

**EVALUATION OF SOIL TO PLANT TRANSFER FACTORS OF NATURALLY
OCCURRING RADIOACTIVE MATERIALS (NORMs) IN SOME VEGETABLES**

T. C. Motimedi

Dissertation submitted in fulfilment of the requirements for the degree of *Masters of Science*
in the Faculty of Agriculture, Science and Technology at Mafikeng Campus of North West
University

SUPERVISOR:

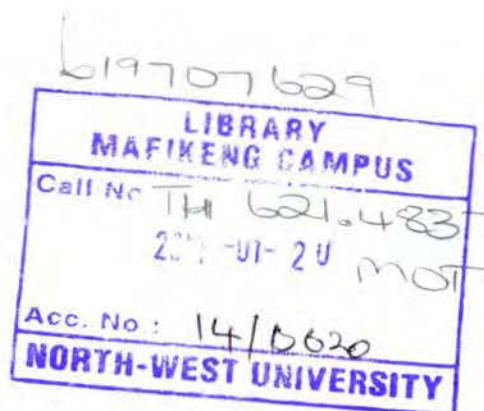
Prof. Dr A. Faanhof

Specialist Scientist: Research and Development, Necsa

Extraordinary professor: Applied Radiation Science,

North-West University

August 2012



060042207L

DECLARATION

I declare that this dissertation, Evaluation of soil to plants transfer factors of naturally occurring radionuclides in some vegetables carried out in the Radio-Analysis Laboratory of the South African Nuclear Energy Corporation (Necsa) in collaboration with the Centre for Applied Radiation Science and Technology (CARST) of the North West University, Mafikeng Campus, is my work in design and has not previously been submitted for the masters degree to any university in the Republic. All authors of the material contained in this work have been fully acknowledged.

Signature: Tshepo Confidance Motimedi

Date: 19/09/2013

Tshepo Confidance Motimedi

ACKNOWLEDGMENTS

I take this opportunity to express my sincere gratitude to the supervisor of this study Prof. Dr Arnaud Faanhof for the immense time and advice. Without his guidance and supervision this work would have not been completed.

I also like to thank my study mentor Immanda Louw for her mentorship; your contributions are really appreciated. I would also like to extend my appreciation note to Dr Hester Oosthuizen for all the necessary assistance in finalizing the dissertation write-up.

I also thank God for the strength he gave me throughout my studies; surely His greatness will continue to be seen in all the good things that I achieve.

I thank my grandparents and my father for their invaluable support. Your support and contributions towards my education are engraved in my heart.

Special thank you, to my late mother, to family and friends who also supported me through this journey, your courageous words have kept me going forward.

Finally I would like to express my gratitude to the Centre for Applied Radiation Science and Technology, North West University (Mafikeng Campus) for financing the studies and making it real and the South African Nuclear Energy Corporation for availing all the resources which contributed to this study.

LIST of Abbreviations

α	Alpha particle
β	Beta particle
γ	Gamma ray
ALARA	As Low As Reasonably Acceptable
AM	Arithmetic Mean
ARC	Agricultural Research Council
BFC	Bioconcentration Factor
BEGe	Broad Energy Germanium Detector
CF	Concentration Factor
CR	Concentration Ratio
CTBTO	Comprehensive Nuclear Test-ban Treaty Organization
GM	Geometric Mean
GSD	Geometrical Standard Deviation
IAEA	International Atomic Energy Agency
ICRP	International Commission of Radiological Protection
INAA	Instrumental Neutron Activation Analysis
IUR	International Union of Radiology
K_d	Distribution coefficient
NAA	Neutron Activation Analysis
Necsa	South African Nuclear Energy Corporation
NNR	National Nuclear Regulatory
NORM	Naturally Occurring Radioactive Material
SD	Standard Deviation
UNSCEAR	United Nations Scientific Committee on the Effect of Atomic Radiation

ABSTRACT

Mining activities, such as mining, milling and processing of uranium, thorium and other radioactive materials introduce large amounts of material containing naturally occurring radioactive nuclides into the environment. The activities have the potential of increasing the concentration of natural radionuclides in the environment and may possibly damage the agricultural land and environmental species. The radiological health burden imposed to men is also a concern. Mobility of the Naturally Occurring Radioactive Materials (NORMs) into the agricultural land and the surface water system is the starting point for ingestion of contaminated food and internal radiation exposure. Understanding the mobility of natural radionuclides in different species of the environment, which includes plants, animals and aquatic organisms, have been reviewed in this study to assess the impact of the radionuclides and to enhance the radiological protection plan against radiation exposure. The transfer factor model as a parameter used to quantify the soil to plants transfer of the natural radionuclides and other elements from the soil to edible parts of the plants was discussed in the study.

In this study, the experimental plan to evaluate the soil to plant transfer factors of naturally occurring radionuclides from the ^{238}U , ^{235}U , and ^{232}Th series and their progeny, from soil to some vegetables grown under controlled conditions has been outlined with the intention to present more realistic soil to plant transfer factors. The use of contaminated soil from an area affected by mining activities and the soil from an uncontaminated area are recommended for the study under controlled conditions. It is also recommended that contaminated water and uncontaminated water be used for irrigation purposes in the study. Although recommended transfer factors are available in the National Nuclear Regulatory (NNR) document LG 1032, this research focused on planning the study under controlled conditions as compared to the available data obtained under uncontrolled conditions. Furthermore, the results obtained from the study will be used to assess the radiological impact on humans whom might be exposed to radiation as a result of consuming contaminated food. The techniques of Instrumental Neutron Activation Analysis and gamma spectroscopy have been discussed as possible methods to be used during the study.

KEY WORDS

Transfer factors, Transfer factors under controlled conditions, Mobility of natural radionuclides into agricultural land, NORM nuclides in vegetables, Instrumental Neutron Activation Analysis, Gamma spectroscopy.

TABLE OF CONTENTS

DECLARATION	i
ACKNOWLEDGMENTS	ii
LIST of Abbreviations	iii
KEY WORDS.....	iv
List of Figures.....	viii
List of Tables	ix
CHAPTER 1	1
INTRODUCTION AND BACKGROUND.....	1
1.1 Transfer Factors	1
1.2 Layout of the Study.....	1
1.3 Naturally Occurring Radioactive Material (NORM).....	2
1.3.1 Origin of NORM.....	2
1.3.2 Thorium.....	2
1.3.3 Uranium	3
1.4 NORM Exposure Concerns	3
1.5 Significance of the Study	6
1.6 Aim of the Study.....	6
1.7 Objectives	6
CHAPTER 2	7
LITERATURE REVIEW ON TRANSFER FACTORS	7
2.1 Transfer factors	7
2.1.1 Factors influencing transfer factors.....	8
2.1.2 Time dependency of radionuclides transfer to plants.....	8
2.2 Radioactivity in soil	9
2.2.1 Radioactivity in soil fertilizing materials.....	10
2.3 Radioactivity in water	10
2.4 Food contamination	12
2.5 Soil to plant transfer of natural radionuclides.....	13
CHAPTER 3	15
THE REVIEW OF TRANSFER FACTOR MODELS.....	15
3.1 Transfer factor models	15
3.2 Reliability of transfer factor models	15
3.3 Transfer factors quantification	16

3.4	Interaction of radionuclides in soil.....	17
3.4.1	The solid-liquid distribution coefficient concept	18
3.4.2	Relationship between the K_d and the root uptake	19
3.4.3	Transfer factor (F_v) in agricultural ecosystem	19
3.4.4	Transfer in natural and semi-natural environment	20
3.4.4.1	Transfer to mushrooms	22
3.4.4.2	Accumulation of radionuclides in plants.....	22
3.4.5	Transfer factors to animals.....	22
3.5	Transfer factors of radionuclides in aquatic environments	24
3.5.1	Modeling the transfer of NORM nuclides in aquatic species	24
3.5.2	Bioconcentration factors for naturally occurring radionuclides.....	25
CHAPTER 4		27
RADIATION AND INTERNAL DOSE CALCULATIONS.....		27
4.1	Radiation.....	27
4.2	Radioactive decay	27
4.3	Pathways to humans.....	28
4.4	Effects of ionizing radiation in body cells	28
4.5	Health risks related to ionizing radiation	30
4.6	Internal radiation dose.....	31
4.7	Theoretical calculation of the internal dose	33
CHAPTER 5		39
AGRICULTURAL INDUSTRY		39
5.1	Agricultural sector in South Africa.....	39
5.2	Production of agricultural products (2009/ 2010).....	39
5.3	Vegetables grown in South Africa	40
5.4	Classification of vegetables.	40
CHAPTER 6		44
INSTRUMENTATION AND DATA COLLECTION TECHNIQUES.....		44
6.1	Neutron Activation Analysis	44
6.1.1	Introduction.....	44
6.1.2	Concept and principles of NAA.....	44
6.1.3	Interaction of neutrons with matter	46
6.2	Instrumental Neutron Activation Analysis (INAA).....	48
6.2.1	Application of INAA	49

6.2.2. Current trends in INAA.....	49
6.2.3 Advantages and limitations of the INAA method.....	51
6.3 Fundamental equations for the INAA method.....	52
6.4 Neutron source for INAA	53
6.4.1 South African Fundamental Atomic Research Installation (SAFARI -1).....	53
6.4.2 The irradiation facilities used for Neutron Activation Analysis	57
6.4.3 General procedure for neutron activation analysis.....	58
CHAPTER 7	60
STUDY PLAN TO EVALUATE SOIL TO PLANT TRANSFER FACTORS	60
7.1 Definition of concepts.....	60
7.2 Background and rationale	60
7.3. Literature review on NORM transfer to vegetables.....	61
7.4 Research problem and objectives.....	62
7.5 Research methodology, material and methods	63
7.5.1 Phase 1 - Analysis and quantification of source material	64
7.5.2 Phase 2 - Designing of the test beds.....	66
7.5.3 Phase 3 - Selection of Vegetables	66
7.5.4 Phase 4 - Irrigation and monitoring of plants.....	68
7.5.5 Phase 5 - Harvesting	68
7.5.6 Phase 6 - Analysis of samples.....	68
7.6 Calculations of the activities and the errors involved	69
7.7 Calculations of the transfer factors	69
7.8 Hypothesis on the outcome of the planned research.....	69
7.9 Possible benefits to be gained by the study.....	69
7.10 List of stakeholders envisaged	70
7.11 Budgetary requirements	70
7.12 Time frame and activities	71
7.13 Conclusion and recommendations	73
List of references for all chapters.....	74
Annexure 1.....	79
Annexure 2.....	88

List of Figures

Figure 3.1	Processes involved in the transfer of radionuclides to fruits.....	21
Figure 4.1	Schematic representations of exposure pathways.....	29
Figure 4.2	General graphs depicting the characteristics of ionizing radiation in cells...29	
Figure 4.3	Mathematical model used to describe the kinetics of radionuclides in the GI Tract.....	32
Figure 6.1	Concept of NAA.....	45
Figure 6.2	Schematic representation of the neutron fluence rate spectrum in a nuclear reactor	48
Figure 6.3	2 D Sketch of the SAFARI-1 core.....	54
Figure 6.4	A view of the SAFARI-1 reactor facility.....	55
Figure 6.5	Schematic view of the SAFARI-1 reactor.....	56
Figure 6.6	Example of the rabbit and sample vials for irradiation.....	57
Figure 7.1	INAA procedure envisaged	65
Figure 7.2	Steps of the design to evaluate soil to plants transfer factors in vegetables.....	67

List of Tables

Table 1.1	Decay series of the NORM nuclides.....	5
Table 3.1	Soil to plant transfer factor values for NORM nuclides from IAEA.....	17
Table 4.1	South African default value for intake via ingestion.....	35
Table 4.2	Dose conversion factors for ingestion by members of the public (in Sv/Bq).....	36
Table 4.3	Dose calculation example of consumption of contaminated maize (in Sv/a)	38
Table 5.1	Vegetable production in South Africa for the past five years.....	40
Table 5.2	List of vegetables grown in South Africa and production quantity value.....	41
Table 5.3	Classification of the vegetables based on edible part (FAO).....	42
Table 5.4	Classification of vegetables on the basis of family (FAO).....	43
Table 7.1	Anticipated activities and time-lines.....	72

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Transfer Factors

Transport of Naturally Occurring Radioactive Materials (NORMs) in the environment from soil to plants can result in contamination of the human diet and increased health risks as a result of excessive exposure to radiation. Pathway analysis of these NORM nuclides using transfer factor modelling assists in evaluating human exposure to radiation and accompanied health risks from NORM; by calculating the amount of radionuclides which have been taken up by plants in agricultural ecosystems and the radioactivity of those nuclides. In assessing the hazards from release of radionuclides into the environment, mathematical models are used in which the pathways of radionuclides from the release point to humans are qualitatively described by their transfers between “environmental compartments”. The radionuclide transfer between these compartments is usually described by transfer parameters, that is either individual parameters (describes the transfer from one discrete environmental compartment to another) or an aggregated parameter (describes a transfer via a complete chain of parameters)⁽¹⁾. Transfer factor modelling is used to estimate the amount of radioactivity present in foodstuffs by calculating the concentration ratios of radioactivity in the food to that in the soil and as a result of that, the radiological effects can be assessed for different population groups eating contaminated foods. There are different methods and instruments used for estimations of transfer factors of radionuclides in food-stuffs. In this study background on Neutron Activation Analysis and gamma spectrometry techniques will be discussed as the preferred techniques to be used in the future experimental phase of the study.

1.2 Layout of the Study

The study consists of seven chapters which are briefly discussed below:

Chapter 1 provides a general overview of the study, which includes an introduction and background information, the motivation for the study, research problem and research objectives.

Chapter 2 entails a literature review about the soil to plant transfer factors of radionuclides and food contamination.

Chapter 3 gives more theoretical information about the transfer factors in all compartments and an overview of distribution coefficients and bioconcentration factors.

Chapter 4 outlines the general overview of the possible radiological effects of radiation to people as a result of consuming contaminated foodstuffs.

Chapter 5 gives an overview of the agricultural industry in South Africa; a description of vegetables and their production is also outlined.

Chapter 6 gives an overview of Instrumental Neutron Activation Analysis.

Chapter 7 the plan to conduct the future experimental study is outlined, including time-lines, collaborating partners and a cost estimate of funding required to embark on the real-time study to improve the default transfer factors of NORM nuclides for radiological hazard evaluation; the anticipated methodology for evaluating the results is also deliberated upon.

1.3 Naturally Occurring Radioactive Material (NORM)

1.3.1 Origin of NORM

Naturally occurring radionuclides of terrestrial origin are present in various concentrations in all media in the environment, including the human body. Only those radionuclides with half-lives comparable to the age of the earth and their decay products exist in large quantities in materials. Extraction and processing of minerals containing natural radionuclides result in waste with elevated NORM concentrations being left on the earth's surface⁽¹⁾. Uranium and thorium, and their daughter nuclides emit different types of radiations. Table 1 shows the decay series of ^{238}U , ^{235}U and ^{232}Th indicating that naturally occurring radionuclides mainly emit alpha, beta and gamma radiation. The radiation emitted can have severe human health effects if ingested and/or inhaled. The effects of NORM nuclides from the primordial decay series can be evaluated by understanding their characteristics and their natural occurrences.

1.3.2 Thorium

Thorium occurs naturally in the earth's crust at an average lithospheric concentration of 8-12 $\mu\text{g/g}$ (ppm), or 35-50 mBq/g ^{232}Th . Thorium occurs in nature in six isotopic forms, thorium-228, thorium-230, thorium-232, thorium-234, thorium-231 and thorium-227. Of these, thorium-230 and thorium-234 are the decay products of the natural uranium-238 series,

while thorium-231 and thorium-227 belong to the uranium-235 series and the others belong to the thorium-232 series. Thorium usually occurs in geological materials as a trace constituent in phosphate, oxide and silicate minerals and adsorbed onto clays and other soil colloids. It occurs as a major species only in a few rare minerals such as thorianite (ThO_2), and thorite (ThSiO_4). A large part of naturally occurring thorium is found incorporated in zircon and monazite which contains about 3-9% and up to 20% of ThO_2 respectively. Along with zircon, monazite is concentrated with other resistant heavy minerals in stream and beach sands ⁽²⁾. Thorium is released to the environment as ThO_2 into surface waters from mining, milling and processing, and its low solubility makes it less concentrated in most water sources as compared to other elements such as uranium.

1.3.3 Uranium

Isotopes of uranium are naturally occurring within the two uranium decay series, either as the parent (i.e. ^{238}U or ^{235}U) or as a daughter nuclide within the series (i.e. ^{234}U). Natural decay series radionuclides occur ubiquitously in rocks, soil, and water together with potassium-40; and together they contribute to most of the naturally occurring radioactivity in the environment ⁽³⁾. Uranium is the heaviest element present in almost all minerals, rocks, sand, soil, and is important because of its chemical and radiotoxicity. Natural uranium can be detected in low concentrations in nearly all materials from the environment. In radiochemical equilibrium, it consists of the isotopes ^{234}U , ^{235}U and ^{238}U with the activity ratio of 1:0.0462:1, corresponding to a mass ratio of 0.0054: 0.711:99.2836 % respectively. All three nuclides are alpha emitters, which have a particular biological effectiveness ⁽⁴⁾. The main component of natural uranium is ^{238}U , and its half-life is 4.5 billion years which is almost equal to the age of the earth. The mobility of uranium in plant tissue is limited, because of its ability to adsorb to cell-wall materials; therefore the concentrations of uranium are expected to be higher in the tissue found in the lower parts of the plants as compared to the upper parts of the plants. The radionuclide concentrations in plants are often linearly related to the soil radionuclide concentration and as a result of that relationship, the transfer factor parameter is adequate to predict not only soil to plant transfer but also the concentration in the plant ⁽¹⁶⁾.

1.4 NORM Exposure Concerns

Naturally occurring radioactive material (NORM) exist in large quantities in the environment. The concentration and properties of the radionuclides give rise to radiation exposure and this creates a scientific interest in NORM studying their behaviour in the environment, their solubility and physical properties (half-life). Most countries in the world have industries

which produce NORM waste through mining and processing of minerals. The processing of these materials produces changes in the concentration of these nuclides in the environment. The amount of radioactivity released to the environment can increase human exposure and can result in harming the environment if the industry's activities are not regulated. In 2007 the International Atomic Energy Agency (IAEA) established a working group to improve the modelling of transfer of radionuclides from residues containing naturally occurring radioactive material for the purpose of radiological assessment; the study confirmed that contaminants have direct effects on the environment, that is direct effects on biota (flora and fauna) and environmental degradation, which can result in loss of agricultural land ⁽¹⁾. The pathway of these radionuclides to the human body is one of the main concerns. The following pathways are examples of how radioactive nuclides move from the environment into the human body: transport by surface water, transport by groundwater, deposition of the material on the ground surface and in the air and uptake into the food chain and drinking water. Understanding all pathways and having an emergency plan for any accidental release to the environment assists in reducing the radiological effect. Most of the radioisotopes are alpha emitters, so when they are ingested or inhaled, they contribute significantly to the radiation dose that people receive. On the other hand taking into account that uranium and thorium are always present in soil, their gamma radiation causes also external exposure with the consequent absorbed doses ⁽⁵⁾. The population is exposed to natural radioactivity at different levels depending on natural radioactive minerals concentrations in each region in the world ⁽⁶⁾. Studies on radiation levels and radionuclide distribution in the environment provide vital radiological baseline information. Such information is essential in understanding human exposure from natural and man-made sources of radiation and is necessary in establishing rules and regulations relating to radiation protection ⁽⁷⁾. Concentration of radioactivity in the environment is being monitored to maintain the As Low As Reasonably Acceptable (ALARA) principle of environmental and human protection from natural radiation sources. A high concentration of radioactivity in the environment is associated with the mining and milling of uranium in most countries. Other long lived radionuclides in the environment are associated with weapon testing and nuclear power generation. However, in South Africa natural radioactivity is associated with mainly, gold / uranium mining and processing. Other major industries associated with NORM are the coal, copper, phosphate and heavy minerals sand sectors ⁽⁸⁾.

Table1 Decay series of the NORM Nuclides.

URANIUM DECAY SERIES			ACTINIDE DECAY SERIES			THORIUM DECAY SERIES		
Nuclide	Half-life	Major radiation	Nuclide	Half-life	Major radiation	Nuclide	Half-life	Major radiation
²³⁸ U	4.5 x 10 ⁹ a	α	²³⁵ U	7.038 x 10 ⁸ a	α	²³² Th	1.41 x 10 ¹⁰ a	α
²³⁴ Th	24 d	β	²³¹ Th	25.5 h	β	²²⁸ Ra	5.75 a	β
^{234m} Pa	1.2 m	β	²³¹ Pa	3.3 x 10 ⁴ a	α	²²⁸ Ac	6.1 h	β
²³⁴ U	2.4 x 10 ⁵ a	α	²²⁷ Ac	21.8 a	α, β	²²⁸ Th	1.91 a	α
²³⁰ Th	7.5 x 10 ⁵ a	α	²²⁷ Th	18.7 d	α	²²⁴ Ra	3.66 d	α
²²⁶ Ra	1.600 a	α	²²³ Ra	11.4 d	α	²²⁰ Rn	55.6 s	α
²²² Rn	3.8 d	α	²¹⁹ Rn	3.96 s	α	²¹⁶ Po	0.15 s	α
²¹⁸ Po	3.1 m	α	²¹⁵ Po	1.78 ms	α	²¹² Pb	10.6 h	β
²¹⁴ Pd	27 m	β	²¹¹ Pd	36.2 m	β	²¹² Bi	60.6 m	α, β
²¹⁴ Bi	20 m	β	²¹¹ Bi	2.17 m	α	²¹² Po	0.3μs	α
²¹⁴ Po	160 μs	α	²⁰⁷ Tl	4.77 m	β	²⁰⁸ Tl	3.1 m	β
²¹⁰ Pb	22 a	β	²⁰⁷ Pb (stable)			²⁰⁸ Pb (stable)		
²¹⁰ Bi	5 d	β						
²¹⁰ Po	140 d	α						
²⁰⁶ Pb (stable)								

1.5 Significance of the Study

The development of the transfer factor model is considered as a tool to assess the radiological effects of radiation from NORM nuclides transferred from the biota to foodstuffs and to estimate the amount of radioactivity that could be present in foodstuffs or edible parts of the plants. The model is based on calculation of the concentration ratio of radionuclides in the soil to that of radionuclides in the crop. Calculations of the total amount of radioactivity ingested can be used to estimate annual internal exposure for members of the public. Both gamma spectrometry (to detect gamma emitting radionuclides) and Instrumental Neutron Activation Analysis (INAA) techniques have been used in most radionuclide transfer studies.

Due to concerns around radioactivity release (particularly waste containing NORM nuclides) from mines and processing industries to the environment, uptake of radionuclides by the public via the food chain is a topic of interest. Existing transfers as given in the National Nuclear Regulator licensing document LG-1032 ⁽⁹⁾ do not seem to match with data obtained in the analysis of water, fish and plant materials, and accordingly more realistic transfer data of NORM nuclides from the biota into humans will be the main focus of this study.

1.6 Aim of the Study

The aim of the study is to do thorough literature study on soil to plant transfer factors and to plan an experimental phase to determine soil to plant transfer factors of naturally occurring radioactive materials (NORMs) under controlled conditions.

1.7 Objectives

The objectives of the study were:

- To do a theoretical investigation on soil to plant transfer of NORM including their daughter nuclides.
- To design an experimental plan to study soil to plant transfer factors of naturally occurring radioactive materials (NORMs) in some major foodstuffs consumed in South Africa, on plants grown under controlled conditions in contaminated soil affected by mining and milling of gold.

