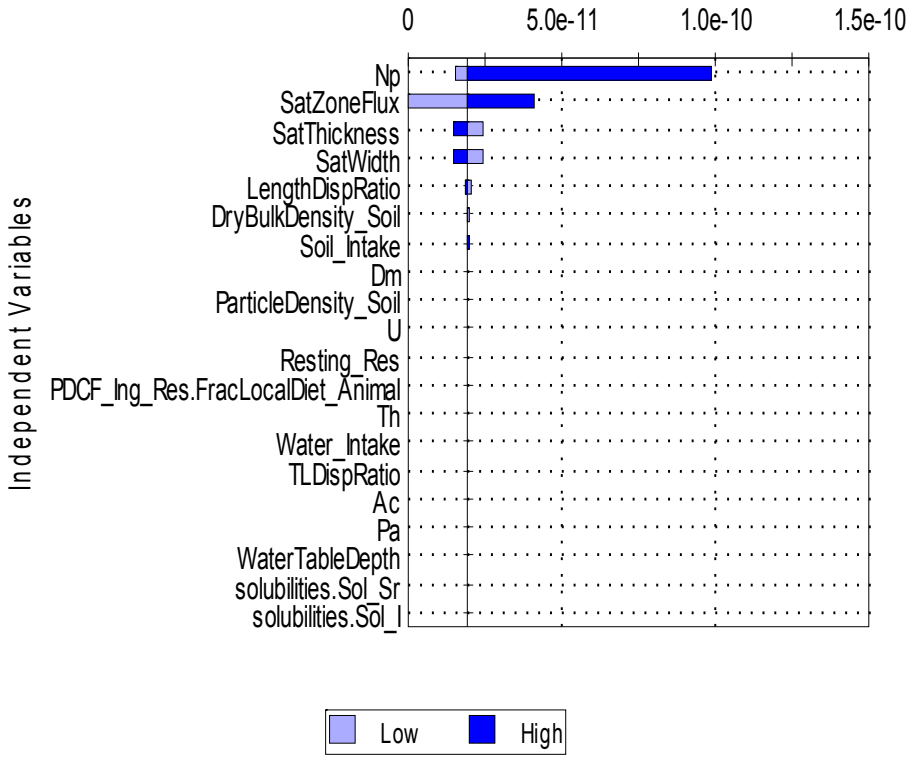


Figure F-18 Results

Appendix G


Tornado Sensitivity Chart - Analyzed Result: Resident.TotalTEDEAll_Farmer [m2/s3]
0
5.0e-11
1.0e-10
1.5e-10
Independent Variables
Np
SatZoneFlux
SatThickness
SatWidth
LengthDispRatio
DryBulkDensity_Soil
Soil_Intake
Dm
ParticleDensity_Soil
U
Resting_Res
PDCF_Ing_Res.FracLocalDiet_Animal
Th
Water_Intake
TLDispRatio
Ac
Pa
WaterTableDepth
solubilities.Sol_Sr
solubilities.Sol_I
Low
High