CHAPTER 2

LITERATURE REVIEW ON TRANSFER FACTORS

2.1 Transfer factors

In assessing the hazards from the release point of radionuclides into the environment, mathematical models are used in which the pathways of radionuclides from the release point to humans are qualitatively described by transfers between “environmental compartments”. The radionuclide transfer between these compartments is in most cases described by transfer parameters concerned, that is either individual parameters that describe the transfer from one part of the environmental compartment into the other part or aggregated parameters that looks into all chains of parameters ⁽⁹⁾. Both types of parameters have particular applications and in most cases are used as the step to evaluate transfer of radionuclides from the environment into the human body. The transfer of radionuclides along the food chain has been studied extensively over 50 years following nuclear weapon testing, release from military sites and civilian uses of nuclear energy; data are compiled by amongst others the IAEA ⁽¹⁰⁾. Many authors have reported on radioactive food contamination in the environment and its transfer or pathway mechanism to plants, animals and the human population has been reported ⁽¹¹⁾. The transfer factor of radionuclides is generally defined as the ratio of the radioactivity concentration in plants to that in soil ^(12, 15). The transfer factor (TF) of radionuclides as proposed by the International Union of Radiologists (IUR) can be represented as follows ^(13, 14).

$$TF = \frac{\text{Concentration of radionuclides in plant (Bq/kg dry crop mass)}}{\text{Concentration of radionuclides in soil (Bq/kg dry soil mass in the upper 20 cm)}}$$

Using the dry weight in this regard minimizes the uncertainties. Migration and accumulation of contaminants (including radionuclides) in the soil-plant system is complex and assessment models such as the transfer factor model are used to estimate the accumulation through the food chain. There are considerable differences in the uptake and translocation of long lived radionuclides among different plant species. Up till now several investigations on mobilization of natural radionuclides (such as ²³⁸U and ²²⁶Ra) in different compartments (soil,

plant, and water) as well as the transfer between them have been performed at different uranium mining sites around the world using the transfer factor model. The transfer factor parameter can also be used as an index for the accumulation of the trace elements by plants or as the transfer of elements from soil to plants ⁽¹¹⁾.

2.1.1 Factors influencing transfer factors

Soil to plant transfer of radionuclides is influenced by several factors, which vary considerably. The main factors that cause this variability for any radionuclide are the type of soil used for growing plants, climatic conditions, type of plants, part of the plant concerned, physico-chemical form of the radionuclides and interfering elements. For example the availability of calcium and potassium in the soil for uptake will affect the uranium, thorium and radium content of the plant. Soil types that traps potassium in its crystal lattice, and the presence of phosphate that forms insoluble compounds with thorium, have been observed to reduce radionuclide availability in plants. There are considerable differences in the uptake and translocation of long lived radionuclides among different plant species ⁽¹¹⁾. In 2003 Vera Tome *et al.* ⁽¹⁷⁾ in a study to determine the soil to plant transfer of natural radionuclide, noted that the uptake of radium is greater than the uptake of uranium or thorium; this difference has been influenced by the solubility of these elements as a result of oxidation states and that the element radium has a high affinity for the regular exchange site of the soil. It is generally agreed that transfer factor values of elements in the oxidation state +II are always greater than those of elements in the +IV oxidation states.

2.1.2 Time dependency of radionuclides transfer to plants

The period (length of time) that the radionuclide has been in the soil is important as it relates radionuclide transfer from soil to plants for equilibrium conditions, this could be because of the fact that some radionuclides have short half-lives and some will decay completely before they can be transferred from the soil to the plants, or even after uptake and consumption of the foodstuff. This arises because radionuclides transferred to the environment are gradually fixed by natural sorbents (soils, bottom sediments in water ecosystems, etc.) and are lixiviated to lower soil layers and accordingly become less biologically available for inclusion into food chains ⁽¹⁰⁾.

Time-dependence of radionuclides is often quantified by reference to the ecological half-life, which is an integral parameter relating to the reduction of activity or activity concentration in

a specific medium. According to the definition ecological half-life is equal to the period over which the concentration of radionuclides, in some definite component of a trophic chain, is decreased by a factor of two, excluding the effects of radioactive decay⁽¹⁰⁾.

In general the following conclusions have been reached with regard to transfer factors:

- There are no systematic differences between soil-plant transfer factors in temperate, subtropical and tropical environments.
- The effect of transfer of a) soil pH, b) nutrient status of the soil and c) time elapsed since the soil was contaminated with radionuclides is generally independent of the climatic zone.
- There exist ecosystems with a relatively high or low uptake (by factor 10 or even 100 times higher or lower than the average values).
- A higher or lower uptake condition is nuclide specific; an ecosystem may show a relatively high or low uptake for a particular radionuclide and not at all for other radionuclides.

2.2 Radioactivity in soil

Humans have always been exposed to natural radiation arising from within and outside the earth. The exposure to ionizing radiation from natural sources occurs because of the naturally occurring radioactive elements in the earth's crust, cosmic rays entering the earth's atmosphere from outer space and the internal exposure from radioactive elements through food, water and air. Natural radioactivity is widespread in the earth's environment and it exists in various geological formations in soil, rocks, plants, water, and air. The natural radioactivity in soil comes from the U and Th series and natural K⁽¹⁹⁾.

Measurements of natural radioactivity in soil have been performed. In the studies it was observed that most of the naturally radioactive elements present in soil are primordial radionuclides from the uranium series, thorium series, actinium series and ⁴⁰K. The minimum radioactivity was found in sandy soils. The radionuclides in the radioactive decay chains starting from ²³⁸U, ²³⁵U and ²²⁸Th are highly radiotoxic, in particular ²³⁰Th, ²²⁶Ra, ²¹⁰Pb, ²¹⁰Po, ²³¹Pa, ²²⁷Ac, and ²²⁸Ra. The radioactive gas (radon) that arises from the disintegration of ²³⁸U and ²³²Th in the earth's crust is considered the main source of exposure to ionizing radiation for humans, representing 40% of the annual accumulated dose⁽²⁰⁾ Gamma radiation emitted from naturally occurring radioisotopes such as ²²⁶Ra and ²³²Th and their decay

products, and ^{40}K , which exist at trace levels in all ground formations represent the main external source of radiation to the human body. More specifically, natural environmental radioactivity due to gamma radiation depends primarily on the geological and geographical conditions, and appears at different levels in the soils of each region in the world ⁽²¹⁾. Soils are naturally radioactive, because of their mineral content. The natural radioactivity may vary considerably from one type of soil to another. Abbady *et al.* ⁽²¹⁾ used gamma ray spectrometry to determine the activity concentration of naturally occurring ^{226}Ra , ^{232}Th , and ^{40}K radioisotopes in three types of soil (cultivated, reclaimed and under reclamation soil) from some areas in Qena Governorate, and Wadi EL-Lagita (Eastern Desert) Upper Egypt. The results showed that reclamation soils has the highest concentrations of ^{226}Ra , ^{232}Th , and ^{40}K ; under reclamation soil has the lowest concentrations and the cultivated soil samples had average activity concentration of ^{226}Ra , ^{232}Th and ^{40}K equal to 13.2, 13.0 and 181.1 Bq/kg respectively. The values obtained in the study for ^{232}Th and ^{40}K fall within the world average values of 30, 35 and 400 Bq/kg for ^{226}Ra , ^{232}Th and ^{40}K respectively except for ^{226}Ra in reclamation soil which reached an average value of 41.1 Bq/kg. Typical soils contain approximately 300 kBq/m³ of ^{40}K to a depth of 20 cm.

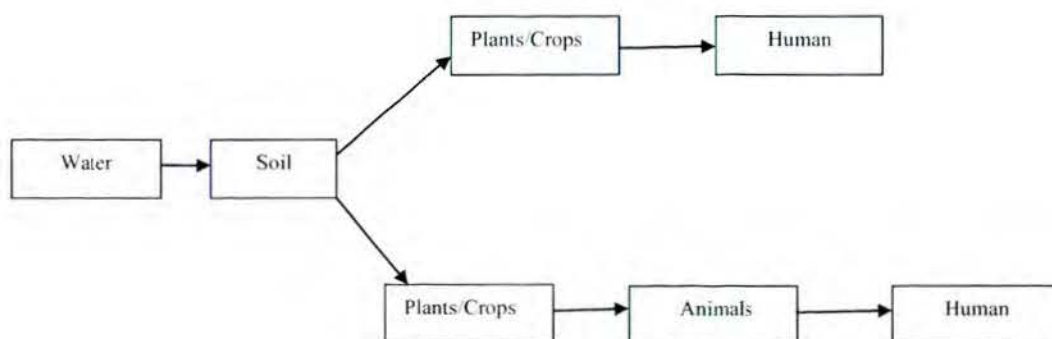
2.2.1 Radioactivity in soil fertilizing materials

The sources of radioactivity in soil other than those of natural origin are mainly due to extensive use of fertilizers rich in phosphate for agricultural purposes. Phosphate rocks contain relatively high concentrations of naturally occurring radioactive material from the uranium, actinium, and thorium decay series (^{238}U , ^{235}U , and ^{232}Th). Phosphate rock is the starting raw material for all phosphate products. It can be of sedimentary, volcanic or biological origin. Concentrations of the decay products of the ^{232}Th series and ^{40}K in phosphate rocks of all types are similar to those observed normally in soil, whereas the concentration of ^{238}U and its decay products tend to be elevated in phosphate deposits of sedimentary origin. A typical concentration of ^{238}U in a sedimentary phosphate deposit is 1500 Bq/kg. The uranium content of fertilizers can vary according to their phosphate content. Rock phosphate contains high levels of ^{238}U and ^{226}Ra ⁽⁷⁾.

2.3 Radioactivity in water

In agricultural projects, water is considered as one of the most important aspects since it is used for irrigation, and the quality of water used contributes significantly to the growth of the plants. Concentration of minerals in water has its own way of affecting plant growth. The

presence of radioactive material in water doesn't only affect the plant growth but also contributes to internal exposure of humans to radiation via ingestion of foods that are being irrigated with contaminated water. Naturally occurring radioactive materials have always been part of the environment and the existence of them in water contributes to the radiation dose, contaminated water used for irrigation in this case is considered as the main contaminator since it contaminates foodstuffs. The conceptual pathways of contaminated water into the human body are given below:



Radioactive nuclides from uranium and its decay series enter the human body mainly through food and drinking water. Water comes into contact with several minerals under the earth's surface, and uranium is transferred to water by leaching. The water consumed by livestock and used for irrigating purposes can also be a source of this radionuclide. Sea water can be a contamination source for sea foods. Water from streams, lakes and ponds should also be considered as a source of contamination ⁽²²⁾. Surface water, resulting from mining of uranium, gold and processing of other minerals, used for irrigation can be regarded as a major contributor of NORM nuclides into foodstuffs since the water can contain large concentrations of those minerals. The thermodynamic properties of dissolved elements/radionuclides and their concentration in minerals can be used to compute solution–mineral equilibrium relations. These theoretical calculations provide information about the possible conditions for extent of the element/radionuclide mobility. Such information helps us to understand the element/radionuclide concentrations in ground water, and predict the risk of their release in leachates from mining activities and radioactive waste ⁽²⁾. Of the long lived radionuclides, uranium is the most soluble; the concentrations of uranium are usually ten times higher than those of other NORM nuclides ⁽²⁷⁾.

2.4 Food contamination

As mentioned in Section 2.2, all soil used anywhere in the world for agriculture contains radionuclides to a greater or lesser extent. These radionuclides and other elements can then be taken up by crops and transferred to food, leading to a concentration in food and feed of between 50 and 150 Bq/kg. The ingestion of radionuclides in food is one of the pathways leading to human exposure from natural and man-made sources. Excessive contamination of agricultural land, such as may occur in a severe accident, can lead to unacceptable levels of radionuclides in food. The radionuclide contaminants of most significance in agriculture are those that are relatively highly taken up by crops, have high rates of transfer to animal products such as milk and meat, and have relatively long radiological half-lives. However, the ecological pathways leading to crop contamination and radioecological behaviour of the radionuclides are complex and are not only affected by the physical and chemical properties of the radionuclides but also by factors which includes soil type, cropping system (including tillage), climate, season, and where relevant, biological half-life within animals ⁽¹⁸⁾. The major radionuclides of concern occurring naturally are ^{238}U , ^{235}U , ^{232}Th and their progeny since they have long half-lives and exist in large quantities due to uranium mining and processing of minerals.

In order to understand the radionuclide transfer in agricultural lands and semi-natural systems it is ideally important to know the mechanisms that determine the radionuclides behaviour because these kinds of systems are both complex and various ⁽²³⁾. Transfer factors of radionuclides are in most cases obtained under equilibrium conditions. The presence of naturally occurring radionuclides in agricultural foodstuffs increases the internal radiation dose and the study of their transfer will always present interesting scientific research. In 2007, Faanhof *et al.* ⁽²⁸⁾ assessed the potential radiological impact of radionuclides on foodstuffs grown in a catchment area influenced by the mining and mineral processing industry. In their study Instrumental Neutron Activation Analysis and gamma spectrometry methods were applied. Equilibrium between ^{210}Po and ^{210}Pb was assumed if the samples in question were to be stored for a year and equilibrium between the two uranium isotopes (^{238}U and ^{234}U) was accepted as the samples were obtained from the catchment area dominated by the mining and processing of uranium. ^{230}Th was assumed not to be in equilibrium with ^{238}U since the mobility of thorium is regarded to be low. The results showed high concentrations of radionuclides in crops and low concentrations in fish samples.

2.5 Soil to plant transfer of natural radionuclides

Many scientists in the world have developed an interest in the study of the transfer of radionuclides from soil to plants; transfer factor modelling was utilized in most studies to estimate the ingestion dose to the public from radioactivity found in vegetables and other foodstuffs such as fruits, meat and milk. In one of these studies of interest, an experiment to examine the use of the transfer factor to assess the soil to plant transfer of radionuclides under field conditions was performed ⁽¹⁵⁾. Irrespective of biological necessity, plants have been observed to take up many cations present in their root region; primordial radionuclides are no exception since they are present in soil, rocks and other sources in the environment. In soil, each radioactive element follows complex dynamics, in which part of it is transported into soil solutions while another part gradually becomes strongly bound to the soil particles and a portion of these radionuclides in the solution can be incorporated via roots into the plants. In some cases the radionuclides have chemical similarities with other elements that plants use for their growth and therefore it is important to study their transfer to plants, as these are basic links in evaluating the transport of the radionuclides along the food chain ⁽²⁹⁾. To quantify transfer to plants, transfer factor models are used, which use corresponding transfer coefficients of each radionuclide. Vera Tome *et al.* ⁽¹⁷⁾ studied the soil to plant transfer factors of natural radionuclides and stable elements in a Mediterranean area. The transfer factor of ^{238}U , ^{234}U , ^{232}Th , ^{230}Th , ^{228}Th , and ^{226}Ra were obtained in plant samples (grass-pasture) collected around the soil of a disused mine. In the study it was observed that the transfer of radium to plants is greater than the transfer of uranium and thorium and that there was no linear relationship between the concentration in plants and the substrate for the stable elements. The results also showed the preferential uptake of ^{226}Ra and some essential elements such as Ca, Mn, and P in contrast to uranium and thorium. Shtangeeva ⁽²⁵⁾ studied the uptake of uranium and thorium by native and cultivated plants. In the study some of the factors affecting the uptake of uranium and thorium by plants were discussed and it was highlighted that the concentration of uranium and thorium in soil differ significantly as a result of soil type, parent rock, climate and vegetation season. It was also reported that the concentration of uranium and thorium is much higher in plant roots than in leaves and seeds and the rate of radionuclide translocation from roots to shoots is probably species dependent. It was also reported that the concentration of radionuclides in plants are not so often linearly related to the concentration of radionuclides in the soil. This can complicate the measure of bioavailability. The temporal variation of both uranium and thorium in plants was also

discussed and it was noted that the concentration of the elements in tissues can vary with the vegetation season. The concentration of other elements in plants may be controlled by light and the biological clock; however, this variations maybe specie-specific. It was then concluded that the plants grown in radionuclide enriched soils demonstrate significant increases in concentration of uranium and thorium in the roots compare to that in the upper plant parts. Thorium was less available for uptake by plants than uranium and that the relationship between uranium and thorium in soil and in plants depends significantly on the soil type. Chibowski ⁽²⁶⁾ studied radioactive contamination and heavy metal contents in vegetables and fruits using transfer factor modelling. The study showed that the transfer factors of beetroot and leek are much higher than the transfer factor found in grass and corn.

CHAPTER 3

THE REVIEW OF TRANSFER FACTOR MODELS

3.1 Transfer factor models

The deposition of radionuclides on vegetation and soil represents the starting point for their transfer in the terrestrial environment and food chains. The migration and accumulation of contaminants in cultivated soils can be viewed as a complex exercise that involves processes such as leaching, capillary rise, runoff, sorption, root uptake and re-suspension into the atmosphere. Assessment models normally make use of a plant/substrate concentration ratio, referred to as the transfer factor (TF), to estimate the transport of radionuclides and other elements of interest through the food chain. The ratio describes the amount of radionuclides/elements expected to enter the plants from the substrate, under equilibrium conditions ⁽¹⁷⁾. To perform an assessment of the impact of the released radionuclides in the environment, models are developed and applied. Models are a potential useful part of the assessment process; they provide more realistic predictions and are the major criterion for the quality and the reliability of results. Reliable results of assessment models are essential for radiological impact statements, estimates of dose due to annual releases and estimates of dose in the case of accidental releases. Radiological models consist of three compartments, namely; (i) the model structure, (ii) radiological parameters, for example Transfer factors, and (iii) the assumptions on the living habits of man and agricultural practices ⁽³⁰⁾.

3.2 Reliability of transfer factor models

Modelling requires good knowledge on the dynamic behaviour of radionuclides in the environment and the reliability of the model's results depends on the aim of the model's application ⁽²⁹⁾. In this case the soil-plant transfer factor model is developed to predict the movement of radionuclides from contaminated soil into the plants roots and possibly to man's diet. However, the reliability of the model depends at least on the quality of parameters which are necessary to run it.

3.3 Transfer factors quantification

The transfer factors of radionuclides in most cases are quantified by the ratio of their activity concentrations in soil to that in plants. In 1982, the International Union of Radioecology (IRU) decided to standardize the depth of soil in defining the transfer factor values. Instead of the real rooting depth, a standardized depth of soil was adopted ⁽³⁰⁾. All roots and activity present in the actual rooting zone are assumed to be present in the standardized zone. For grass, this value is 10 cm and for all the other crops including fruit trees the value is 20 cm. Transfer factors are commonly used to quantify the radionuclide uptake from soil to plants. However, the definition is based on the ratio of the activity concentration in plants to soil (all in the unit Bq/kg dry weight) within the layer of a standardized thickness. This is not appropriate for forest and some other natural and semi-natural ecosystems because of the multi-layer characters of the soils and the high inhomogeneity of distribution of root systems over the soil profile. In this case the aggregate transfer factor T_{ag} is used as an alternative to quantify the radionuclide availability to various types of natural or semi-natural vegetation, animals or other products. The T_{ag} is defined as the ratio of the radionuclide activity concentration in plants or any other natural or semi-natural product (Bq/kg fresh or dry weight, depending on the product) divided by the total deposition in the soil (Bq/m²). Also an alternative method of transfer factor quantification is the concentration ratio (CR or CF) which is defined as the ratio of the activity density of the radionuclides in the receptor compartment to that in the donor compartment. It is in most cases used to define the activity concentration in aquatic organisms in relation to activity concentration in water; with the intention to include the ratios as feed to plant tissue, soil, animal tissue, fish muscle and water. From the radiological point of view, the transfer factor of radionuclides regarding environmental exposure pathways is quantified by the three factors as described below:

$$\text{Transfer factors (F}_v\text{)} = \frac{\text{Nuclide concentration in plant tissue} \left(\frac{\text{Bq}}{\text{kg}} \right)}{\text{Nuclide concentration in soil} \left(\frac{\text{Bq}}{\text{kg}} \right)}$$

$$\text{Concentration Factors (CF)} = \frac{\text{Nuclide concentration in biota tissue} \left(\frac{\text{Bq}}{\text{kg}} \right)}{\text{Nuclide concentration in filtered water} \left(\frac{\text{Bq}}{\text{l}} \right)}$$

$$\text{Aggregate transfer factors coefficient } (T_{\text{agg}}) = \frac{\text{Nuclide concentration in plant tissue } \left(\frac{\text{Bq}}{\text{kg}}\right)}{\text{Nuclide deposition in soil } \left(\frac{\text{Bq}}{\text{kg}}\right)}$$

The factors above have proved to be useful in quantifying the transfer along exposure pathways for assessment purposes related to regulations, emergency response, and rehabilitative efforts. Large scale efforts in the evaluation and collection of empirical data sets regarding radionuclide transfer as expressed by factors such as those above have resulted in compendia published by bodies such as the IAEA ⁽³¹⁾. The recorded transfer factors values for naturally occurring radionuclides and their progeny are shown in Annexure 1. Table 3.1 provides the compiled information. It will be obvious that due to the large differences in maximum and minimum values and the accordingly uncertainty, it will be difficult if not impossible to set default data for South African crops based on these values.

Table 3.1 Compiled soil-to-plant transfer factor values for uranium, thorium, radium, lead and polonium. (IAEA Quantification of soil to plant transfer factors) ⁽³¹⁾

Element	Plant group	Plant compartment	Soil	Min	Max
Uranium	All	All	All	3.0×10^{-5}	1.4×10^1
Thorium	All	All	All	1.2×10^{-6}	2.7
Radium	All	All	All	1.1×10^{-5}	1.3×10^2
Lead	All	All	All	1.5×10^{-4}	2.5×10^1
Polonium	All	All	All	1.6×10^{-5}	1.0

3.4 Interaction of radionuclides in soil

Most published information on the behaviour and movement of radionuclides in soil reflects the pattern observed after deposition to the soil surface. The residence times for turnover of radionuclides in a defined soil layer are derived generally on the basis of the total contents of radionuclides rather than on the basis of specific fractions extractable with defined extracting agents. As a result, models for radionuclide movement in soil can be defined and applied. In studies of their interactions, the simple approach in describing the availability of radionuclides is the apparent half-life concept. The assumption is that after a certain period, half of the radionuclides disappear from a certain layer. A refinement of this concept is that of resident time. The soil is assumed to be designed into different layers which serve different purposes, the radionuclides move through subsequent layers, staying in each layer for a certain period of

time. The advantage of this approach is that processes which cause migration do not have to be considered but the disadvantage is that diffusion, dispersion and vertical transport cannot be distinguished ⁽³³⁾. The transfer values of radionuclides vary enormously; the main factors which cause this variation for particular radionuclides are the type of crops and type of soil. Soil properties that are likely to affect the transfer factor values include mineralogical and particle size distribution, organic matter content, pH and fertility ⁽³⁵⁾.

In defining the interaction of radionuclides with other minerals and soil, the following concept and other processes such as the solid-liquid distribution coefficient approaches are used.

3.4.1 The solid-liquid distribution coefficient concept

Dissolved radionuclide ions can bind to solid surfaces by a number of processes often classified under the broad term of sorption. The behaviour and ultimate radiological impacts of radionuclides in soils are largely controlled by their chemical form and speciation, which strongly affects their mobility, the residence time within the soil rooting zone, and the uptake by biota. The degree of radionuclide sorption to the solid phase is often quantified using the solid-liquid distribution coefficient (K_d), which can be used when making assessments of the overall mobility and likely residence times of radionuclides in soils. The K_d value is an important parameter that is used to estimate the potential for adsorption of dissolved radionuclides or contaminants in contact with soil. It is also defined as the ratio of the contaminant concentration associated with the solid to the contaminant in the surrounding aqueous solution when the system is at equilibrium. The concentration of the contaminants in groundwater is controlled primarily by the amount of the contaminant present at the source, the rate of release from the source, hydrologic factors such as dispersion and dilution. It is also controlled by geochemical processes which include aqueous geochemical processes, adsorption and desorption, and precipitation and diffusion. The K_d parameter is related to the partitioning of contaminant between the solid and the aqueous phases, and it can be expressed as ⁽³⁶⁾:

$$K_d = \frac{\text{Mass of adsorbate sorbed}}{\text{Mass of adsorbate in solution}}$$

In this case the mass of the adsorbate sorbed refers to the amount of the adsorbate on the solid at equilibrium whereas the mass of the adsorbate in solution denotes the total dissolved adsorbate remaining in the solution at equilibrium. The K_d value is given in units of ml/g ⁽⁴⁷⁾.

3.4.2 Relationship between the K_d and the root uptake

The radionuclides soil-to-plant transfer is assessed by measuring the soil to plant concentration factor (F_v), defined as the ratio of the radionuclide content in the plant to that in the soil; (Bq/kg) dry weight plant tissue per (Bq/kg) dry weight soil. The concentration factor can be assumed to be mostly controlled by the root uptake, since other sources of plant contamination are often of lesser significance (except for mosses).

The radionuclide concentration in plants (C_v) is assumed to be linearly correlated to the radionuclide level in the soil solution (C_{ss}). The relationship is controlled by the selectivity of the plant-root system represented by the bioaccumulation factor (B_p) given as:

$$C_v = C_{ss} \cdot B_p$$

Where B_p is the radionuclide plant-soil transfer factor (Bq/kg plant tissue / Bq/l soil solution). Therefore, the plant to soil solution bioaccumulation factor is assumed to be dependent on the concentrations of competitive radionuclide species in soil solution.

3.4.3 Transfer factor (F_v) in agricultural ecosystem

The transfer factor for the uptake of radionuclides from soil to plants in agricultural ecosystems is defined as the ratio of the dry weight concentration in plants to the dry weight concentration in a specific soil layer. The dry weight is used to reduce the uncertainty. The accumulation of radionuclides in farm crops varies considerably for different soils. The difference in transfer factors of farm crops for different soils may be one or two orders of magnitude. Cultivation of agricultural crops is based on application of various methods of processing, different doses and combinations of fertilizers, irrigation in dry areas, drainage in boggy territories, etc. Technologies of crop cultivation or changes in soil properties lead to redistribution of radionuclides in the root zone and subsequently change the radionuclide accumulation in crops ⁽³⁴⁾. As an example the uptake of radionuclides by fruits and wheat is discussed.

3.4.3.1 Transfer to fruits

Fruit and vegetables form part of human diets and is consumed on a daily basis. The transfer of nuclides to fruit is also an important aspect when it comes to monitoring radiation to man. Radionuclides accumulated in the fruit as a result of uptake from the soil or as the result of

accumulation on the fruit from nuclide fallout, can contribute towards internal radiation dose. Radionuclides find a way into the fruits and other parts of the fruit by mechanisms which support their transportation; this includes retention, absorption and translocation. Above the ground contamination may be as an influence of processes such as interception, retention, absorption and translocation. Fruits are either directly contaminated or indirectly contaminated.

- **Direct contamination of the fruits**

In this method of contamination as a result of radionuclide fallout processes such as interception, retention, and absorption occurs.

- **Indirect contamination of the fruits**

This process occurs as the result of contamination above the ground part of the plant and it is followed by translocation of radionuclides into the fruit body. Absorption and translocation plays a major role in this process of fruit contamination, and is influenced by the ability of the plant to absorb water, mineral and other substances which may include radionuclides in the leaves and other parts of the plant ⁽³⁵⁾. Figure 3.1 illustrates the processes involved in fruit contamination.

3.4.3.2 Transfer to wheat plants

The migrations of natural radionuclides were studied in wheat, by Pulhani *et al.*⁽⁴⁶⁾ who studied the transfer of natural ^{238}U , ^{232}Th , ^{226}Ra , and ^{40}K from soil to wheat grain as the edible portion of the wheat plant. In the study neutron activation analysis and gamma-spectrometry were used to estimate the activity of uranium and thorium. Two study areas were selected to study the transfer of natural radionuclides. The accumulation of thorium in the wheat seedlings was associated with the variation in the concentration of other nutrients and trace elements. It was also observed that the ^{238}U and ^{232}Th concentrations of the grain in the fertilized soil are reduced by a factor of 2 and 1.5 respectively ⁽⁴⁵⁾. Shtangeeva *et al.*⁽⁴⁷⁾ studied the thorium uptake by wheat at different stages of plant growth. In the study, seeds of wheat *Triticum vulgare* (vill) Horst were germinated on a moist filter paper and grown in soil containing thorium.

3.4.4 Transfer in natural and semi-natural environment

The behaviour of radionuclides in the forest ecosystem differs significantly from other ecosystems and as a result the forest ecosystem has to be given specific consideration because

of the difference in the radionuclide's geochemistry and exposure pathways from other agricultural ecosystems that are more generally considered in assessments. Radionuclides can be effectively trapped and recycled in the forest environment; which means that the trapped radionuclides will have long residence times in that environment, increasing environmental exposure and possibly human exposure to radiation. The radionuclides in the forest stand a chance to be transferred to environmental species such as the trees, mushrooms, berries, etc. Transfer of natural radionuclides in forests has been studied to quantify their transfer to vegetables and fruit. In the studies the aggregate transfer factor model was applied.

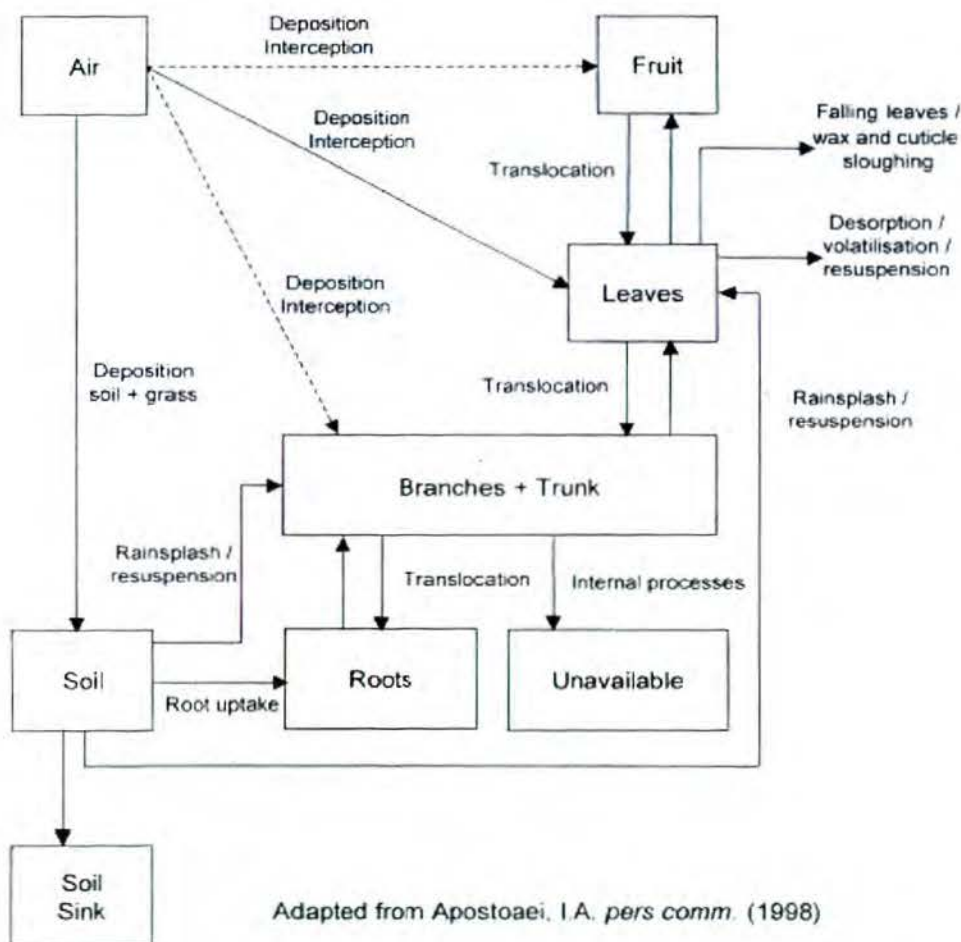


Figure 3.1: Processes involved in the transfer of radionuclides to fruits ⁽⁸⁾.

3.4.4.1 Transfer to mushrooms

The increased interest in the forest ecosystem following the Chernobyl accident has been associated with a greater emphasis on the radiological impact of naturally occurring foods (such as mushrooms) which are collected in forest environments. It has been recognized that mushrooms are collected in large numbers in the forest and can accumulate radionuclides to a considerable degree. Mushrooms grow in the forests and fields and have nutritional and medicinal values that act as antitumoral, antiviral and also have the ability to reduce cholesterol. The consumption of mushrooms does not only serve as food but also as medicine. Although consumed as foodstuff, mushrooms can accumulate toxic elements, which includes natural radionuclides. Rosa *et al.* ⁽³⁷⁾ determined the presence of natural radionuclides in mushrooms. The study evaluated the concentration of uranium (^{238}U , ^{234}U) isotopes and thorium (^{232}Th , ^{230}Th , and ^{228}Th) isotopes. The concentration of daughter nuclides, that is ^{226}Ra , ^{228}Ra , and ^{210}Po were also evaluated. Mushrooms as edible plants that grow in the forest have a tendency of accumulating large amounts of heavy and natural radionuclides.

3.4.4.2 Accumulation of radionuclides in plants

Soil solutions contain elements which include natural radionuclides at a certain concentration; plants need essential elements for their growth. Although roots serves as the natural barrier preventing transport of many trace elements including radionuclides to the upper parts of the plants; some NORM nuclides still find a way to the upper parts of the plant due to translocation. The rate of radionuclide translocation from roots to shoots is probably species-dependent and therefore differs with different species. Accumulation of uranium and thorium is much higher in plant roots than in leaves and in seeds. The uptake of radionuclides in farm crops varies considerably (up to three orders) for different soil types. Uptake of bivalent ^{226}Ra is mostly ruled by factors affecting the soil exchange capacity. For ^{210}Pb and ^{210}Po transfer factors are too limited to point to major soil properties ruling the transfer. Transfer factor values of heavy natural radionuclides for different species of plants differ by 10-100 times, and for different soil types by up to 10 times ⁽³⁴⁾.

3.4.5 Transfer factors to animals

Under normal circumstances, animals eat and drink directly from the environment. Contaminated grazing land presents a hub of radiation exposure for animals and also increases chances of radiation exposure to humans. Understanding the behaviour of radionuclides in

animals and the contamination route is therefore important for enhancement of a radiological protection plan for human.

3.4.5.1 Contamination routes

Animals can be contaminated by three different routes namely;

- Through the skin,
- By inhalation
- By ingestion.

Of the three routes, inhalation and ingestion are regarded as the major routes of contamination; inhalation is important since the lung surfaces and the site of the gaseous exchange are more permeable to a wide range of elements. Ingestion of contaminated feed, soil that adheres to the surface of forage or grass and water also contributes to the animal's exposure. However, intake via drinking water is generally a small contributor to the total radionuclide intake in animals due to low intake rates. Radionuclide intake via soil ingestion can be significant, but the availability for absorption of soil-associated radionuclides is often low. This makes the ingestion of contaminated feed the primary contributor and usually determines the radionuclide content of animals.

3.4.5.2 Modeling the transfer in animals

Activities that occur within the internal body of the animals, i.e. digestion and absorption of radionuclides ingested, determine the exact contamination of the animals. However, absorption plays a major part as it determines the amount of radionuclides that is being absorbed. The absorption occurs mainly in the gastrointestinal tract; during these activity minerals and other elements are distributed in the body and are measured by the difference between daily intake of the radionuclides and the excretion of those nuclides that were not absorbed. The transfer of radionuclides in animals is enhanced by the transfer coefficient of the nuclides of interest. The transfer of radionuclides to animal feed, milk, meat and eggs is quantified by the equations given below. The transfer of radionuclides is also quantified by the equilibrium ratio of the activity concentration of the radionuclides concerned to the dietary intake. The transfer factor in milk is denoted by F_m , and in both meat and eggs F_r

$$F_m(\text{d/kg}) = \frac{\text{Radionuclide Milk Concentration (Bq/kg)}}{\text{Feed Concentration (Bq/kg)} \times \text{Feed Intake (kg/day)}}$$

$$F_f(d/kg) = \frac{\text{Radionuclide Meat/egg Concentration (Bq/ kg)}}{\text{Feed Concentration (Bq/ kg) x Feed Intake(kg / day)}}$$

3.5 Transfer factors of radionuclides in aquatic environments

Aquatic radioecology as a science of the radionuclide migration in the aquatic ecosystem started in 1920 with the discovery of the high accumulation of some natural radionuclides (^{226}Ra and ^{238}U) by aquatic organisms. During the subsequent years the environmental behaviour of numerous natural and artificial radionuclides were studied. At present a great number of data is available on the radionuclide accumulation by different species of aquatic organisms, both under laboratory and natural conditions. Normally the elemental composition of organisms is specific for each biological species. The degree of element accumulation depends on the biological function of a particular element and its amount, which is necessary for metabolism. The elemental composition of aquatic organisms may differ considerably depending on the composition of the aquatic media and the bottom sediments.

3.5.1 Modeling the transfer of NORM nuclides in aquatic species

To quantify the transfer of radionuclides in the aquatic environment, parameters such as bioconcentration factors are used. This parameter gives better transfer factor results and is a simple approach to determine the contaminant concentration in a given organism as a function of its concentration in water. The bioconcentration factor (BCF) is calculated as the ratio of a contaminant's concentration in the whole body or target tissue of interest (e.g. muscle) to the concentration of the contaminant in water.

The results can be expressed as a unitless ratio if the radionuclide concentrations are expressed on a mass basis (i.e. Bq/kg wet tissue $\div$ Bq/kg of water) or it can be expressed in units of l/kg (i.e. Bq/kg wet weight in tissue $\div$ Bq/l of water.). Therefore the BCF is a parameter that represents the net effects of all the bioaccumulation and elimination processes affecting the transfer of radionuclides to food. Three idealized patterns of BCF's have been described as follows:

- The BCF of radionuclides in biological material is constant
- The BCF of nuclides is inversely proportional to its concentration in water
- The BCF for the nuclides is inversely proportional to the concentration of a non-isotopic carrier element.

3.5.2 Bioconcentration factors for naturally occurring radionuclides

Naturally occurring radionuclides in the marine environment contribute significantly to the background doses received by some marine organisms. Dose rates calculated for a series of natural radionuclides in phytoplankton, zooplankton, molluscs, crustacean and fishes indicate that significant doses were contributed from ^{40}K and ^{210}Po . The radionuclide ^{40}K is of limited interest because it is an isotope of an essential element that is under homeostatic control and its concentrations are determined primarily by body build and type. ^{210}Po is of special interest because it is the decay product of ^{210}Bi , which is the daughter nuclide of naturally occurring ^{210}Pb , and has a relatively short half-life of about 140 days. Data available indicate that ^{210}Po is accumulated in different tissues of marine organisms to levels greater than those resulting from the decay of its long lived precursor ^{210}Pb .⁽⁴³⁾

Generally, radionuclide uptake by biota and sorption to particles are modelled with the aid of bioconcentration factors and the distribution coefficients (K_d) values. In natural systems the bioconcentration factors are influenced by processes such as physical, chemical and biological processes which may change the environmental conditions and natural variability⁽⁴⁵⁾.

3.5.2.1 Transfer in the freshwater environment

Radionuclides which are scattered in the environment finds a way to the water system, either they are deposited in the ground water or on the surface of the watershed. Deposition of such nuclides may result as a long term source of radionuclides in the fresh water ecosystem. Radionuclides which are trapped in the water system somehow find a way to the agricultural environment and possibly to humans. Radionuclides are deposited in the water stream by different mechanisms which include direct deposition from the source (this process can be easily simulated by a relevant input model parameter) and indirect deposition which involves sets of processes. In this deposition, different processes such as radionuclide dissolution and dispensation occur. Radionuclides in water can either be adsorbed by the solid particles positioning them between the solid and the liquid phases. Solid particles in this case settle out to the bottom of the lake or the river, whereas the radionuclides dissolved in water can also be adsorbed in the bottom sediments and be transferred to deeper sediment layers⁽³¹⁾. Radionuclide wash-offs from the watershed is not a major process that enhances the contamination of the water ecosystems. The removed amount of radionuclides and the removal rate are not significant enough to be considered in the food chain models, but from the aquatic point of view one can view the route of contamination as an important one. This

route has the potential of collecting a small number of radionuclides from potentially contaminated areas that remain affected by precipitation of radionuclides.

Transportation of radionuclides by the flowing of water (wash-off) is generally distinguished by the following pathway⁽³¹⁾:

Liquid wash-off, when radionuclides are transported to the soluble phase with water and solid wash-off, which occurs when radionuclides are transported in particulate form with suspended matter. Wash-off is significantly lower for larger delays after deposition, but is still active years and decades after deposition. This stage is referred to as long term wash-off.

3.5.5.2 Physical processes involved in the freshwater ecosystem

Hydraulic processes are mainly responsible for the transport of toxic substances by water, whereas geochemical processes influence the interaction of dissolved radionuclides with suspended matter and bottom sediments. Sedimentation and re-suspension are of importance for controlling the two-way migration of radionuclides from the water column to the bottom sediments and vice versa⁽³¹⁾. Thus, the main physical processes controlling the migration of radionuclides in water bodies are described below:

- Diffusion and dispersion caused by gradients of concentration and the turbulent motion of water;
- Transport caused by the water current;
- Exchange of contaminants between the dissolved and solid phases;
- Deposition and re-mobilization of the radionuclide following the interaction with suspended matter and bottom sediments.

The first two processes are independent of the radionuclide characteristics, whereas the last two are related to the physical and chemical properties of the pollutant, and therefore depend on the radionuclide⁽³¹⁾.

CHAPTER 4

RADIATION AND INTERNAL DOSE CALCULATIONS

4.1 Radiation

Radiation was discovered in 1895 by the German physicist Conrad Roentgen. During his study of the properties of cathode rays and electric current he discovered that the cathode tube is emitting some rays and he called them X-rays. Just over three months after Roentgen's discovery of X-rays, radioactivity was discovered by Henri Becquerel. He experimented with crystals of a uranium salt called potassium uranyl sulphate, which were known to be highly fluorescent. In his experiment Becquerel wrapped a photographic plate in black paper and placed uranium crystals immediately outside the covered photographic plate, he firstly exposed the plate and crystals to sunlight for several hours and found that the dark spots which were placed in the plate corresponded with the position of the uranium crystals. Interest in the existence of radiation grew from the wrong conclusion made by Becquerel that the radiation which had passed through the wrapping and exposed the photographic plate was due to phosphorescence produced by the effects of sunlight on the uranium crystals. Following the conclusion made by Becquerel, Marie Curie reasoned that other elements may also give out the new type of rays discovered by Becquerel and soon found that the substance thorium emitted these rays as well and she coined the term radioactivity to describe the new form of energy produced by uranium and thorium ⁽³⁸⁾. Since the discovery of radioactivity both uranium and thorium and their progeny have become known to be natural radiation sources and are described as natural radioactivity since they are found naturally in the earth's crust. Their natural abundances in the earth's crust as described in the chart of nuclides ⁽²⁴⁾ are as follows; ²³⁵U has a natural abundance of 0.72%, ²³⁸U is 99.275% and ²³²Th is 100%.

4.2 Radioactive decay

An atom, defined as the smallest unit of matter, constitutes both chemical and physical properties. It consists of a nucleus surrounded by electrons. The nucleus has protons and neutrons which bring about nuclear stability by balancing the proton-neutron ratio. The nuclei that have an imbalance in the ratio of neutrons and protons tend to undergo changes within the

nucleus to achieve a more stable configuration of protons and neutrons. The changes are accompanied by the emission of electromagnetic radiation from the nucleus together with the release of a substantial amount of energy related to the binding energy of the nucleons in their final nuclear configurations. These changes are referred to as radioactive decay of the nucleus and the whole process is described as radioactivity. The decay route for primordial radionuclides and their progeny are given in Table 1 of Chapter 1.

4.3 Pathways to humans

Being part of the environment, radiation exists in many different types of materials and it has different ionizing capability, i.e. ionizing radiation and non-ionizing radiation. Ionizing radiation has the ability to knock-off an electron from any material, non-ionizing radiation is weak and it can be deflected easily compared to ionizing radiation. Radiation from materials existing naturally results from the primordial radionuclides such as ^{238}U , ^{235}U , ^{232}Th and their progeny. In the environment naturally occurring radiation is more concentrated in rocks and soil. Natural radiation in foodstuffs is due to contamination of agricultural ecosystems. In agricultural ecosystems crops take up radionuclides from contaminated soil and contaminated water, while fish takes up radionuclides from contaminated sea water or fresh water. The exposure pathways of radionuclides from the source into the environment, including NORM from mining and processing of minerals into agricultural ecosystems, to humans are illustrated in Figure 4.1.

4.4 Effects of ionizing radiation in body cells

The effects of ionizing radiation are characterized either as stochastic or non-stochastic (also known as deterministic) effects. A stochastic effect is one in which the probability of occurrence increases with increasing dose, but the severity in affected individuals does not depend on the dose. There is no threshold dose for effects that are truly stochastic because these effects arise in single cells and it is assumed that there is always some small probability of the event occurring even at very small dose. A deterministic effect is one that increases in severity with increased dose, usually above a threshold dose in affected individuals ⁽³⁹⁾. The non-stochastic effects can be controlled by setting the annual dose limits lower than the acceptable threshold and in the process this threshold will not be reached; also the stochastic effects can be minimized by applying annual dose limits which are acceptable. Figure 4.2 describes the stochastic and non-stochastic effects of radiation dose to living cells.

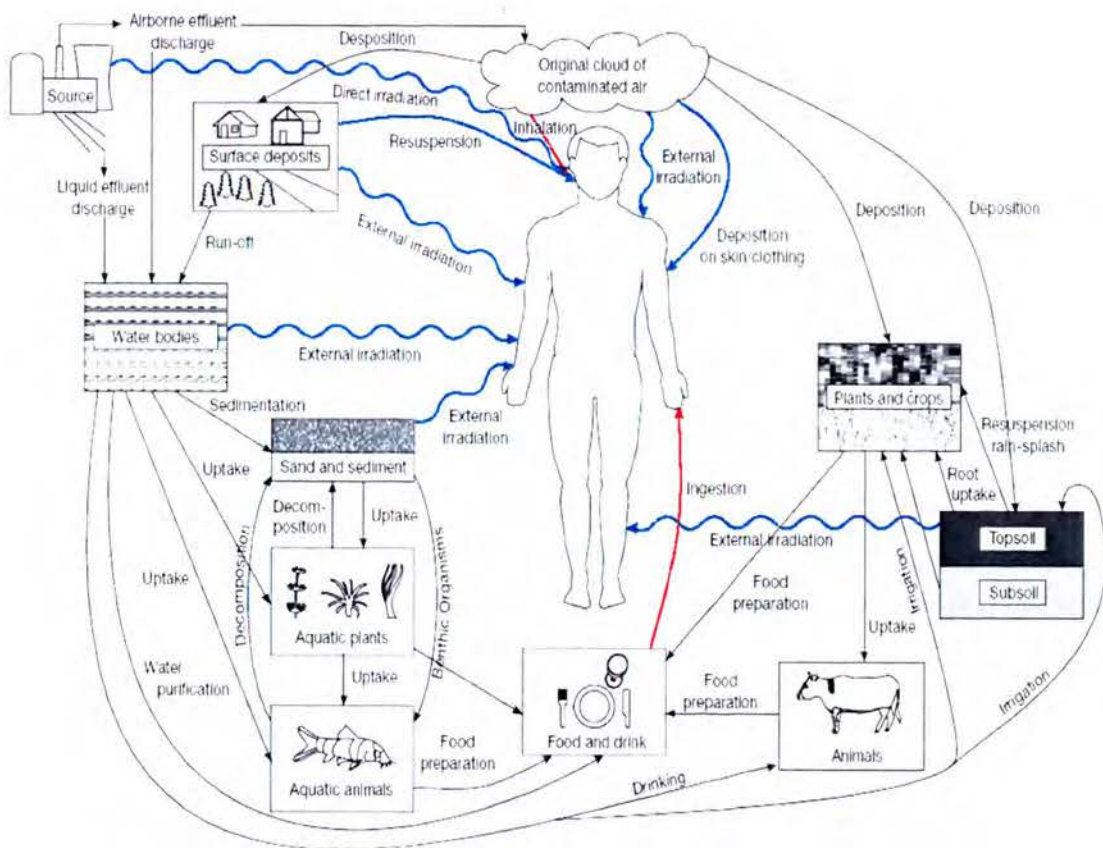


Figure 4.1 Schematic representations of exposure pathways (32).

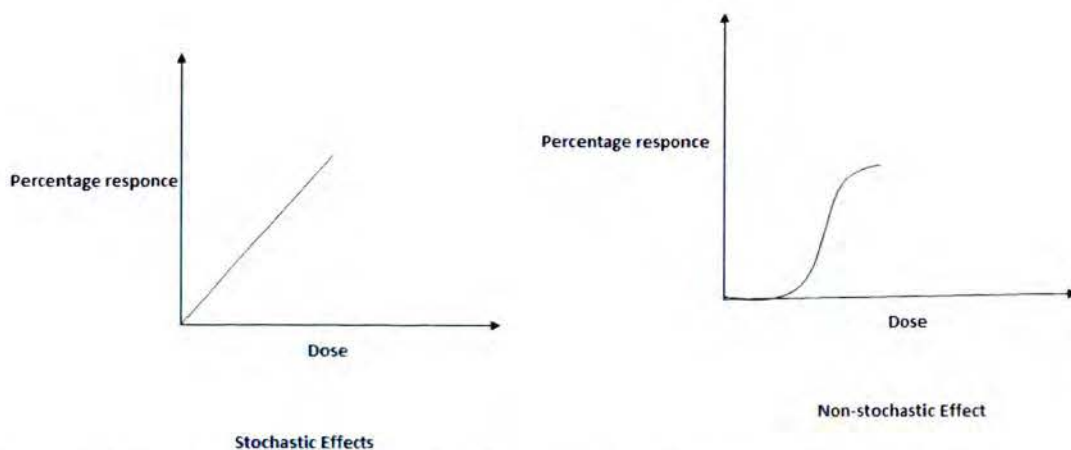


Figure 4.2 General graphs depicting the characteristics of ionizing radiation in cells.

4.5 Health risks related to ionizing radiation

Health risks at the lower doses are associated with environmental radioactivity mainly from NORMs (^{238}U , ^{235}U and ^{232}Th nuclides and their progeny) and low occupational exposure due to the sources, and are extrapolated from the high dose data. The estimation of the human health risks associated with radiation exposure are based mechanistically on the view that the detrimental effects of irradiation have their origin in exposed cells or, in the case of heritable effects, in cells directly descendent from them. The effects considered include radiation-induced genomic instability, bystander effects, abscopal effects, induced clastogenic factors and hereditary effects ⁽⁴⁰⁾. The effects are briefly explained below.

- If a single cell is irradiated and survives, it may produce daughter cells that over generations have increasing numbers of alterations in their genomes, even though the daughters themselves were not irradiated. This effect is called induced genomic instability. The alterations in genomes of the daughter cells can include alterations in their chromosomes, mutation of their genes and other deoxyribonucleic acids (DNA).
- The bystander effect is the ability of the irradiated cells to convey manifestations of damage to neighboring cells not directly irradiated. The bystander phenomenon has been tentatively linked to an elevated risk of health effect at low dose in humans (cancer, congenital abnormalities, neurological disease and hereditary effects) but none of these health effects has so far been scientifically shown to be associated with such radiation induced effect. However, the possibility cannot be excluded but remains purely speculative. The major concern in the low dose exposure range is the increased risk with increased radiation dose. The conventional approach is to consider that at low dose only some cells in the human body are hit by the ionizing radiations, that their total number is dose dependent and that the probability to get a cell transformed into a cancer cell depends on the number of cells being hit or ionized. Bystander effect suggests that the target for radiation is larger than the individual ionized cell and that a linear extrapolation of risks from high to low doses could underestimate the risk at low dose. The bystander effect has been demonstrated especially after high-LET (high linear energy transfer) exposure.
- An abscopal effect is said to occur if there is a significant response in a tissue that is physically separated from the region of the body exposed to radiation. The abscopal effect is also described as a reaction that occurs outside the irradiated part of the cell

and effects have been observed in cells which get exposed during activities related to radiation therapy.

- Blood plasma from irradiated animal or human cells can contain clastogenic factors capable of inducing chromosomal damage in an unexposed cell.
- Heritable effects are those effects observed in offspring born after one or both parents have been irradiated prior to conception. Trans-generational effects are those that are expressed beyond the first generation.
- Finally, some of the manifestations of non-targeted and delayed effects noted above can arise spontaneously and after exposure to other toxic agents.

The impact of ionizing radiation on the immune system can be assessed by estimating the changes in cell numbers or by using a variety of functional assays. A high dose of radiation produces immune-suppression mainly due to the destruction of cells.

4.6 Internal radiation dose

Estimation of internal radiation doses due to inhalation or ingestion of radionuclides is in most cases based on assumptions and calculations. To make it simple and convenient different models such as the gastric internal (GI) tract model (Figure 4.3) have been developed to describe the paths of the radionuclides in the body and how they are excreted. The IAEA Safety Standard Series ⁽⁴¹⁾, describe the pathways of radionuclides taken directly and indirectly in to the humans body by inhalation and ingestion. In the process where the radionuclide is taken by ingestion, the gastro internal tract model is used, the model describes a human as a composite of different compartments. Each organ and tissue of deposition is assumed to consist of one or more compartments and from each of these compartments the radionuclides are translocated at an appropriate rate to the excretion pathways. In understanding the internal dosimetry and dosimetry models some terms are defined: intake, uptake, deposition and content. Intake refers to the quantity of radionuclides incorporated into the body through inhalation, ingestion or injection, while uptake refers to the quantity of radionuclides that is absorbed into systemic circulation by injection directly into the blood or by absorption via the respiratory or GI (Gastric Intestine) tract. Deposition is that quantity of radionuclides that is deposited into an organ; and content refers to the quantity of radionuclides that resides in the compartment of interest. The uptake and excretion of radionuclides from the human body is described in Figure 4.3, the gastro intestine track model. It is a four compartment model comprising of the stomach, small intestine, upper large intestine and lower large intestine. The

mean residence time of radionuclides in each GI compartment is 1, 4, 13, and 24 hours respectively. Absorption of radionuclides is usually assumed to occur from the small intestine. For the estimation of equivalent dose to the wall of the GI track from radionuclides in the lumen, doses are calculated to the mucosal cell layer ⁽⁴²⁾.

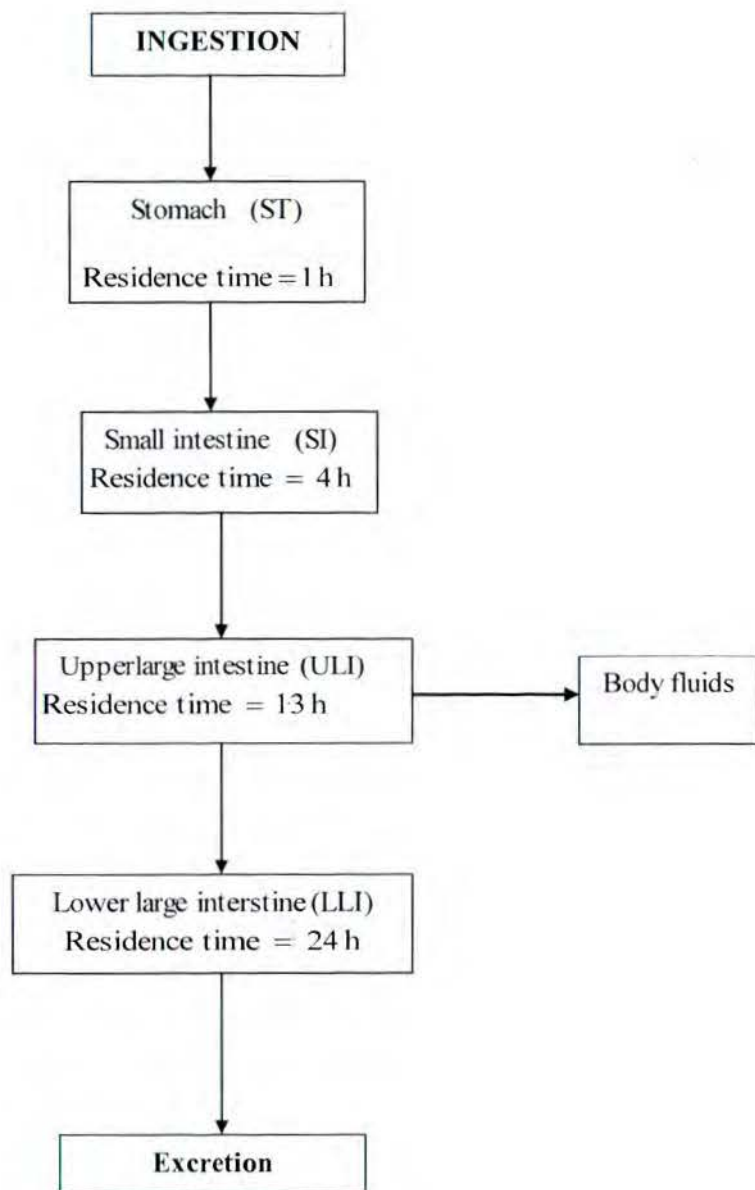


Figure 4.3 Mathematical model used to describe the kinetics of radionuclides in the GI tract ⁽⁴²⁾.

4.7 Theoretical calculation of the internal dose

Ingestion of contaminated foodstuffs depends on the dietary habits of the affected individual or group, and the concentration of the radionuclides concerned. Equivalent dose and committed effective dose are used in the radiological assessment of internal radiation. In achieving the results, dose conversion factors for ingestion are used, which vary with age groups. The values are calculated by using the different age-dependent models for respiratory tract, gastrointestinal tract and other systemic biokinetic behaviour of radionuclides.

The annual effective ingestion dose to man due to consumption of contaminated foodstuffs is given by:

$$\text{Dose (Sv/a)} = \text{Concentration (Bq/kg)} \times \text{Annual intake (kg/a)} \times \text{Dose conversion factor (Sv/Bq)}$$

To calculate or estimate the ingestion dose, the concentration of radionuclides in different crops or food stuffs and the consumption rate of the foodstuffs are used. The committed dose is calculated as follows:

$$D_i(g) = \int dt \sum_p a_p(g) \cdot C_{ip} \cdot K_{ip} \cdot DFI_i(g)$$

$D_i(g)$ Represent dose committed for lifetime to individual of age group g from the ingestion of radionuclide i

C_{ip} Concentration of radionuclide i in product p (Bq/kg or Bq/l)

$a_p(g)$ Consumption rate (kg or l per day) of product p by individual of age group g

$DFI_i(g)$ Effective dose equivalent factor (Sv/Bq ingested) for radionuclide i, and age group g

K_{ip} Correction factor that takes into account the reduction in the content of radionuclides i in product p resulting from processing and delay from harvest to consumption. The general

equation for this factor is $A^* \cdot e^{-\lambda_d t_d}$, where A is the reduction in processing and t_d is the delay time due to storage and treatment and λ_d is the decay constant of the radionuclide.

The contribution of these products to the collective dose is calculated by:

$$CD_i = \int dt \sum_p Y_p \cdot C_{ip} \cdot K_{ip} \cdot CDFI_i(P)$$

Where

CD_i Collective dose from ingestion of radionuclide i.

Y_p Annual production (Kg or l per year) of product p in the area of interest.

$CDFI_i(P)$ collective dose factor (Sv.man/Bq) for radionuclide i and product p; the calculation of the collective dose factor $CDFI_i(P)$ can be made by weighting the individual age dependent dose factors with the population fractions in each age group and with the consumption fraction of each product by members of each age group.

$$CD_i(g) = \sum_{year=1}^n \sum_p A_p(g) \cdot C_{ip}(h_y) \cdot K_{ip} \cdot DFI_i(g)$$

Where:

$C_{ip}(h_y)$ Concentration of radionuclides i in crop p at harvest time of year y (Bq/kg fresh weight).

$A_p(g)$ Ingestion rate (kg fresh weight per year) of crop p by individuals of age group g.

Similarly the collective dose may be attained by the following equation;

$$CD_i = \sum_{year=1}^n \sum_p Y_p \cdot C_{ip}(h_y) \cdot K_{ip} \cdot CDFI_i$$

Where:

$C_{ip}(h_y)$ Concentration radionuclides i in crop p at harvest time of year y (Bq/kg fresh weight).

Y_p Ingestion rate (kg fresh weight per year) of crop p by individuals of age group g.

To illustrate the process the following example is given for the consumption of maize as one of the staple foods in South Africa.

As outlined above we need three basic pieces of information,

1. The activities of the radionuclides of interest. This information is available from the laboratory analysis. In principle one only needs the activity of the longer-lived nuclides and can assume radioactive equilibrium with their shorter-lived daughters. Thus basically one needs to know the concentration of ^{238}U , ^{230}Th , ^{226}Ra , ^{210}Pb , ^{210}Po , ^{231}Pa , ^{227}Ac , ^{232}Th , ^{228}Ra and ^{224}Th . Of these ^{230}Th and ^{231}Pa are not readily available as their analytical sensitivity is low. In this case one may assume equilibrium between $^{238}\text{U}/^{230}\text{Th}$ and $^{227}\text{Th-Ac}/^{231}\text{Pa}$.
2. The annual consumption of the maize. This depends on the dietary habit and age category of the person exposed. Default consumption rates can be obtained from the licensing guide LG1032 issued by the Council for Nuclear Safety ⁽⁹⁾, currently named the National Nuclear Regulator. Data extracted from this document are given in Table 4.1.
3. The dose conversion factor. This depends on the nuclide of interest and the age category of the person exposed. These data can be extracted from the IAEA's Safety Series 115 ⁽⁷⁵⁾. The relevant data are given in Table 4.2.

Table 4.1 South African default values for intake via ingestion ⁽⁷⁵⁾.

Consumption per year in kg fresh weight

	Age					
	< 1 a	1-2 a	2-7 a	7-12 a	12-17 a	> 17 a
Freshwater Fish	0.5	1	5	10	10	25
Meat	10	20	50	75	100	100
Poultry	7.5	15	35	60	75	75
Eggs	3	6	15	25	30	30
Cereals and Grains	45	60	75	90	128	150
Root crops	51	68	85	102	145	170
Other Vegetables Fruits and Nuts	39	52	65	78	111	130
Water (Litres)	200	260	300	350	600	730
Milk (Litres)	300	300	300	300	300	250

It will be obvious that one now needs a type of matrix approach to perform the required dose calculation, which is a function of the type of food and its age dependent consumption rate, the age dependent dose conversion factor and the concentration of the radionuclides in the foodstuff.

Table 4.2 Dose conversion factors⁽⁷⁶⁾ for ingestion by members of the public (in Sv/Bq)

	< 1 a	1 - 2 a	2 - 7 a	7 - 12 a	12 - 17 a	> 17 a
U-238	3.4E-07	1.2E-07	8.0E-08	6.8E-08	6.7E-08	4.5E-08
Th-234	4.0E-08	2.5E-08	1.3E-08	7.4E-09	4.2E-09	3.4E-09
Pa-234m						
U-234	3.7E-07	1.3E-07	8.8E-08	7.4E-08	7.4E-08	4.9E-08
Th-230	4.1E-06	4.1E-07	3.1E-07	2.4E-07	2.2E-07	2.1E-07
Ra-226	4.7E-06	9.6E-07	6.2E-07	8.0E-07	1.5E-06	2.8E-07
Rn-222						
Po-218						
Pb-214	2.7E-09	1.0E-09	5.2E-10	3.1E-10	2.0E-10	1.4E-10
Bi-214	1.4E-09	7.4E-10	3.6E-10	2.1E-10	1.4E-10	1.1E-10
Po-214						
Pb-210	8.4E-06	3.6E-06	2.2E-06	1.9E-06	1.9E-06	6.9E-07
Bi-210	1.5E-08	9.7E-09	4.8E-09	2.9E-09	1.6E-09	1.3E-09
Po-210	2.6E-05	8.8E-06	4.4E-06	2.6E-06	1.6E-06	1.2E-06
U-235	3.5E-07	1.3E-07	8.5E-08	7.1E-08	7.0E-08	4.7E-08
Th-231	3.9E-09	2.5E-09	1.2E-09	7.4E-10	4.2E-10	3.4E-10
Pa-231	1.3E-05	1.3E-06	1.1E-06	9.2E-07	8.0E-07	7.1E-07
Ac-227	3.3E-05	3.1E-06	2.2E-06	1.5E-06	1.2E-06	1.1E-06
Th-227	3.0E-07	7.0E-08	3.6E-08	2.3E-08	1.5E-08	8.8E-09
Ra-223	5.3E-06	1.1E-06	5.7E-07	4.5E-07	3.7E-07	1.0E-07
Rn-219						
Po-215						
Pb-211	3.1E-09	1.4E-09	7.1E-10	4.1E-10	2.7E-10	1.8E-10
Bi-211						
Tl-207						
Th-232	4.6E-06	4.5E-07	3.5E-07	2.9E-07	2.5E-07	2.3E-07
Ra-228	3.0E-05	5.7E-06	3.4E-06	3.9E-06	5.3E-06	6.9E-07
Ac-228	7.4E-09	2.8E-09	1.4E-09	8.7E-10	5.3E-10	4.3E-10
Th-228	3.7E-06	3.7E-07	2.2E-07	1.5E-07	9.4E-08	7.2E-08
Ra-224	2.7E-06	6.6E-07	3.5E-07	2.6E-07	2.0E-07	6.5E-08
Rn-220						
Po-216						
Pb-212	1.5E-07	6.3E-08	3.3E-08	2.0E-08	1.3E-08	6.0E-09
Bi-212	3.2E-09	1.8E-09	8.7E-10	5.0E-10	3.3E-10	2.6E-10
Po-212						
Tl-208						

Blank data are not available and assumed “zero” in dose calculations

Accordingly, let us take the example of the consumption of maize.

1. The activities of the radionuclides of interest. Given the following results from the laboratory analysis given in mBq/g (Bq/kg):

^{238}U 10 (As ^{230}Th is not known we assume all daughters of ^{238}U to be 10 mBq/g)
(Take ^{235}U and its short-lived daughters as 1/20,9 times 10 mBq/g)

^{230}Th Below detection limit

^{226}Ra 20 (Take all daughters of ^{226}Ra up to ^{210}Pb as 20 mBq/g)

^{210}Pb 5 (As ^{210}Po is not known we assume all daughters of ^{210}Pb to be 5 mBq/g)

^{210}Po Not determined

^{231}Pa Not determined (As ^{231}Pa is not known take it to be 0,5 mBq/g as for ^{227}Ac)

^{227}Ac 0,5 (Take ^{231}Pa also as 0,5 mBq/g)

^{227}Th 0,25 (Take the rest of the daughters also as 0,25 mBq/g)

^{232}Th 0,75 (Take the value as is: 0,75 mBq/g)

^{228}Ra 1,5 (Take its short-lived daughter also as 1,5 mBq/g)

^{224}Th 0,75 (Take the rest of the daughters also as 0,75 mBq/g)

2. The annual consumption of the maize is taken from the default values in Table 4.1.

Consumption per year in kg fresh weight

	Age					
	< 1 a	1-2 a	2-7 a	7-12 a	12-17 a	> 17 a
Cereals and Grains	45	60	75	90	128	150

3. The dose conversion factors are taken as given in Table 4.2.

Table 4.3 gives the worked-out radiological exposure to the various age groups of the public. The data manipulation is best done in a spread-sheet (Excel, QPRO or alike) as for other type of foodstuffs the category may change (intake per year) and the radionuclide concentrations of the foodstuff concerned will also vary. However, once the database is set-up some simple adaptations will provide immediate result and avoid going through otherwise time consuming calculations.

Table 4.3 Dose calculation example of consumption of contaminated maize (in mSv/a)

Cereals and Grains Consumption in kilogram per year							
Activity mBq/g	Consumption x Activity x Dose per unit intake = Yearly Dose						Average Life-time Exposure mSv/a
	< 1 a	1 - 2 a	2 -7 a	7 - 12 a	12 - 17 a	> 17 a	
	45	60	75	90	127,5	150	
10,00	0,153	0,072	0,060	0,061	0,085	0,068	0,069
10,00	0,018	0,015	0,010	0,007	0,005	0,005	0,006
10,00							
10,00	0,167	0,078	0,066	0,067	0,094	0,074	0,075
10,00	1,845	0,246	0,233	0,216	0,281	0,315	0,319
20,00	4,230	1,152	0,930	1,440	3,825	0,840	1,160
20,00							
20,00							
20,00	0,002	0,001	0,001	0,001	0,001	0,000	0,001
20,00	0,001	0,001	0,001	0,000	0,000	0,000	0,000
20,00							
5,00	1,890	1,080	0,825	0,855	1,211	0,518	0,649
5,00	0,003	0,003	0,002	0,001	0,001	0,001	0,001
5,00	5,850	2,640	1,650	1,170	1,020	0,900	1,102
0,48	0,008	0,004	0,003	0,003	0,004	0,003	0,003
0,48	0,000	0,000	0,000	0,000	0,000	0,000	0,000
0,50	0,293	0,039	0,041	0,041	0,051	0,053	0,054
0,50	0,743	0,093	0,083	0,068	0,077	0,083	0,091
0,25	0,003	0,001	0,001	0,001	0,000	0,000	0,000
0,25	0,060	0,017	0,011	0,010	0,012	0,004	0,006
0,25							
0,25							
0,25	0,000	0,000	0,000	0,000	0,000	0,000	0,000
0,25							
0,25							
0,75	0,155	0,020	0,020	0,020	0,024	0,026	0,027
1,50	2,025	0,513	0,383	0,527	1,014	0,155	0,296
1,50	0,000	0,000	0,000	0,000	0,000	0,000	0,000
0,75	0,125	0,017	0,012	0,010	0,009	0,008	0,011
0,75	0,091	0,030	0,020	0,018	0,019	0,007	0,012
0,75							
0,75							
0,75	0,005	0,003	0,002	0,001	0,001	0,001	0,001
0,75	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Total mSv/a	17,67	6,02	4,35	4,52	7,73	3,06	3,88

CHAPTER 5

AGRICULTURAL INDUSTRY

5.1 Agricultural sector in South Africa

South Africa as a developing country has a vibrant economy that relies on the mining and agricultural sectors and other industries. The mining of uranium, gold, platinum and other minerals contributes significantly to the growth of the economy and job creation. The agricultural sector also contributes to the same economy through production of good agricultural foodstuffs; primary agriculture contributed 3% to gross domestic product (GDP) of the country in 2009/2010. In the past five years the economy has improved significantly from the contribution made by the mining and the agricultural sectors. The agricultural sector created about 8% of the jobs. The export of agriculture products has been slower compared to import and the major imports in this sector include product such as wheat, rice, vegetable oils and poultry meat. Only 12% of South African land is suitable for rain fed crops, with only 3% of land fertile for agricultural food production, while 69% is suitable for grazing; 1.3 million ha of land is under irrigation ⁽⁴⁸⁾. Since both industries (mining and agriculture) contribute significantly to the economy of the country, it is vital to quantify the effects of mining activities, particularly gold mining, on the agricultural land. To minimize possible damage of the agricultural land due to mining activities, the released radionuclides should be monitored. In terms of export activities of agricultural products, South Africa has exported about 20.3% of its products in 2010/2011 to the Netherlands and United Kingdom as compared to the export percentage of 20.7% in the 2009/2010 period. An increase of 6.9% in the export value was observed in the 2010/2011 period as compared to the previous year ^(49, 50).

5.2 Production of agricultural products (2009/ 2010)

In 2007 to 2008 the price of agricultural products increased by 14.3% as compared to the increase of about 24.6% during the previous year. In 2010/11, the producer price of agricultural products decreased on average by 14.3%. Prices of vegetables decreased by 7.2% while the prices of fresh fruits increased by 13.3%. The producer prices of animal products

were increased by 3.6%. Generally the 2010/ 2011 report noted that the gross value agricultural production increased by 6.9% ⁽⁵³⁾. Table 5.1 shows the trend of vegetable production in South Africa for the past five years.

Table 5.1 Production table for vegetables in South Africa for the past five years ⁽⁵⁰⁾.

Year	Production ('000 tons)
2006	4205
2007	4239
2008	4530
2009	4311
2010*	4558

* Indicates preliminary values

5.3 Vegetables grown in South Africa

Vegetables play an important role in the human diet as a result of their nutritional aspects; they contain carbohydrates, proteins, vitamins, minerals and other important trace elements. Consumption of vegetables has increased gradually due to the fact that they form part of the daily diet for humans and animals. Their production in the market has increased remarkably based on their demand. The Food and Agriculture Organization (FAO) defines vegetables as plants cultivated both as field crops and garden crops, both in the open and under glass. Table 5.2 list the vegetable produced in South Africa. Main production was for white maize, yellow maize, potatoes, tomatoes, onions, green mealies, pumpkins, carrots and cabbage with the quantity of white and yellow maize dominating other vegetable production.

5.4 Classification of vegetables.

Vegetables can be categorized according to respective groups based on the edible part; i.e. leafy vegetables, shoot vegetables, pot and seed vegetables, root and bulb vegetables, flower vegetables and fruit vegetables. Vegetables can also be classified by family, i.e. Cole crops or Crucifers, Cucurbits, Legume Vegetables, Lilies, Solanaceous crops and Mushrooms ⁽⁵¹⁾. The basic approach in this regard, is classifying vegetables on the basis of their commonalities among their groups, this include the edible part (tissues and organs consumed), the ecological adaptation and the taxonomy respectively ⁽⁵²⁾.

Table 5.3 and Table 5.4 give the general classification of vegetables on the basis of edible part and family respectively.

Table 5.2 List of vegetables grown in South Africa and the production quantity value ⁽⁵⁰⁾.

Vegetable	Quantity produced ('000 tons)
White maize	6052
Yellow maize	4308
Potatoes	2072
Tomatoes	544
Onions	518
Green mealies	339
Pumpkin	230
Squashes	171
Cabbage	149
Carrots	142
Other vegetables	110
Sweet potatoes	63
Beetroot	57
Lettuce	38
Gem squash	27
Green beans	24
Cucumbers	21
Amadumbe	15
Cauliflower	15
Mushrooms	12
Green peas	12
Asparagus	1

Table 5.3 Classification of the vegetables based on edible part (FAO) ⁽⁵²⁾

Vegetable group		Definition	Examples
i.	Leafy vegetables	Crops grown mainly for their leaves. Rich in vitamins and minerals.	Malabar nightshade (<i>alugbate</i>), amaranth (<i>kulitis</i>), lattice, jute (<i>saluyot</i>) and malunggay (horse radish tree)
ii.	Shoot vegetables	These are plants grown primarily for their edible shoots, mainly the young succulent stem.	Asparagus, Bamboo, Celery
iii.	Pot and seed vegetables	These vegetables belong to the Leguminosae or Fabaceae family, and are grown for their young pods and seeds.	Snap bean, pole sitao, winged bean, okra, sweet corn.
iv.	Root and Bulb vegetables	Plants grown for their shallow underground roots and stem	Carrot, potato, onion, radish, tannia.
v.	Flower vegetables	Generally described as edible flowers	Horse radish tree (<i>Malunggay</i>), katuray (<i>sesbania grandiflora</i>), squash, rose, sunflower.
vi.	Fruit vegetable	These are the vegetables grown for their fleshy, succulent fruits.	Ampalaya, eggplant, tomato, peppers, melon.

Table 5.4 Classification of vegetables on the basis of family (FAO) ⁽⁵²⁾

	Vegetable	Description by family	Example
i.	Cole Crops or Crucifers	Vegetable crops belonging to the Cruciferae or Brassicaceae (mustard) family, with edible leaves or heads	Cabbage, cauliflower, mustards, pechay, radish and Chinese cabbage.
ii.	Cucurbit	Vegetables belonging to the Cucurbitaceae (ground and squash) family. They grow mainly on their fruits but some have edible young shoots and flowers, and they are also called Vine crops.	Bottle gourd, charantia, cucumber, luffa, melons and squash.
iii.	Legume vegetables	Members of the Leguminosae or Fabaceae (Bean) family and are rich in protein.	Bush sitao, katuray, kidney bean, lima bean, pea, pole sitao.
iv.	Lilies	The vegetables are classified under the Liliaceae (Lily) family	Asparagus, garlic, onion
v.	Solanaceous crops	Vegetables belonging to the Solanaceae (nightshade or Eggplant) family and with the exception of white potato are called fruit vegetables.	Eggplant, tomato, peppers, white potato.
vi.	Mushrooms	Edible fungi belonging to the division Basidiomycota (club fungi), the edible part commonly consist of an upright stalk and umbrella shaped cap	Straw mushroom, puffball, termite mushroom, “kabuting –higante”

Annexure 2 gives the data base of vegetables and their botanical names; the data is adopted from the world programme for the census of agriculture 2010 ⁽⁵²⁾.

CHAPTER 6

INSTRUMENTATION AND DATA COLLECTION TECHNIQUES

6.1. Neutron Activation Analysis

6.1.1 Introduction

Neutron Activation Analysis (NAA) is an analytical technique based on the measurement of characteristic radiation from radionuclides formed directly or indirectly by neutron irradiation of the material of interest ⁽⁵³⁾. NAA is primarily a method of trace element determination (concentrations ppm-ppb range) although minor and major elements may be determined in some applications. The method originated with Hevesy and Levi in 1936, but did not become a practical method of analysis until the development of the nuclear reactor in the 1940s as a high intensity neutron source. The introduction of the NaI(Tl) scintillation γ -ray detector in the 1950s and the high resolution Ge(Li) γ -ray detector (1960s) established NAA as a major method of trace element determination in biological materials ⁽⁵⁴⁾. Currently NAA is accepted as an important technique for elemental analysis of different materials ⁽⁵⁵⁾. In the last three decades NAA has been found to be extremely useful in the determination of trace elements in many disciplines, which include nutritional and health related studies, geological as well as material science studies ⁽⁵³⁾.

6.1.2 Concept and principles of NAA

The concept of NAA is to produce radioactive isotopes by exposing the sample to a high flux of neutrons in a nuclear reactor. The produced isotopes decay, mostly through beta decay, and in the process gamma rays with discrete energies are emitted. The process is schematically shown in Figure 6.1. In the process an incident neutron hits the target nucleus resulting in neutron capture; the captured neutron interacts with the target nucleus via non-elastic collision forming a compound nucleus in an excited state. The compound nucleus decays into a more stable configuration through emission of one or more characteristic prompt gamma rays. The new configuration yields a radioactive nucleus which also decays by emission of one or more

characteristic delayed gamma rays but at much slower rate according to the half-life of the radioactive nucleus. The reaction is known as the (n, γ) reaction.

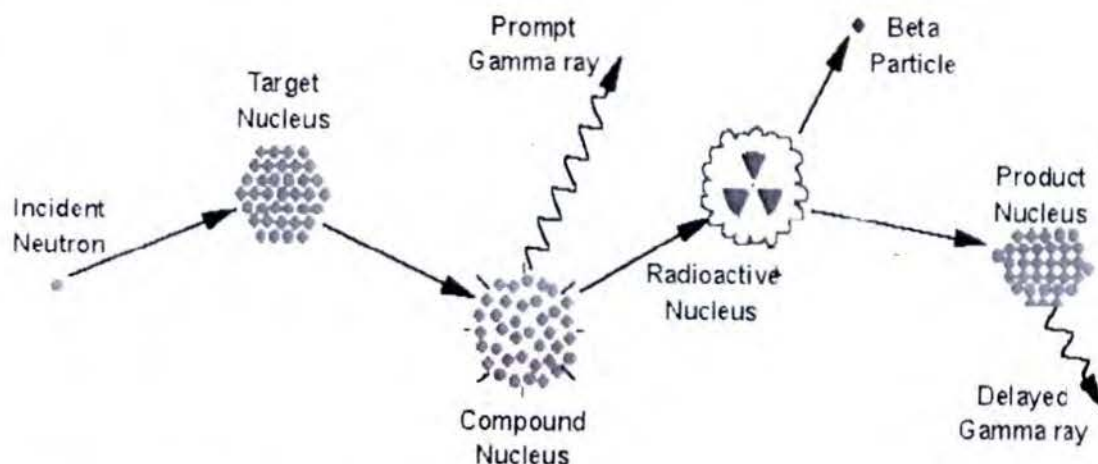


Figure 6.1 Concept of NAA ⁽⁶⁶⁾

In principle neutron activation analysis falls into two categories, namely prompt gamma ray neutron activation analysis (PGNAA) and delayed gamma ray neutron activation analysis (DGNAA). Both activation analysis methods consist of the following steps:

- selection of the optimum nuclear reaction,
- preparation of the sample for irradiation,
- irradiation of the samples,
- counting the irradiated samples, and
- analysis of the counting results.

6.1.2.1 Prompt gamma ray neutron activation analysis (PGNAA)

Prompt gamma ray neutron activation analysis is a non-destructive radioanalytical technique capable of rapid or simultaneous “in-situ” multiple elemental analyses across the entire periodic table, from hydrogen to uranium. The method is valuable for measurement of elements that do not form neutron capture products with delayed gamma ray emissions; only the prompt capture gamma rays are measured. The elemental coverage of PGNAA complements that of conventional instrumental neutron activation analysis (DGNAA). PGNAA can measure all elements except for oxygen in most common materials. Because nearly every neutron capture results in an (n, γ) reaction, the yields of prompt gamma rays per

neutron is greater than that of delayed gamma rays. However, PGNA has poor sensitivity compared to DGNAA ⁽⁵⁶⁾. Limitation of the PGNA technique with reactor neutrons are related to the background and relatively low neutron fluxes at a beam station close to the reactor.

6.1.2.1 Delayed gamma neutron activation analysis (DGNAA)

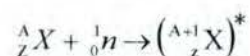
The delayed gamma neutron activation analysis method measure the radioactive decay of the product's nucleus while PGNA only measures the prompt captured gamma rays. It is applicable to elements that form artificial radioisotopes. The delayed rays are analyzed over seconds, hours, days, weeks, or even months. The DGNAA improves the sensitivity for long lived radionuclides as it allows short lived ones to decay and effectively eliminate interferences. This category of NAA is characterized by long irradiation periods.

6.1.3 Interaction of neutrons with matter

The reaction of neutrons with materials can be elastic or inelastic. In an elastic collision the total energy of the neutron before collision is conserved, that is the total kinetic energy before collision equals the total kinetic energy after collision; with inelastic collision the kinetic energy is not conserved, that is some of the kinetic energy of the neutron is absorbed by the material. During activation, the neutron enters the nucleus of an atom to form what is generally known as a compound nucleus. The compound nucleus may release some of its energy by emitting a gamma photon or other elementary particle such as a neutron, proton or alpha particle. When a neutron interacts with the nucleus three interaction reactions may occur, namely compound nucleus formation, potential scattering and direct interaction.

6.1.3.1 Compound nucleus

In compound nucleus formation, the incident neutron is absorbed by the target nucleus. The neutron's kinetic energy is shared among all the nucleons. If the target nucleus is ${}^A_ZX$ where Z is the number of protons, A the mass number and X the chemical symbol of the element, then the compound nucleus formation can be represented as



The compound nucleus is highly unstable, since it is in an excited state, and for it to be stable it undergoes a de-excitation process.

Radiative capture, the (n,γ)-reaction, involves absorption of a neutron followed by emission of gamma rays. This reaction is the most common neutron reaction. It is called radiative capture because the nucleus of the material captures the neutron and radiates a gamma photon. It can occur for almost any nucleus and all neutron energies.

6.1.3.2 Potential scattering

Potential scattering is a type of elastic scattering that can take place for any energy of the incident neutron. This mode of interaction does not involve the formation of a compound nucleus; it appears simply as the result of the presence of the nucleus. The scattering is a function of the forces which act on the neutron in the vicinity of the target nucleus and these forces depend on the dimensions and the shape of the nucleus.

6.1.3.3 Direct interaction

High energy neutrons can also interact with nuclei directly. In this type of interaction a direct collision between the neutron and the nucleus results in the absorption of the incident neutron and the ejection of one or more nucleons, either protons or neutrons. However, few neutrons in a research reactor have enough energy for this reaction.

Interactions of neutrons with matter are described in terms of the so-called cross sections (σ), which can be thought of as the measure of the probability for a reaction to occur. There are three common types of reaction cross sections, namely absorption, fission and scattering. The total cross section (σ) which is a dimension of an area, is the sum of the cross sections for scattering and for absorption denoted by (σ_s) and (σ_a) respectively.

$$\sigma_t = \sigma_s + \sigma_a$$

The cross section depends on the energy of the incident neutron and the dependency is very complex, it results from the structure of the target nuclei and the type of interaction.

In nuclear reactors, neutrons vary with energy and fluence rate, and can be categorized as thermal neutrons, epithermal neutrons and fast neutrons. The cross section for thermal neutrons is inversely proportional to the neutron velocity and also inversely proportional to the square root of the neutron energy. Neutrons cross sections in the epithermal region can be high and as a result the neutron cross neutrons section versus neutron energy relationship may show resonance peak. Most of the procedures associated with NAA use the thermal neutrons for

activation, whereas activation with epithermal neutrons is preferred to enhance the activation elements with a high ratio of resonance neutron cross section. Figure 6.2 below describes the variation of neutrons in a reactor with regard to their fluence rate and energy⁽⁵⁷⁾.

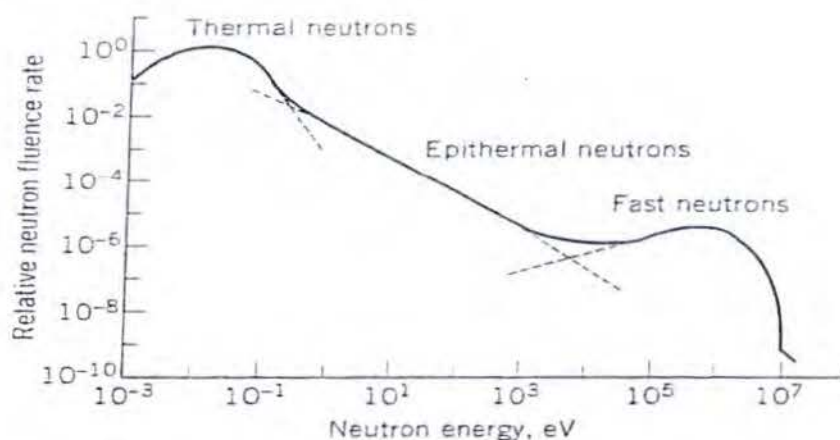


Figure 6.2 Schematic representation of the neutron fluence rate spectrum in a nuclear reactor⁽⁵⁷⁾

6.2 Instrumental Neutron Activation Analysis (INAA)

Instrumental neutron activation analysis is the most commonly used technique in neutron activation analysis. The technique is sometimes referred to as non-destructive neutron activation analysis. In this method, the product nuclides produced during activation are quantified on the basis of its decay mode and its half-life. The emitted γ -rays are detected by high resolution gamma ray spectroscopy using intrinsic Ge, Ge(Li) or Si(Li) detectors or in some cases by using NaI(Tl) scintillation spectrometry. Other techniques used include β - γ and γ - γ coincidence spectrometry. In principle INAA is an absolute method of analysis and the concentration of an element can be calculated if the absolute disintegration rate (A_i) is measured and if ϕ (the neutron flux) and σ are known⁽⁵⁴⁾. The INAA method is characterized by (i) activation via irradiation with reactor neutrons, (ii) measurement of gamma radiation after one or more decay intervals, and (iii) interpretation of the resulting gamma spectra in terms of the elements present and their concentrations. INAA is widely used because of the advantage that it has, the samples do not have to undergo any chemical treatment, neither prior, nor after activation and because of limited sample handling operations. Sample contamination is limited as compared to sample analysis methods in which

the sample has to be dissolved ⁽⁵⁸⁾. Also INAA is unique in several important aspects such as being largely independent of matrix effects, being suitable for analysis of materials that are difficult to dissolve, being relatively insensitive to sample contamination and having specific means of detection. Due to these advantages, sensitivity and accuracy, it has a special role as a reference technique for other analytical methods ⁽⁵³⁾. The signals in INAA are related to the properties of the atomic nucleus, and the results are not affected by the chemical or physical properties of the element. The method is well described by physical laws and selectivity is ambiguous for all elements, since the combination of the nuclear properties such as the decay constant and the energies and intensities of the gamma radiation is uniquely characterized for each radionuclide ⁽⁵⁸⁾. All contribute to a high degree of accuracy that makes INAA the method of choice in many areas of material analysis.

6.2.1 Application of INAA

Instrumental neutron activation analysis has found use in many fields of science. Particularly, advantage is taken of the fact that the samples do not have to undergo chemical treatment before and after activation/ neutron irradiation and again light elements such as H, C, N, O, and Si, which in many materials belong to the major matrix components do not produce radioactive products upon neutron activation; therefore these elements do not interfere with the determination of the activity of the nuclides of interest. The non-destructive nature of INAA makes the technique attractive for application in geochemistry and related sciences ⁽⁵⁸⁾. Advances in semiconductor detector systems coupled with improvements in nuclear reactors have widened the scope of neutron activation analysis. Instrumental neutron activation analysis has made high sensitivity non-destructive determinations possible. Neutron activation analysis has been used successfully in research as diversified as nutrient uptake in plants, petro-genetic modelling of geologic phenomena, identification of impurities in new metals and alloys, environmental monitoring, and analysis of forensic evidence for criminal and civil cases ⁽⁵⁹⁾.

6.2.2. Current trends in INAA

It is generally accepted that INAA is a mature technique, the principles of the method are well understood and there are almost no fundamental aspects in the method that imply further development, innovation or for which technological breakthroughs are foreseen, that would change the role of neutron activation analysis dramatically ⁽⁵⁵⁾. Its application is widely known in the following fields of science, of which only a few examples are given.

6.2.2.1 Archaeology

INAA has been used for chemical composition analysis of ancient pottery from the Buddhist sites of Andhra Pradesh. Pottery samples were collected from seven different locations for analysis using INAA to determine their elemental concentrations. The concentration of 20 elements which included aluminium, alkali, alkaline earth and transition elements were used for grouping the pottery. The method has also been used in the study of Caribbean ceramics, where eight ceramic samples were studied and analyzed for the development of the compositional Caribbean ceramics database ^(60, 61).

6.2.2.2 Biomedicine

In medical research the INAA method has been used to analyze the effects of age and gender on trace element mass fraction in human iliac crest with the objective to use the intact bone samples and bones commonly used for biopsies-iliac crest ⁽⁶²⁾. In the study human iliac crest samples were collected from the forensic laboratory and analyzed for trace elements (Co, Fe, Rb, Sr, Zn, Cs, Eu, Hg, Sb, Sc, and Se) and it was concluded that there is no statistical age variation in the samples.

6.2.2.3 Environmental sciences

The INAA method has grown enormously in environmental analysis research. It has been used for air pollution studies, biological monitoring, environmental pollution, and soil sample analysis ⁽⁵³⁾. The method has also been used to determine uranium and thorium concentrations in Egyptian monazite prepared from the beach sand of the Abu-Khashaba area in Egypt ⁽⁵⁴⁾.

6.2.2.4 Forensics

Because of its detection sensitivity INAA has found an important application in forensic chemistry. It is used for the detection of gunshot residues, which involves analysis of moistened swabs of the back of the hands of the suspect for the determination of barium and antimony. A prominent example is the use of INAA in the John F. Kennedy assassination investigation, where bullet-lead specimen samples were analyzed using the INAA technique ⁽⁶³⁾.

6.2.2.5 Geological and geochemistry

INAA has been used for determination of major, minor and trace elements present in clays, rocks, soils and other geological materials. For example, it has been employed in the study of soil samples from different parts of the Abuja metropolis to assess the effects of elements found in soil in the area ⁽⁶⁴⁾. The application of the technique has grown enormously and it can be justified by the number of papers being published in this field.

6.2.2.6 Nutrition

Neutron activation analysis has been applied in nutrition studies in a wide variety of food products; for example, in the study conducted by Faanhof *et al.* ⁽²⁸⁾ where food products grown in a catchment area affected by mining and mineral processing industries were analyzed, and has also been used to determine the elements present in plasma and egg yolk of the Bothrops jararaca snake species ⁽⁶⁵⁾.

6.2.3 Advantages and limitations of the INAA method

As mentioned earlier, INAA has many advantages over other analytical techniques. However, interference can still occur when different compound or product nuclei produce similar gamma rays. This problem can be circumvented by choosing alternate gamma rays or making use of the half-lives of the nuclei; for example by counting only after the short lived radionuclides has decayed. Other interferences can occur if another type of nuclear reaction concurrently produces the radionuclide of interest in addition to the sample neutron capture process, for example the $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ and the $^{23}\text{Na}(n,\gamma)^{24}\text{Na}$ reactions. Sensitivity and accuracy depend on the concentrations of the elements and radionuclide parameters; sensitivities vary from 10^{-3} to 10^{-10} gram per gram of sample. Accuracy is usually between two and ten per cent of the reported value, depending on the element analyzed and its concentration in the sample. The detection limit for a particular element depends upon the measured count-rate (R) of the gamma ray being monitored and the background radiation (i.e. the Compton continuum underneath the gamma-peak in the spectrum). The sensitivity of the measurement can be improved by increasing the measurement time which also improves the overall signal or total number of counts. Another limitation is when the instrumental neutron activation analysis produces a large background that masks the signal of interest, during that process the signal to noise ratio (S/N) becomes very low and the detection limit is also

reduced ⁽⁵⁹⁾. This is the case when biological samples contain large amounts of phosphorus (especially bone, teeth).

6.3 Fundamental equations for the INAA method

Considering the formation of a compound nucleus in a reactor through the activation process, the nucleus of the stable atom (A) will capture/ absorb an incident neutron from the neutron flux (ϕ) and form or yield an active isotope (A*) of the same element but with a heavier mass number. The production of the compound nucleus or radioactive nucleus is given by the activation equation written as follows:

$$A = \phi \cdot \sigma \cdot N \cdot (1 - e^{-\lambda \cdot t})$$

Where:

- A the activity of a particular radionuclide in the sample (Bq),
- ϕ the flux density of the neutrons at the irradiation position ($\text{cm}^{-2} \cdot \text{s}^{-1}$),
- σ the cross-section of the reaction and the target atom being used for activation (cm^2),
- N the number of (stable) atoms of the element in the sample
- λ the decay constant of the radionuclide in the sample that is activated, and λ (s^{-1}) can be represented as $\ln 2 / T_{1/2}$ and $T_{1/2}$ is the half-life (s) of the nuclides,
- t the irradiation period in seconds (s).

The maximum induced activity, A_{Max} obtained for an irradiation time much longer than the half-life of the product nuclide is given by

$$A_{\text{Max}} = N \sigma \phi$$

After the irradiation process, some of the radionuclides will decay according to their individual half-lives before the counting process and in that case the activity at the start of the counting period is represented by the following equation.

$$A = \phi \cdot \sigma \cdot N \cdot (1 - e^{-\lambda \cdot t_i}) \cdot (e^{-\lambda \cdot t_d})$$

Where:

- t_i the irradiation time in seconds (s)
- t_d the decay time in seconds (s)

6.4 Neutron source for INAA

The most commonly used neutron source for instrumental neutron activation analysis is the nuclear reactor. Over the past fifty years, research reactors have progressed through a variety of tasks. These have included material research using neutron scattering and diffraction, material characterization by activation analysis and radiography, isotope production, irradiation testing, as well as training and services as centre of excellence in the science and technology industries ⁽⁵³⁾. The development of the nuclear reactor in the 1940s made it possible for the instrumental neutron activation analysis method to be exploited. In South Africa the SAFARI-1 reactor is mainly used for research projects, which incorporates neutron tomography, neutron diffraction, neutron scattering, neutron radiography, nuclear technology products (NTP) such as the production of radioisotopes for medical applications and Neutron Transmutation Doped (NTD) silicon. It is also used for neutron activation analysis. In support of the safe operation and commercial needs of NTP, SAFARI-1 applies an integrated ISO 2001 accredited management system incorporating quality, health and the environment ⁽⁶⁶⁾.

6.4.1 South African Fundamental Atomic Research Installation (SAFARI -1)

The SAFARI-1 reactor is a 20 MW tank in pool type materials testing reactor owned and operated by the South African Nuclear Energy Corporation (Necsa) at its Pelindaba site near Pretoria, South Africa. An 8 x 9 grid houses 28 fuel elements, 5 control rods, 1 regulating rod, in-core irradiation facilities and reflector elements (Figure 6.3). The core is fuelled with MTR type fuel elements with 19 plates. The reactor vessel is cylindrical in shape except for one flattened side which is also the wall of the rectangular core box adjacent to the pool side facility. This large ex-core poolside facility allows irradiations to be performed in relatively high neutron fluxes since it is directly adjacent to the fuel elements. The reactor is also equipped with a number of beam tubes, which are used for neutron radiography, neutron scattering and prompt gamma neutron activation facilities, while hydraulic and pneumatic rabbit facilities provide for the irradiation of various material samples ⁽⁶⁷⁾. The reactor is housed inside an aluminium vessel with fuel in the form of plates that are about 50 mm wide and 500 mm long whereby each plate consists of a uranium/aluminium alloy that is sandwiched between two pure aluminium plates. The reactor was designed for 90% enriched ²³⁵U, but has been operated for years at about 40% enrichment due to strategic reasons and has recently been converted to run on low enriched uranium (LEU) of about 20% enrichment. A number of plates are mounted inside a long square tube of pure aluminium and couplings are

attached to each end of this tube to form a fuel element. At the bottom of the reactor vessel is a rectangular metal grid into which the fuel elements are fitted to form the reactor core. Three edges of the core are covered by aluminium and beryllium reflector plates whereas one edge is close to the cut-away side of the vessel to keep the row of fuel elements close to the poolside face. Figures 6.4 and 6.5 give a view of the reactor from the top of the pool and a graphic layout of the design respectively.

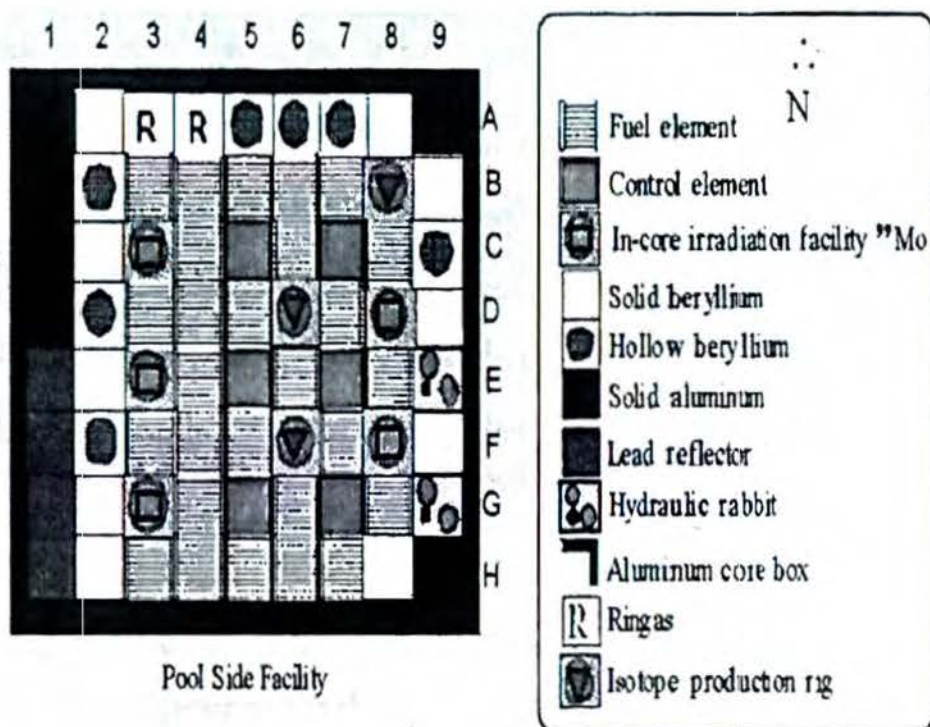


Figure 6.3 2-D Sketch of the SAFARI-1 core ⁽⁶⁷⁾

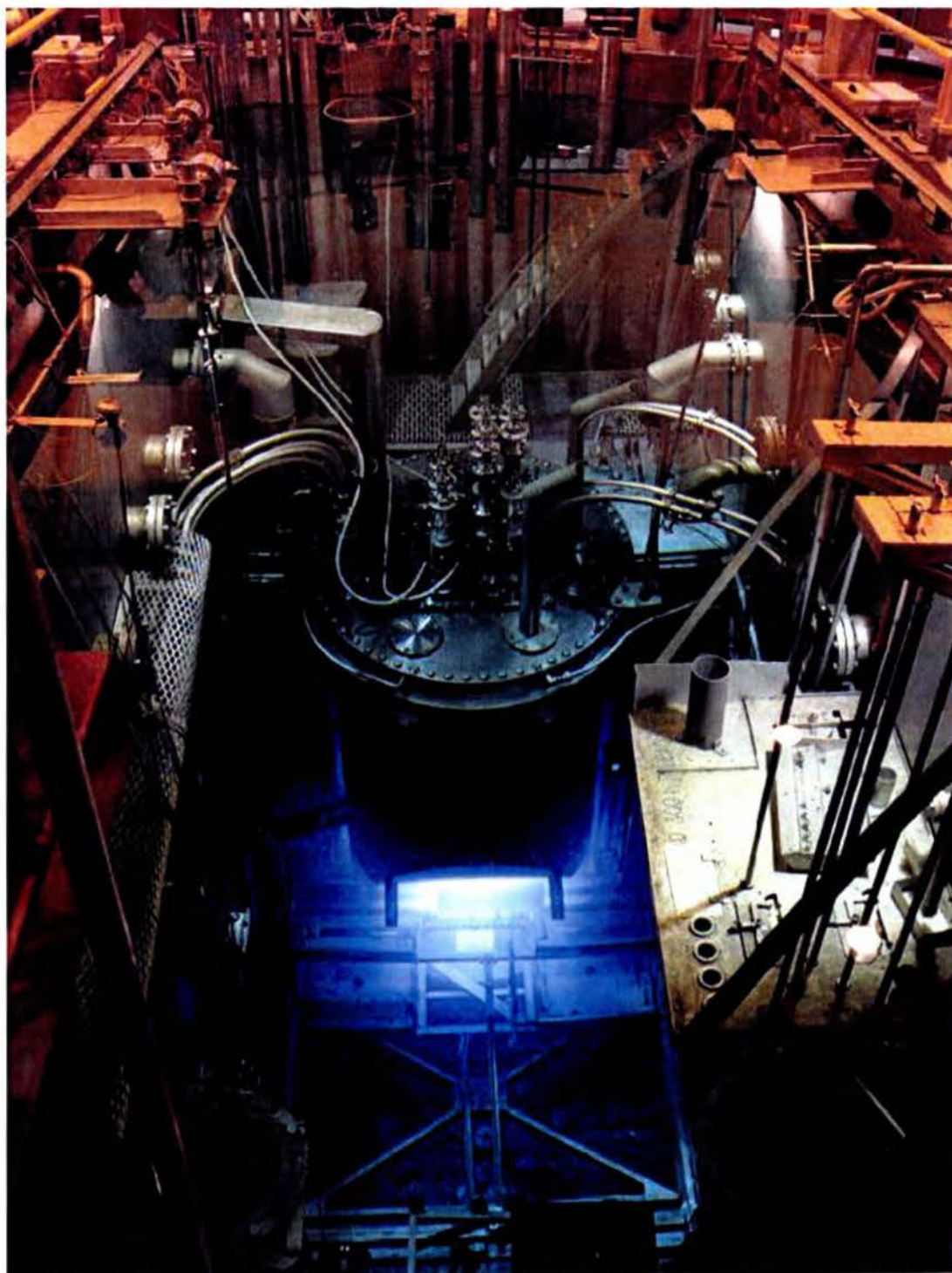


Figure 6.4 A view of the SAFARI-1 reactor facility ⁽⁶⁶⁾

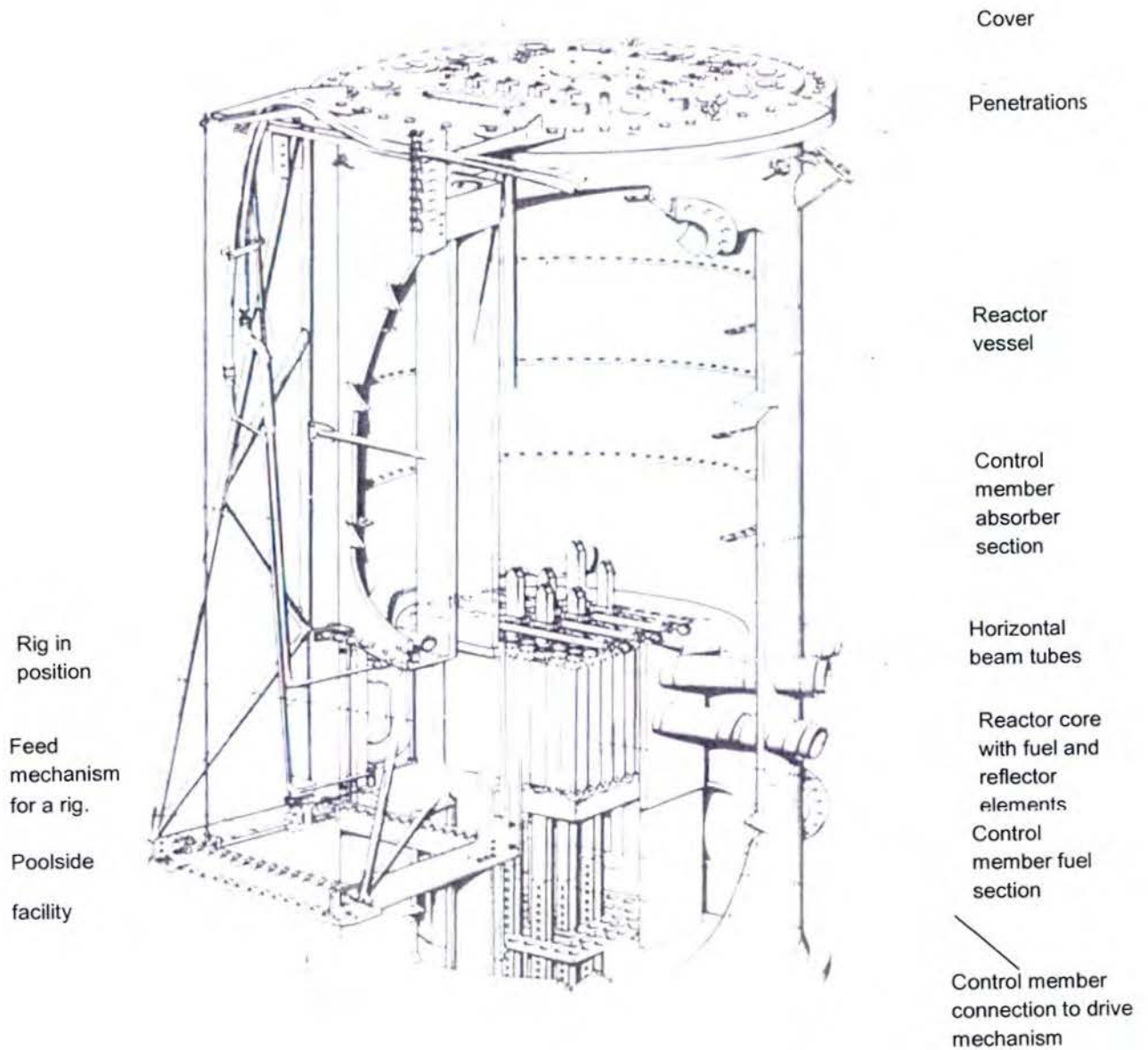


Figure 6.5 The schematic view of the SAFARI No.1 reactor ⁽⁶⁶⁾

6.4.2 The irradiation facilities used for Neutron Activation Analysis

6.4.2.1 Pneumatic Rabbit System (PRS).

The pneumatic transfer system is used for relatively long irradiation periods of up to 30 min. The pneumatic transfer system consists of many devices and assemblies for sending and loading of irradiation capsules also known as rabbits ⁽⁶⁸⁾. Basically the pneumatic transfer system consists of:

- an irradiation and transfer system that pneumatically transfers the rabbits to an irradiation position outside the reactor core, but within the reactor vessel;
- transfer tubes, a loader-receiver bay and photo-sensors to locate the movement of the rabbit;
- an emergency rabbit recovery system; and
- high purity and high density polyethylene irradiation capsules (rabbit).

The pneumatic transfer system is mainly used for long-lived radionuclide measurements. The samples are placed in vials which in turn are placed in special capsules called rabbits for irradiation. After irradiation the samples are unpacked from the rabbits and transferred to the gamma counting facilities.



Figure 6.6 Example of rabbits and sample vials for irradiation ⁽⁶⁸⁾

6.4.2.2 RINGAS (Routine Instrumental Neutron and Gamma Analysis System)

The main purpose of the RINGAS pneumatic transfer system is to transport rabbit assemblies from the rabbit feed station to the desired in-core positions in the reactor, one at a time, to be irradiated with neutrons for a predetermined time. There are two irradiation positions, one where samples can be irradiated under the full neutron energy spectrum and one position that is shielded with cadmium to allow irradiation of the samples with epi-thermal and fast neutrons. This last facility is mainly used for the determination of heavier elements as the activation of the lighter elements is relative suppressed and accordingly their interference in the gamma-ray spectra is reduced and the sensitivity of the heavier (toxic) elements is enhanced.

The rabbit assemblies are then extracted from the reactor and counted at a delay station to determine their activity. If this exceeds a predetermined level the rabbit will be sent to the waste station to avoid possible over-exposure of personnel at the counting station. If the activity is acceptable, the rabbit assemblies are transported to a separator gate where the samples are separated from the rabbit body to lower background gamma-ray interferences. The rabbit and sample are then counted and thereafter transported to the waste station. The rabbit bodies can be re-used approximately five times before they become brittle due to the high gamma-dose at the irradiation positions.

RINGAS is operated through a computer controlled system, which is able to detect failures and/or errors during the sample analysis. This RINGAS computer control system indicates the position of the rabbits and samples at various positions in the pneumatic transfer system.

6.4.3 General procedure for neutron activation analysis

There are five steps that clearly define the procedure of neutron activation analysis, that is sample preparation, the irradiation step, the post irradiation step, the counting step and the nuclide identification and activity determination.

- 1. Sample preparation:** In this step samples are collected, cleaned, dried and homogenized, followed by encapsulation in polyethylene capsules to be prepared for irradiation.
- 2. Irradiation:** The prepared samples undergo irradiation in a flux of neutrons; the nuclides in the sample absorb neutrons and become activated.

- 3. Post irradiation:** This step depends on the matrix used and the elements of interest. There are basically three considerations, namely
- a) the elements of interest and the matrix concerned determines the choice of the irradiation position (bare-tube or the cadmium shielded one),
 - b) the half-life of the nuclide of interest determines the decay- and counting-time, and
 - c) chemical separation techniques can be used to improve the sensitivity and sometime the specificity for nuclides with overlapping gamma peaks. This, however, is not commonly used as it may pose radiation risk to the operator/analyst and could introduce errors common to chemical manipulations.
- 4. The counting step:** Since most neutron induced reactions lead to gamma emitting radioisotopes which can be easily detected by scintillation detectors, this step follows to distinguish between nuclides in the samples. The identified nuclides are detected and depicted in a spectrum showing energies of each radionuclide in the sample.
- 5. The nuclide identification and activity calculation step:** Sophisticated software programmes are used nowadays to determine the energy of the gamma-lines in the spectrum, allocate possible nuclides to the energies and calculate the induced activity at the end of the irradiation period.

Lastly it should be mentioned that in the majority of cases neutron activation analysis is based on a comparator technique, whereby, along with the samples known quantities (masses) of the elements of interest are irradiated and measured for the induced neutron reactions. One thus eliminates unknown or ill-defined parameters like the neutron flux and neutron energy distribution at the various irradiation positions, which will vary with the time due to burn up in the reactor fuel.

CHAPTER 7

STUDY PLAN TO EVALUATE SOIL TO PLANT TRANSFER FACTORS

7.1 Definition of concepts

The Transfer factor of radionuclides is generally defined as the ratio of the radioactivity concentration in plants to that in soil.

General description of Transfer factor:

$$TF = \frac{\text{Concentration of radionuclides in plant (Bq/kg dry crop mass)}}{\text{Concentration of radionuclides in soil (Bq/ kg dry soil mass in the upper 20 cm)}}$$

7.2 Background and rationale

As discussed in Chapter 2 the transfer factor is a useful parameter to determine the migration of radionuclides from the soil into the plant. It relates the concentration of the substrate in the plant to the concentration in the soil through concentration ratios using the dry weight of the plant and the soil to minimize uncertainties ⁽¹²⁾. Determination of the transfer factor can be helpful when determining the radiological impact of natural radiation to the environment and thus can be used for better monitoring of the movement of radionuclides in the environment.

Mining activities may introduce large amounts of naturally occurring radioactive materials (NORMs) to the environment. The existence of large quantities of this material induces a radiological burden to man and possible damage to agricultural land and water resources. Crop production as part of agricultural practices utilizes both soil and water. Therefore it is compulsory to use suitable soil and water to produce good vegetables. As mentioned in Section 2.1.2, factors which have the ability to influence the transfer of radionuclides have been recorded and include ⁽¹¹⁾;

- The type of soil used for growing the plant,
- Climate conditions,
- Type of plants used,
- Part of the plant concerned,

- Physico-chemical form of the radionuclides and;
- Other elements which have a tendency of interfering with the processes.

Contaminated water can also be a major contributor of radionuclides in food products if the water used for irrigation has an excessive concentration of natural radionuclides (see Section 2.3).

7.3. Literature review on NORM transfer to vegetables

A detailed literature review on soil-to-plant transfer factors has been given in Chapter 2 of this study. This section highlights some studies concerned with accumulation/uptake of natural radionuclides by vegetables.

In 2005 Pulhani *et al.* ⁽⁴⁶⁾ conducted a study to evaluate the uptake of natural radioactivity in wheat plants from soil. In the study two morphologically different soils were used and comparable transfer factor values were observed. The uptake of uranium was less than the uptake of radium by plants and it was also observed that under natural field conditions the concentration of radionuclides tends to reach a constant value in the receptor compartment.

Shtangeeva and co-workers ⁽⁴⁷⁾ also studied the uptake of thorium by wheat at different stages of plant growth, applying greenhouse techniques. In this study the accumulation of thorium in the plant affected uptake of other elements including essential minerals required by the plant. The study showed more accumulation of thorium in the root zone as compared to other parts of the plant; this accumulation was associated with the variation of the concentration of other nutrients and trace elements. In another study conducted by Shtangeeva ⁽²⁵⁾ uptake of uranium and thorium by native and cultivated plants was examined. It was found that plants grown in radionuclide enriched soils have a significant increase of thorium and uranium concentrations and that thorium was less available for uptake by plants as compared to uranium.

Lauria *et al.* ⁽⁶⁹⁾ evaluated the level of radium and uranium in vegetables grown using different farming management systems. The farming systems employed examined the difference in the use of phosphate fertilizers and manure fertilizer. No difference in concentration of radium and uranium were found in the vegetables for both management systems. The concentration of uranium and radium were generally low.

Hegazy *et al.* ⁽⁷⁰⁾ studied the accumulation of radionuclides and soil-to-plant transfer of radionuclides in the Nile Delta Coastal black sand habitats with more emphasis on the transfer

of uranium and thorium. Complex issues associated with the transfer of uranium and thorium was noted. The findings suggested that at least a 50% increase of organic matter and clay content of the soil decreases the uptake of uranium and thorium by plants by more than 50%.

In 2002, Lozano *et al.*⁽⁷¹⁾ investigated the distribution of long-lived radionuclides of the uranium-238 series in sediments and a small river in a uranium mineralized region. In this investigation the behaviour of radium, thorium and uranium was associated with their mobility in the environment.

Santos *et al.*⁽⁷²⁾ determined the concentrations of natural radionuclides (^{232}Th , ^{238}U , ^{226}Ra , ^{228}Ra and ^{210}Po) in vegetables, particularly in leafy vegetables, fruits, roots, bean and rice and other foods consumed on a daily basis. The studies showed that ^{228}Ra and ^{210}Pb contribute significantly to the radiation dose for the population and the contribution to dose was (obviously) also influenced by the intake rate. The dose as a result of naturally occurring radionuclides correlated with the UNSCEAR value. In a similar study, Jha *et al.*⁽⁷⁶⁾, also determined the concentration of the natural radionuclides in different food products including vegetables in an area close to mining. Instrumental Neutron Activation analysis was used in this study.

7.4 Research problem and objectives.

The main aim of this study was, to do a thorough literature study and to plan an experimental phase to determine soil-to-plant transfer factors of naturally occurring radioactive materials (NORMs). It is envisaged that contaminated soil from an area affected by mining and milling of uranium and gold will be used. Contaminated water from the catchment area around these activities will be used for irrigation. For better evaluation of the transfer factors, uncontaminated soil and uncontaminated water will also be used for control purposes.

All experiments will be performed under controlled conditions, which include the use of greenhouse techniques. The major aim of the study is to design, to develop and to make use of controlled techniques for studying uptake of natural radionuclides.

- To investigate the transfer of NORM nuclides from the ^{238}U , ^{235}U and ^{232}Th decay series and their progeny nuclides in some vegetables grown under controlled conditions in contaminated soil affected by mining and milling of gold and uranium ores.

- To estimate the potential differences in the annual radiation dose for members of the public using the experimentally obtained transfer factors compared to the modeled dose using existing literature transfer factors.

It is expected that the plants to be used in the study will be those that are most produced and consumed in the Republic of South Africa (see Table 5.2), and that they will reflect the seasonal variation in the vegetation growth-periods of the plants. This is encouraged by the findings in the literature that plants have preferences on planting seasons and that the mobility of some radionuclides are crop specific. Obviously one wants to target the staple foods consumed by the larger South African population. However, one should also include specific foodstuffs suspected of possible high uptake of NORM nuclides as e.g. mushrooms, which are rich in calcium and accordingly can be expected to be enriched in radium as well, or in other words investigate which foodstuffs are rich in elements with similar chemical properties to NORM-elements.

7.5 Research methodology, material and methods

In attempting to achieve the objectives outlined above, two analytical techniques will be applied, Instrumental Neutron Activation Analysis (INAA) and Gamma Spectroscopy. The Neutron Activation Analysis protocol that will be employed in the study is shown in Figure 7.1. The technique is described in more detail in Chapter 6. NAA is useful for the determination of the uranium and thorium concentrations and elements that are chemically analogues to the NORM nuclides, while other radionuclides will be determined using gamma ray spectrometry. In case INAA is not readily accessible or appears to be too costly, ICP-MS may offer a feasible alternative.

The samples will be measured with a broad energy gamma ray spectrometric system consisting of an n-type coaxial high purity germanium (HPGe) detector (Canberra BE5030) with 2 keV resolution at 1.33 MeV. The detector is mounted within a lead castle with an inside dimension of 40 cm x 40 cm x 40 cm cubic. The lead castle is made of 13 cm thick lead with less than 50 Bq/kg of ^{210}Pb activity and it is lined with a 2 cm layer of lead with an activity less than 10 Bq/kg inside. The lead castle is lined with 1 mm of cadmium, 2 mm of copper and 4 mm of Perspex used to reduce x-ray formation. The lead castle has a Perspex “shield” which is shaped around the entire setup. A perspex “shield” allows flushing with nitrogen which traps and prevents the radon gas to enter the cavity of the lead castle. Before counting can be done energy calibration, peak width calibration and efficiency calibration will be performed.

Data will be acquired using Genie-2000 software ⁽⁷⁴⁾. The gamma-ray spectra will also be evaluated using VGLA software developed by STUK for analysis of airborne particulates within the regime of the Comprehensive Nuclear Test-ban Treaty Organization (CTBTO).

7.5.1 Phase 1 - Analysis and quantification of source material

After an agreement has been reached between all the stakeholders foreseen (see Section 7.8.3) in this research, an area affected by mining and milling of uranium and gold will be identified; the soil from this area will be analysed for existence and concentration of naturally occurring radionuclides. Another area which has been used for agricultural activities and not affected by mining activities will be identified; its soil will be analysed for the same substances and their concentration respectively. The activity concentrations of all the soils will be recorded and filed as they will be used during the interpretation of the results. The physical and chemical properties of the soils (as mentioned in Section 3.4) from the two areas will be studied fully to evaluate the possible effects which can influence the outcome of the study. An acceptable quantity of the soil required for cultivation of the envisaged crops will be collected and transported to the Agricultural Research Council (ARC) to commence the project. Once the study has been concluded the contaminated soil will be returned to its place of origin, to avoid leaving ARC with a burden of contaminated soil. Two types of water will be used for irrigation purposes, contaminated water and uncontaminated water. A catchment area that contains water with significant concentrations of NORM nuclides will be identified and analysed for concentration of such elements; tap water will also be analysed and used for control purposes. The contaminated water (adequate to complete the study) will be transported from the resource to the ARC for use. The concentration of other elements which are not of specific interest in the study, but which can assist in knowing the preference of the plant with regard to the uptake of essential elements will be recorded.

Fertilizers which will be used in the study to increase fertility of the soil for agricultural purposes will be analysed for the natural radionuclides content. This process is important because most fertilizers are made from rock phosphate which contains a significant concentration of natural radionuclides that can also have an effect on the outcome of the results. Excessive concentrations of natural radionuclides will increase the concentration of the same elements in the soil.

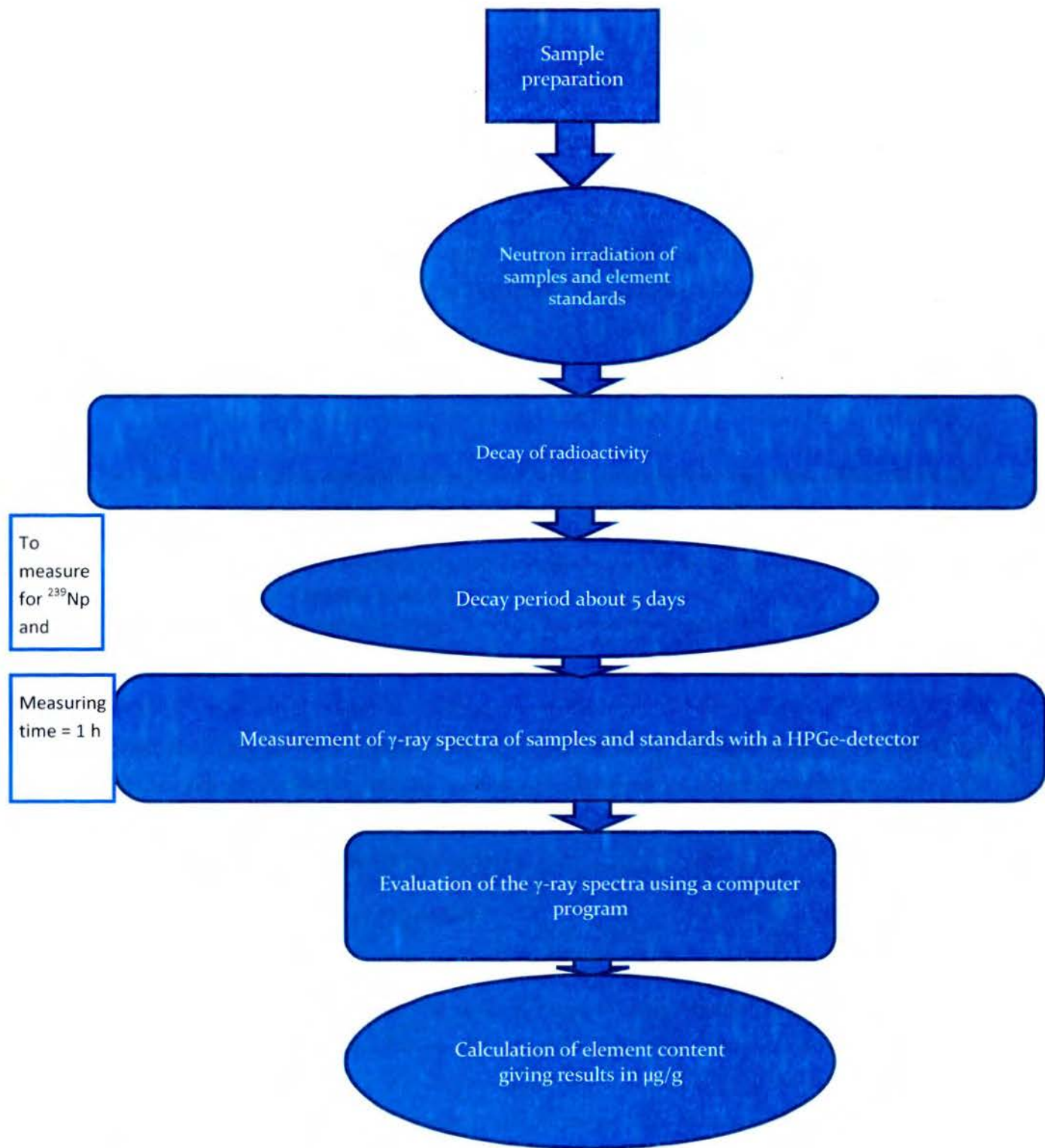


Figure 7.1 INAA procedure envisaged

7.5.2 Phase 2 - Designing of the test beds

Eight beds of the same standard size will be designed using the soils as identified in Phase 1. The content of each bed will be analysed thoroughly before cultivation can start. Four beds will contain only soils whereas the other four will contain the same soil with added fertilizer. Soils will be mixed thoroughly to ensure that radionuclides are homogeneously distributed in the bed. The process of bed preparation will be followed by cultivation of selected vegetables (Phase 3), analysis and determination of the transfer of radionuclides.

- **Bed 1** will contain contaminated soil, and will be irrigated with contaminated water. This process will quantify the effect of using both contaminated soil and water for agricultural practice.
- **Bed 2** will contain contaminated soil, and will be irrigated with tap water. This activity will clearly show the effect of contaminated soil in plants.
- **Bed 3** will contain uncontaminated soil and will be irrigated with contaminated water. The aim is to depict the effect of using contaminated water in cultivation and results will be used to advise farmers accordingly.
- **Bed 4** will contain uncontaminated soil and uncontaminated water will be used. This bed serves as a control study for the research.

As already mentioned, another four beds similar to the first four beds, as indicated above will be prepared, but they will contain fertilizer. The main aim is to demonstrate the effects of fertilizers in soil and plants and also to advise the farmers to be selective when it comes to choosing the right fertilizers during ploughing. Figure 7.2 gives a clear simulation of all the steps to be taken when conducting the study.

7.5.3 Phase 3 - Selection of Vegetables

In selecting vegetables, farmers of the areas of concern will be requested to advise in terms of the vegetables grown there; this will make it easier to grow vegetables which favour the selected soils. Although plants will be selected on the basis of the cultivation period, the idea of conducting a seasonal study will also be considered, since evaluation of the transfer of such nuclides on the basis of seasonal change is also important. This is encouraged by the fact that some vegetables are grown throughout the year and can adapt to all seasons. The selection of appropriate vegetables will also depend on the part of the plants that we wish to study, that is, root, stem or leafy parts of the vegetable. Information regarding vegetable production and consumption in Chapter 5 of the study will also be used in selecting vegetables consumed in South Africa.

- It is recommended that the plants be given enough time to grow as this will allow better mobility of radionuclides from soil to parts of the plant, a period of three months should suffice.
- Agricultural good practice should be adhered to; this will give specific root depth and conditions of growth for all vegetables.
- Greenhouses are to be used to avoid any fallout of natural radionuclides to the surface of the plants, as this may influence the outcome of the results.
- Avoid all activities that may lead to plant death, as this will delay the study.

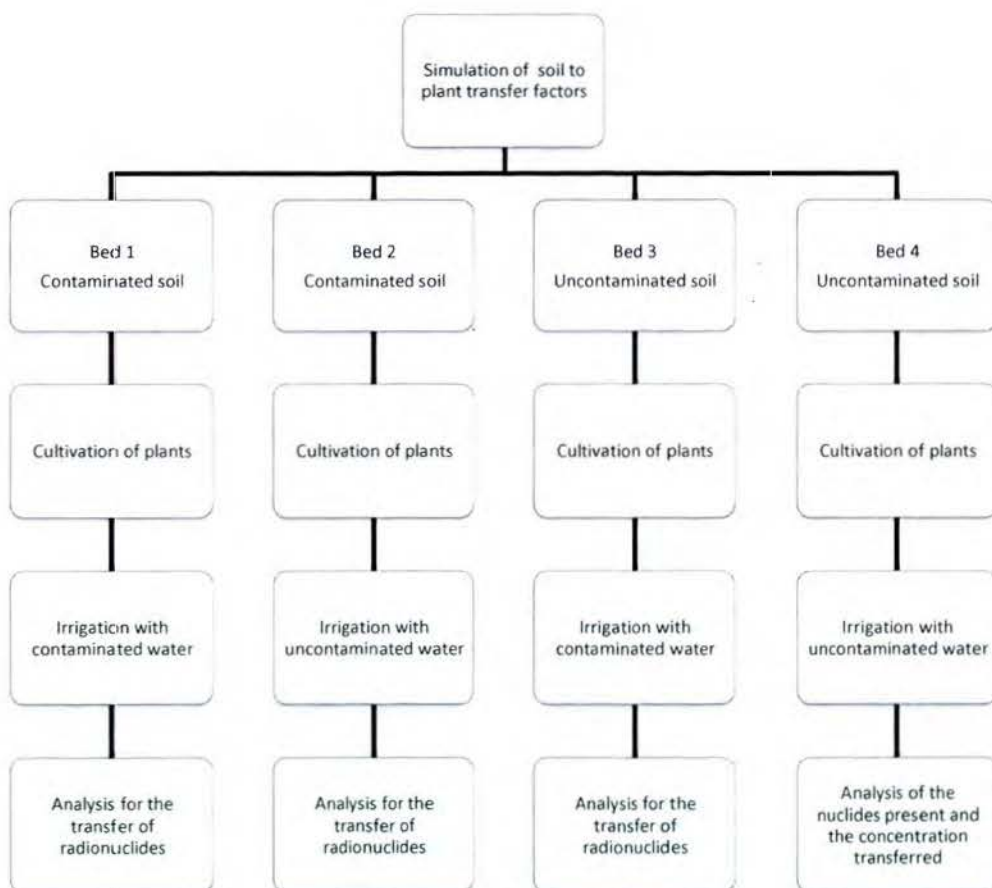


Figure 7.2 Steps of the design to evaluate soil to plants transfer factors in vegetables

7.5.4 Phase 4 - Irrigation and monitoring of plants.

Irrigation will be conducted as required and plants will be monitored.

7.5.5 Phase 5 - Harvesting

Once all vegetables are mature enough, they will be harvested and transported to an analytical laboratory for analysis, e.g. of the South African Nuclear Energy Corporation (Necsa). The laboratory should have all the equipment needed for the analysis of the activity concentrations of the required radionuclides as well as other elements of interest by neutron activation and/or ICP-MS.

7.5.6 Phase 6 - Analysis of samples

During analysis, all intermediate steps will be recorded. This includes sample preparation (drying, milling, ashing), irradiation of the samples and counting.

7.5.6.1 Sample Preparation.

Vegetables will be washed properly so that the activity of adhering soil particles is not accidentally included in the analysis. Samples will be dried in an oven and homogenized. The dry samples will be compressed using a hydraulic press and will be packed in a prescribed container for gamma-spectrometric analysis. Another portion will be prepared to be irradiated in the SAFARI-1 reactor for neutron activation analysis.

7.5.6.2 Measurement of the gamma ray spectra using a HPGe detector

A High Purity Germanium detector (HPGe) as described in paragraph 7.5 of the study will be used for counting. Counting periods of around 12 h per sample are envisaged, although the required sensitivity has to be established based on the mass of the samples after compression.

7.5.6.2 Neutron activation analysis

Proper irradiation/decay/counting regimes will be employed to optimise the sensitivity of the elements of interest. These include the possible chemical analogues to the NORM nuclides, i.e. Ba/Sr/Ca for Ra, Sc/Y/La/Ce/Pr/Nd for Ac/Th/Pa/U, Ge/Sn for Pb, and Se/Te for Po.

7.6 Calculations of the activities and the errors involved

The mathematical errors and uncertainties will be evaluated and reflected in the results accordingly.

7.7 Calculations of the transfer factors

As described in the previous chapters, the transfer factors of the natural radionuclides will be calculated based on element/radionuclide concentration relationship, that is, calculating the ratio of the concentration in the plant to that of the same element/radionuclide in the soil. Dry weight masses will be used to minimize errors.

7.8 Hypothesis on the outcome of the planned research

It is expected that the results obtained from Bed-1 will present significantly higher values of natural radionuclide concentrations in the vegetables as compared to the other beds. High concentrations are also expected for the beds containing contaminated soil and fertilizers, which are irrigated with contaminated water (Bed 3 and Bed 7). Although Bed 4 is used as a control in the study, a significant change may be observed in the control bed that contains fertilizer (Bed 8). This change will indicate the effect of the fertilizers on the soil-to-plant transfers and can be used to deduce the difference brought by fertilizers in other beds. It is also expected that a high concentration of the radionuclides will be observed in the root zones of the plants in all beds. Any significant value observed in the upper part of the plant will be as a result of translocation from roots to leaves for the concerned plants. Finally it is expected that the soil-to-plant transfer factors of radionuclides calculated for this study, performed under controlled conditions, will provide more realistic transfer factors in addition to the default values recorded in the NNR Licensing guide ⁽¹⁰⁾.

7.9 Possible benefits to be gained by the study.

- A better environmental monitoring plan can be developed for areas around mining activities.
- Radioactive waste release plans for mining and associated industries can be reviewed and improved.
- Protection plans for agricultural land and water resources from the mining activities can be enhanced.

- Members of the public will be protected against radiation from intake of contaminated food products.
- Nuclear analytical techniques will be seen as an alternative to strengthen the agricultural research methods for research output in South Africa.
- Possible scientific publications on transfer factors will be attained.

7.10 List of stakeholders envisaged

It is obvious that the proposed study cannot be done in isolation and requires good collaboration between all participating institutions and individuals. The following major stakeholders are envisaged:

- North-West University (Mafikeng Campus)
- Agricultural Research Council
- South African Nuclear Energy Corporation
- Mining Industries in the Mooi river catchment area
- Department of Water Affairs
- National Nuclear Regulator
- Statistics South Africa

7.11 Budgetary requirements

As many stakeholders are envisaged to participate in the study it will be mandatory to implement in the actual project proposal the estimated budgetary requirements of the study. The following budget items are to be envisaged, which obviously are only indicative and have to be worked out in more detail in the project proposal to be tabled for approval by all major stakeholders.

- Costs of the primary researcher (typically a PhD-bursary)
- Identification of areas of interests (mainly travel costs)
- Collection of soil and transport to the ARC (or other collaborating stakeholder)
- Transportation of water to the test beds (continuous process)
- Meetings with stakeholders, including consultants
- Costs of consultations
- Cultivation costs (seedlings, fertilizer, implements, etc.) including labour
- Transportation of the materials to the laboratories for analysis

- Analysis of soil, fertilizers, water and plant materials (e.g. roots, stems, leaves) for NORM nuclides and chemical analogues

7.12 Time frame and activities

Again as many stakeholders are envisaged to participate in the study it will be mandatory also to implement in the actual project proposal the estimated time-lines of the study. The following structure given in Table 7.1 may be envisaged, which obviously is only indicative and has to be worked out in more detail in the project proposal to be tabled for approval by all major stakeholders. The anticipated activities and time-lines are also graphically represented in Annexure 3.



Table 7.1 Anticipated activities and time-lines

Year	Number of months	Activities	
1	4 months	Identification of the study areas and classification of the soils. Identification and analysis of the water resources. Revision of the literature study. Meeting with all stakeholders.	
	2 months	Transportation of soil and water to test bet location. Preparation of beds and cultivation. Evaluation of the results concerning the soil and water to be used.	
	5 months	Cultivation & plant growth processes continues. First harvesting of the vegetables. Transportation to laboratory and analysis for the first season.	
	4 months	2 nd Cultivation of vegetables growing during that period. Analysis and conclusion of the first results. Publication/ issuing of the first results.	
	2	5 months	3 rd Cultivation of vegetables growing during that period. Analysis and conclusion of the second results. Publication/ issuing of the second results.
		5 months	Cultivation of the last set of vegetables occurs. Analysis and conclusion of the 3 rd cultivation results. Publication/ issuing of the 3 rd results.
		5 months	Intensive analysis of the overall results. Comparison with the existing data on transfer factors. Results compared with those of the NNR and IAEA publications. Scientific publication of the study.
	3 months	Final draft of the report and thesis. Transportation of the contaminated soil and contaminated water back to the original source. Decontamination process of the surface at ARC.	
	3	3 months	Submission of the thesis/ reports with future suggestions.

7.13 Conclusion and recommendations

Based on an in-depth review of the literature and understanding the importance to evaluate the soil-to-plant transfer factors of primordial radionuclides and their progeny in agricultural practices, a programme has been drafted to embark on a study to better quantify these transfer factors. This will eventually lead to a better evaluation of the radiological impact on humans and the environment associated with the release of radioactive waste from uranium and gold mining and mineral processing activities.

The proposed experimental phase is recommended as an appropriate subject for a PhD study in order to obtain more realistic data on soil-to-plant transfer factors. This will also provide a better insight in the much debated and speculated radiological impact of mining activities where NORM nuclides are present in appreciable amounts in South Africa.

It should also be noted that the soil-to-plant transfer factors are only part of the pathway of NORM nuclides to humans and animals and the associated radiological impact. There are much more pathways for which the default transfer factors are to be investigated, one of them being the water-to-fish transfer factors as this is also one of the more direct pathways to humans, especially where people are living in areas affected by the wastes generated by mining and mineral processing where NORM is involved.

List of references for all chapters

1. IAEA. 2007. Modelling the transfer of radionuclides from naturally occurring radioactive material (NORM); EMRAS Report of the NORM working group.
2. Langmuir, D. and Herman, J.S. 1980. The mobility of thorium in natural waters at low temperatures. *Geochimica and Cosmochimica Acta* 44: 1753-1766.
3. L'Annunziata, M.F. 2003. Handbook of radioactivity analysis, second edition.
4. Abbasiziar, A., Hosseini, T., Fathivand, A., Heravi, Gh. 2004. Determination of uranium isotopes (^{234}U , ^{238}U) and natural uranium (U-nat) in water samples by alpha spectrometry. *Iran. J. Radiat. Res.*, 2: 1-6.
5. Colmenero Sujo, L., Montero Cabrera, M.E., Villalba, L., Renteria Villalobos, M., Torres Moye, E., Garcia Leon, R., Garcia-Tenorio, R., Mireles Garcia, F., Herrera Peraza, E.F., Sanchez Aroche, D. 2004. Uranium-238 and thorium-232 series concentrations in soil, radon-222 indoor and drinking water concentrations and dose assessment in the city of Aldama, Chihuahua, Mexico. *Journal of Environmental Radioactivity* 77: 205-219.
6. Akhtar, N., Tufail, M., Ashraf, M., 2005. Natural environmental radioactivity and estimation of radiation exposure from saline soil. *International Journal of Environmental Science & Technology* 1: 279-285.
7. Harb, S., El-Kamel, A.H., Abd El-Mageed, A.I., Abbady, A., Negm, H.H. 2008. Natural radioactivity measurements in soil and phosphate samples from El-Sabaea, Aswan, Egypt. IX Radiation Physics & Protection Conference, 15-19 November 2008, Nasr City- Cairo, Egypt.
8. IAEA. 2005. Naturally occurring radioactive materials (NORM IV), proceedings of an international conference held in Szczyrk, Poland. May 2004, IAEA TECHDOC- 1472.
9. Council for Nuclear Safety. 1997. Guideline on the assessment of radiation hazards to members of the public from mining and minerals reprocessing facilities. Licensing guide LG-1032.
10. IAEA. 2009. Handbook of parameter values for the predictions of radionuclear transfer in terrestrial and freshwater environment (draft).
11. Chen, S.B., Zhu, Y.G., Hu, Q.H. 2005. Soil to plant transfer of ^{238}U , ^{226}Ra and ^{232}Th on uranium mining-impacted soil from south-eastern China. *Journal of environmental radioactivity* 82: 223-236.
12. Ambe, S. 2001. Transfer of radionuclides into kumatsuna at different stages of plant development. *RIKEN Review* 35: 90-91.
13. Velasco, H., Juri Ayub, J., Sansone, U. 2008. Analysis of radionuclide transfer factor from soil to plant in tropical and subtropical environment. *Applied Radiation and Isotopes* 66: 1759-1763.
14. Manigandan, P.K. 2009. Activity concentration of radionuclides in the plants in the environment of Western Ghats, India. *African Journal of Plant Science* 3: 205-209.
15. Centofanti, T., Penfield, R., Albrecht, A., Pellerin, S., Fluhler, H., Frossard, E. 2005. Is the transfer factor a relevant tool to assess the soil-to-plant transfer of radionuclides under field conditions? *Journal of Environmental Quality* 34: 1972-1979.

16. Bragea, M., Aldave de las Heras, L., Cristache, C., Carlos Marque Ramon and Toro Laszlo.: Experimental study of the radionuclides transport in soil and plant from waste dump. Proceedings to third European IRPA congress, 14-18 June 2010. Finland.
17. Vera Tome, F., Blanco Rodriguez, M. P., Lozano J.C. 2003. Soil-to-plant transfer for natural radionuclides and stable elements in a Mediterranean area. *Journal of Environmental Radioactivity* 65: 161-175.
18. Tesec. S.a. Environmental contamination: soil, water, forest, plants. European Centre for Technological Safety. <http://www.tesec-int.org/> Chernobyl/ environmental%20contaminatio. htm [Accessed on 19 June 2010].
19. Singh, S., Rani, A., Mahajan, R.M. 2005. ^{226}Ra , ^{232}Th and ^{40}K analysis in soil samples from some areas of Punjab and Himachal Pradesh, India using gamma ray spectrometry. *Radiation Measurements* 39: 431-439.
20. El-Kameesy, S.U., ABD El-Ghany, S., El-Minyawi, S.M., Miligy. Z., El-Mabrouk, E.M. 2008. Natural radioactivity of beach sand samples in the Tripoli Region, North West Libya. *Turkish J. Eng. Env. Sci.* 32 : 245 – 251.
21. Abbady, A., EL-Arabi, A.M., Abbady, A. G.E., Taha. S. 2008. Gamma-ray measurements of natural radioactivity in cultivated and reclaimed soil, Upper Egypt. Proceedings of the international conferences on radioecology and environmental radioactivity, 15-20 June 2008, Bergen, Norway.
22. Brigden, K., Stringer, R., Santillo, D. 2002. Heavy metal and radionuclide contamination of fertilizer products and phosphogypsum waste produced by The Lebanese Chemical Company, Lebanon. Greenpeace Research laboratories, Technical note 13/ 2002.
23. Dobrin, R.I, Dulama, C.N., Toma, A.L. 2006. Soil-Plant experimental radionuclide transfer factors. *Rom. Jour. Phys.*, 51: 73-76.
24. Seelmann-Eggebert, W., Pfennig, G., Munzel, H., Klewe-Nebennius, H. 1998. Chart of Nuclides. 6th edition 1995 revised reprinted 1998.
25. Shtangeeva, I. 2010. Uptake of uranium and thorium by native and cultivated plants. *Journal of Environmental Radioactivity* 101: 458-463.
26. Chibowski, S. 2000. Studies of radioactive contamination and heavy metal contents in vegetables and fruit from Lublin, Poland. *Polish Journal of Environmental Studies* 9: 249-253
27. Laina, S. 1994. ^{238}U series radionuclides as a source of increased radioactivity in groundwater originating from Finnish bedrock. Proceeding of the Helsinki Conference, June 1994. IAHS Publ. no. 222.
28. Faanhof, A., Kotze, D., Louw, I. 2007. A first order assessment of the potential radiological impact of foodstuffs grown in a catchment area influenced by mining and mineral processing industries, using Instrumental Neutron Activation Analysis (INAA) and gamma-spectrometry. The 5th African conference on research reactor utilization, "The role of research reactors in nutrition environment and health related research", 2-3 December 2007, Cairo, Egypt.
29. IAEA. 2007. Modelling the transfer of radionuclides from naturally occurring radioactive material (NORM). Draft TECDOC. 2007. Report of the NORM working group of EMRAS Theme 2. Environmental modelling for radiation safety (EMRAS) programme.
30. Wirth, E. s. a. How can the reliability of radiological assessment models be improved. www.irpa.net/irpa10/cdrom/00921.pdf. [Accessed on 19 November 2011]

31. IAEA. 2009. Quantification of Radionuclides Transfer in terrestrial and freshwater environments for radiological assessments. IAEA TECDOC-1616.
32. Strand P., Dowdall M. 2010. Radioecology and environmental exposure pathways. Proceeding of the third European IRPA congress (June 14-16) 2010. Finland.
33. Igwe, J.C., Nnorom, I.C., Gbraruko, B.C. 2005. Kinetics of radionuclides and heavy metals behaviour in soil: Implications for plant growth. *African Journal of Biotechnology* 4: 1541 – 1547.
34. IAEA. 2009. Handbook of parameter valued for the prediction of radionuclides transfer in terrestrial and freshwater environments (Draft). IAEA TRS-XXXX
35. IAEA. 2003. Classification of soil system on the basis of transfer factors of radionuclides from soil to reference plants: Report of the final research coordination meeting organized by the joint FAO/ IAEA programme of Nuclear Techniques in food and agricultural held in Chania, Crete. (22-26 September 2003) IAEA TECHDOC 1497.
36. IAEA. 2003. International conference on the protection of environment from effects of ionizing radiation. Contributed papers. Stockholm, Sweden. IAEA-CN-109
37. Rosa, M.M.L., Maihara, V.A., Taddei, M.H.T., Dias, F.F. 2009. Sequential determination of U and Th isotopes, ^{226}Ra , ^{228}Ra , ^{210}Pb , and ^{210}Po in mushroom. International Nuclear Atlantic Conference – INAC 2009, Rio de Janeiro, Brazil.
38. Peh, W. C. G. 1996. The discovery of radioactivity and radium. *Singapore med j.* 37: 672 – 630.
39. Suntharalingam, N., Podgorsak, E.B., Hendry, J. H. Radiobiology Chapter 4. Available online at: www-naweb.iaea.org/NAHU/DMRP/documents/Chapter14.pdf [Accessed on 15 August 2011]
40. UNSCEAR. 2006. Effects of ionizing radiation. Report to the general assembly with scientific annexes. Volume I. UNSCEAR Publication 2008
41. IAEA. 1999. Assessment of occupational exposure due to intakes of radionuclides. Safety Standard Series Guide No. RS-G- 1.2
42. IAEA. 2004. Methods for assessing occupational radiation dose due to intake of radionuclides. Safety report series No.37.
43. Sazykina, T.G. 2003. In Scott, E.M., ed. Radioactivity in aquatic biota. Modelling radioactivity in the environment: Chapter 7. 4: 201-222.
44. IAEA. Sediment distribution coefficient and concentration factors for Biota in the marine environment. Technical Report Series no. 422. 2004
45. Kumblad, L., Kautsky, U., Naeslund, B. 2006. Transport and fate of radionuclides in aquatic environments- the use of ecosystem modelling for exposure assessments of nuclear facilities. *Journal of Environmental Radioactivity* 87: 107 – 129.
46. Pulhani, V. A., Dafauti, S., Hegde, A.G., Sharma, R.M., Mishra, U.C. 2005. Uptake and distribution of natural radioactivity in wheat plants from soil. *Journal of Environmental radioactivity* 79: 331- 346.
47. Shtangeeva, I., Ayrault, S., Jain, J. 2005. Thorium uptake by wheat at a different stage of plant growth. *Journal of Environmental Radioactivity* 81: 283-293.
48. South Africa. Department of Agriculture, Forestry and Fisheries. 2010. Annual report. Pocket guide to South Africa 2009/10. Pretoria: Government Printer.

49. South Africa. Agriculture, Forestry and fisheries. 2010. Annual report. Trends in the agricultural sector 2010. Pretoria: Government Printer.
50. South Africa. Agriculture, forestry and fisheries. 2011. Annual report. Pretoria: Government Printer. Economic review of the South African Agriculture 2010/ 11
51. South Africa. Agriculture, Forestry and Fisheries. 2011. Annual report. Crop and Markets, Second quarter 2011, Volume 92, No 948. Pretoria: Government Printer.
52. Food and Agriculture Organization of the United Nation. 2010. A system of integrated agricultural censuses and surveys. World programme for the census of Agriculture 2010, Rome, 2005.
53. IAEA. 2001. Use of research reactor for neutron activation analysis. Report of an advisory group meeting held in Vienna (22-26 June 1998). TECDOC-1215
54. Filby, R. H. 1995. Neutron Activation Analysis. International Union of pure and applied chemistry, Technical report. Part IX.
55. Hassan, A. M. 2008. Modern trends in neutron activation analysis. Application to some African environmental samples. Proceedings of the 3rd environmental physics conference.
56. IAEA. 2006. Database of prompt gamma rays from slow neutron capture for elemental analysis. Final report of coordinated research project. Technical report series no. Vienna.
57. Peter Bode. 1998. Activation Analysis (Encyclopedia of Environmental Analysis and Remediation Editor Robert A. Meyers, John Wiley & Sons).
58. IAEA. 2001. Quality aspects of research reactor operations for instrumental neutron activation analysis, Report of the advisory group meeting held in Accra, Ghana, 1999. TECDOC 1218.
59. Win, D. T. 2004. Neutron activation analysis (NAA). AU J.T 8: 8 - 14
60. Sarathi, D.P., Acharya, R., Nair, A.G.C., Lakshminarayana, S., Das, N.L., Reddy, A.V.R. 2008. Journal of Nuclear and Radiochemical Sciences 9: 7-12.
61. Descantes, C., Speakman, R. J., Glascock M. D. 2008. Compositional studies of Caribbean ceramics. An introduction to Instrumental neutron activation analysis. Journal of Caribbean Archaeology. ISSN 1524 – 4776.
62. Zaichick, S., Zaichick, V. 2009. Neutron activation analysis of trace element content in the bone samples of human iliac crest. 17th international seminar on interaction of neutrons with nuclei, Dubna, Russia 2009.
63. Guinn, V.P. 1979. JFK Assassination: Bullet analyses. Anal. Chem. 51: 484 – 493.
64. Kogo, B. E., Gareje, E. N., Ogunmola, J. K., Ogbole, J. O. 2009. Neutron activation analysis of soil samples from different parts of Abuja Metropolis. Middle East journal of Scientific Research 4: 254 – 262.
65. Saiki, M., Alves, E. R., Cinquini, T. R. F.J., Kubrusly, F. S., Veiga L.R., Winter C. E. 2005. Application of neutron activation analysis for trace element determination in plasma and egg yolk, Samples of Bothrops jararaca. International Nuclear Atlantic conference- INAC, Santos, SP, Brazil, August 28- September 2, 2005.
66. Mokaleng, L. 2008. A database development for multi-element concentrations of medicinal plants using Instrumental neutron activation analysis (INAA) and Inductively coupled plasma mass spectrometry (ICP-MS). M.Sc –thesis. Centre for applied radiation science and technology, North West University, Mafikeng, South Africa.

67. Ball, G. 2003. Reactor calculations in aid of Isotope production at SAFARI-1. *Journal of Radioanalytical and Nuclear chemistry* 25: 65-70.
68. Chung Yong-Sam, Kim Sun-Ha, Moon Jong-Hwa, Kim Hark-Rho, Kim Young-Jin. 2005. Characteristics of pneumatic transfer system and irradiation hole at the Henaro Research Reactor. *Nuclear Engineering and Technology* 38: No.6.
69. Lauria, D. C., Rebeiro, F. C. A., Conti, C. C., Laouairo, F. A. 2009. Radium and uranium levels in vegetables grown using different farming management system. *Journal of Environmental Radioactivity* 100: 176 – 183.
70. Hagazy, K. A., Emam, M. H. 2011. Accumulation and soil to plant transfer of radionuclides in the Nile Delta Coastal Black sand habitats. *International Journal of phytoremediation* 13: 140 – 155.
71. Lozano, J. C., Rodriguez, B. P., Vera T. F. 2002. Distribution of the ^{238}U series in the sediments of a small river in a uranium mineralized region of Spain. *Journal of Environmental Radioactivity* 63: 153- 171.
72. Santos, E. E., Lauria, D. C., Amaral, E. C. S., Rochedo, E. R. 2002. Daily ingestion of ^{232}Th , ^{238}U , ^{226}Ra , ^{228}Ra and ^{210}Po in vegetables by inhabitants of Rio de Janeiro City. *Journal of Environmental Radioactivity* 62: 75 – 86.
73. Jha, S. K., Gothankar, S., Longwai, P. S., Kharbuli, B., War, S. A., Puranik, V. D. 2012. Intake of ^{238}U and ^{232}Th through the consumption of foodstuffs by tribal population practicing slash and burn agriculture in an extremely high rain fall area. *Journal of Environmental Radioactivity* 103: 1-6.
74. Ramatlhale I. I. 2009. Analysis of Naturally Occurring Radioactive Material and Radiocaesium in sediments from the Wonderfontein catchment area in the North West Province and Mosses from Minsk (Belarus) using gamma spectrometry and Gas flow proportional counting. M.Sc. Thesis. Centre for Applied Radiation Science and Technology, North West University.
75. IAEA, Safety Series 115, 1996, Vienna, Austria.

Annexure 1 Soil to Plant transfer factor values for **uranium. (IAEA Quantification of soil to plant transfer factors) ⁽³¹⁾**

Plant group	Plant compartment	Soil	N	GM	GSD	AM	SD	Min	Max
All			781	2.3×10^{-2}	9.1	2.1×10^{-1}	9.1×10^{-1}	3.0×10^{-5}	1.4×10^1
Cereals	Grain	All	59	6.2×10^{-3}	7.7	5.0×10^{-2}	1.4×10^{-1}	1.6×10^{-4}	8.2×10^{-1}
		Sand	6	8.9×10^{-3}	1.1×10^1	2.8×10^{-2}	2.5×10^{-2}	1.9×10^{-4}	6.2×10^{-2}
		Loam	20	7.7×10^{-3}	5.1	1.8×10^{-2}	1.9×10^{-2}	1.6×10^{-4}	6.2×10^{-2}
		Clay	11	3.8×10^{-3}	4.0	9.4×10^{-3}	1.5×10^{-2}	7.6×10^{-4}	5.0×10^{-2}
	Stems and shoots	All	55	2.7×10^{-2}	7.5	1.4×10^{-1}	4.8×10^{-1}	3.0×10^{-5}	3.5
		Sand	6	3.4×10^{-2}	6.0	7.5×10^{-2}	6.5×10^{-2}	2.1×10^{-3}	1.7×10^{-1}
		Loam	25	5.4×10^{-2}	6.30	2.5×10^{-1}	7.0×10^{-1}	7.4×10^{-4}	3.5
		Clay	8	1.0×10^{-2}	3.6	2.3×10^{-2}	3.4×10^{-2}	2.8×10^{-3}	9.8×10^{-2}
Maize	Grain	All	9	1.5×10^{-2}	1.2×10^1	1.2×10^1	2.3×10^{-1}	5.0×10^{-4}	7.1×10^{-1}
	Stems and shoots	All	11	7.8×10^{-3}	1.4×10^{-1}	1.1×10^{-1}	2.9×10^{-1}	1.6×10^{-4}	9.6×10^{-1}
Leafy Vegetables	Leaves	All	108	2.0×10^{-2}	7.3	2.2×10^{-1}	1.1	7.8×10^{-5}	8.8
		Sand	7	1.7×10^{-1}	1.5×10^1	1.5	3.3	1.5×10^{-3}	8.8
		Loam	14	4.3×10^{-2}	3.9	8.7×10^{-2}	8.8×10^{-2}	7.7×10^{-3}	2.7×10^{-1}
		Clay	9	3.6×10^{-3}	4.2	1.0×10^{-2}	1.6×10^{-2}	7.6×10^{-4}	4.3×10^{-2}
		Peat	6	1.8×10^{-1}	9.7	1.5	3.2	7.9×10^{-3}	8.0
Non-leafy Vegetables	Fruits, heads, berries, buds	All	38	1.5×10^{-2}	4.2	3.6×10^{-2}	5.3×10^{-2}	5.2×10^{-4}	2.0×10^{-1}
		Sand	7	1.9×10^{-2}	5.5	4.9×10^{-2}	6.0×10^{-2}	1.3×10^{-3}	1.6×10^{-1}
		Loam	4	2.3×10^{-2}	2.2	2.8×10^{-2}	1.7×10^{-2}	7.6×10^{-3}	4.7×10^{-2}
		Clay	7	1.8×10^{-2}	4.2	4.8×10^{-2}	7.4×10^{-2}	5.0×10^{-3}	2.0×10^{-1}
	Stems and shoots	All	6	5.3×10^{-2}	9.9	2.6×10^{-1}	3.5×10^{-1}	4.3×10^{-3}	7.1×10^{-1}
Leguminous Vegetable	Pods	All	19	2.2×10^{-3}	1.2×10^1	2.2×10^{-2}	4.6×10^{-2}	5.4×10^{-5}	1.5×10^{-1}

Compiled from the IAEA-TECDOC-1616 as a reliable source ⁽³¹⁾.

Soil to plant transfer factor values for **uranium** (continued)

Plant group	Plant compartment	Soil	N	GM	GSD	AM	SD	Min	Max
Leguminous Vegetables	Stems and shoots	Loam	4	3.0×10^{-3}	1.8×10^1	1.5×10^{-2}	2.2×10^{-2}	5.4×10^{-5}	4.7×10^{-2}
		Clay	7	5.5×10^{-4}	4.7	1.4×10^{-3}	1.9×10^{-3}	5.7×10^{-5}	5.0×10^{-3}
		All	21	6.4×10^{-2}	1.4×10^1	8.4×10^{-1}	2.0	7.4×10^{-4}	8.7
Root crops	Roots	Sand	6	2.8×10^{-1}	2.0×10^1	2.4	3.5	5.3×10^{-3}	8.7
		Loam	6	1.2×10^{-2}	6.2	3.5×10^{-2}	5.1×10^{-2}	7.4×10^{-4}	1.4×10^{-1}
		All	46	8.4×10^{-3}	6.2	3.6×10^{-2}	6.5×10^{-2}	4.9×10^{-4}	2.6×10^{-1}
		Sand	9	7.8×10^{-3}	5.9	3.8×10^{-2}	7.6×10^{-2}	9.9×10^{-4}	2.3×10^{-1}
		Loam	10	2.5×10^{-2}	3.2	4.3×10^{-2}	4.3×10^{-2}	2.6×10^{-3}	1.2×10^{-1}
		Clay	5	6.8×10^{-3}	6.2	2.3×10^{-2}	3.9×10^{-2}	7.9×10^{-4}	9.2×10^{-2}
	Stems and shoots	All	37	2.8×10^{-2}	5.4	9.5×10^{-2}	1.6×10^{-1}	2.0×10^{-3}	7.0×10^{-1}
		Sand	9	2.5×10^{-2}	5.6	6.7×10^{-2}	8.3×10^{-2}	2.0×10^{-3}	2.4×10^{-1}
		Loam	11	5.0×10^{-2}	3.0	8.6×10^{-2}	9.8×10^{-2}	1.3×10^{-2}	3.2×10^{-1}
		Clay	5	1.1×10^{-2}	4.3	2.2×10^{-2}	2.3×10^{-2}	2.0×10^{-3}	5.8×10^{-2}
Tubers	Tubers	All	28	5.0×10^{-3}	6.4	1.7×10^{-2}	2.4×10^{-2}	1.8×10^{-4}	8.0×10^{-2}
		Sand	4	1.9×10^{-2}	3.8	3.3×10^{-2}	3.4×10^{-2}	4.3×10^{-3}	7.8×10^{-2}
		Loam	3	2.8×10^{-2}	3.2	4.0×10^{-2}	3.6×10^{-2}	8.2×10^{-3}	8.0×10^{-2}
		Clay	6	9.2×10^{-4}	3.0	1.5×10^{-3}	1.7×10^{-3}	1.9×10^{-4}	4.8×10^{-3}
	Stems and shoots	All	1			1.9×10^{-1}			
	Fruit	All	11	1.2×10^{-2}	5.9	5.7×10^{-2}	1.2×10^{-1}	1.3×10^{-3}	3.7×10^{-1}
Herbs	Leaves	All	66	3.5×10^{-1}	3.6	6.7×10^{-1}	1.1	3.6×10^{-4}	7.5
		All	9	3.6×10^{-2}	4.9	1.1×10^{-1}	1.6×10^{-1}	8.6×10^{-3}	4.1×10^{-1}
Other crops	Leaves sunflower	All	39	7.1×10^{-2}	3.9	3.1×10^{-1}	1.2	8.9×10^{-3}	7.8
		Sand	5	4.1×10^{-1}	5.3	1.7	3.4	1.6×10^{-1}	78
		Loam	22	7.1×10^{-2}	2.9	1.2×10^{-1}	1.4×10^{-1}	1.0×10^{-2}	6.4×10^{-1}
		Clay	11	2.7×10^{-2}	2.1	3.5×10^{-2}	2.8×10^{-2}	8.9×10^{-3}	1.0×10^{-1}

Compiled from the IAEA-TECDOC-1616 as a reliable source ⁽³¹⁾.

Soil to plants transfer factor values for **uranium** (continued)

Plant group	Plant compartment	Soil	N	GM	GSD	AM	SD	Min	Max
Grasses	Grain (flowers)	All	2	1.5×10^{-2}	2.4	1.8×10^{-2}	1.5×10^{-2}	8.2×10^{-3}	2.9×10^{-2}
	Stems and shoots	All	147	1.7×10^{-2}	9.4	1.2×10^{-1}	4.9×10^{-1}	2.0×10^{-4}	5.5
		Sand	19	1.6×10^{-2}	1.7×10^1	2.5×10^{-1}	5.0×10^{-1}	5.5×10^{-4}	1.8
		Loam	34	9.8×10^{-3}	8.4	5.5×10^{-2}	1.0×10^{-1}	3.1×10^{-4}	4.6×10^{-1}
Pasture (natural)	Stems and shoots	All	53	4.6×10^{-2}	5.3	4.2×10^{-1}	2.0	1.3×10^{-3}	1.4×10^1
Fodder leguminous	Stems and shoots	Sand	3	2.7×10^{-3}	1.8	3.0×10^{-3}	1.5×10^{-3}	1.3×10^{-3}	3.9×10^{-3}
		Loam	7	7.2×10^{-2}	3.3×10^1	2.7	5.2	1.8×10^{-3}	1.4×10^1
		All	15	1.5×10^{-2}	4.2	1.2×10^{-1}	4.0×10^{-1}	2.0×10^{-3}	1.6
		Sand	12	1.0×10^{-2}	2.0	1.2×10^{-2}	5.9×10^{-3}	2.0×10^{-3}	2.1×10^{-2}

Compiled from the IAEA-TECDOC-1616 as a reliable source ⁽³¹⁾.

Soil to plant transfer factor values for **thorium**

Plant group	Plant compartment	Soil	N	GM	GSD	AM	SD	Min	Max
All		All	335	3.4×10^{-3}	1.5×10^1	5.8×10^{-2}	2.4×10^{-1}	1.2×10^{-6}	2.7
Cereals	Grain	All	36	2.1×10^{-3}	3.39	3.80×10^{-3}	4.5×10^{-3}	1.6×10^{-4}	2.2×10^{-2}
		Sand	4	4.4×10^{-3}	1.35	4.5×10^{-3}	1.3×10^{-3}	3.0×10^{-3}	6.0×10^{-3}
		Loam	18	2.7×10^{-3}	3.38	4.8×10^{-3}	5.5×10^{-3}	2.1×10^{-4}	2.2×10^{-2}
		Clay	9	1.2×10^{-3}	1.56	1.3×10^{-3}	6.5×10^{-4}	7.0×10^{-4}	2.6×10^{-3}
		Organic	3	2.0×10^{-3}	1.49	2.1×10^{-3}	9.2×10^{-4}	1.6×10^{-3}	3.2×10^{-3}
Maize	Stems and shoots	All	28	6.1×10^{-3}	2.43	9.0×10^{-3}	9.0×10^{-3}	1.6×10^{-3}	3.7×10^{-2}
		Sand	4	1.4×10^{-2}	1.26	1.4×10^{-2}	3.3×10^{-3}	1.1×10^{-2}	1.8×10^{-2}
		Loam	11	6.6×10^{-3}	1.94	7.8×10^{-3}	4.0×10^{-3}	2.4×10^{-3}	1.3×10^{-2}
		Clay	8	3.6×10^{-3}	1.57	3.9×10^{-3}	1.7×10^{-3}	2.0×10^{-3}	6.0×10^{-3}
		Organic	3	2.0×10^{-3}	1.49	2.1×10^{-3}	9.2×10^{-4}	1.6×10^{-3}	3.2×10^{-3}
Leafy Vegetables	Grain	All	18	6.4×10^{-5}	9.23	8.5×10^{-4}	2.6×10^{-3}	1.2×10^{-6}	1.1×10^{-2}
		Loam	10	2.0×10^{-4}	9.34	1.5×10^{-3}	3.4×10^{-3}	1.4×10^{-5}	1.1×10^{-2}
		Clay	7	1.5×10^{-5}	3.70	2.5×10^{-5}	2.1×10^{-5}	1.2×10^{-6}	5.4×10^{-5}
		Organic	3	2.0×10^{-3}	1.49	2.1×10^{-3}	9.2×10^{-4}	1.6×10^{-3}	3.2×10^{-3}
		Organic	3	2.0×10^{-3}	1.49	2.1×10^{-3}	9.2×10^{-4}	1.6×10^{-3}	3.2×10^{-3}
Non-Leafy Vegetables	Stems and shoots	All	2	1.8×10^{-3}		1.8×10^{-3}	1.7×10^{-3}	5.4×10^{-4}	3.0×10^{-3}
		All	24	1.2×10^{-3}	6.03	1.18×10^{-2}	4.3×10^{-2}	9.4×10^{-5}	2.1×10^{-1}
		Loam	13	8.6×10^{-4}	3.32	1.5×10^{-3}	1.6×10^{-3}	9.4×10^{-5}	5.8×10^{-3}
		Clay	7	4.9×10^{-4}	2.81	9.1×10^{-4}	1.4×10^{-3}	1.9×10^{-4}	4.1×10^{-3}
		Organic	3	2.0×10^{-3}	1.49	2.1×10^{-3}	9.2×10^{-4}	1.6×10^{-3}	3.2×10^{-3}
Leguminous Vegetable	Fruits, heads, berries, buds	All	17	7.8×10^{-4}	6.76	3.4×10^{-3}	5.4×10^{-3}	6.2×10^{-5}	1.6×10^{-2}
		Loam	10	2.0×10^{-4}	9.34	1.5×10^{-3}	3.4×10^{-3}	1.4×10^{-5}	1.1×10^{-2}
		Clay	7	1.5×10^{-5}	370	2.5×10^{-5}	2.1×10^{-5}	1.2×10^{-6}	5.4×10^{-5}
		Organic	3	2.0×10^{-3}	1.49	2.1×10^{-3}	9.2×10^{-4}	1.6×10^{-3}	3.2×10^{-3}
		Organic	3	2.0×10^{-3}	1.49	2.1×10^{-3}	9.2×10^{-4}	1.6×10^{-3}	3.2×10^{-3}
Leguminous Vegetable	Stems and shoots	All	6	2.2×10^{-3}	5.1	6.1×10^{-3}	9.2×10^{-3}	3.3×10^{-4}	2.4×10^{-2}
		All	22	5.3×10^{-4}	9.4	2.3×10^{-2}	1.0×10^{-1}	2.5×10^{-5}	4.8×10^{-1}
		Loam	14	1.8×10^{-3}	3.9	4.4×10^{-3}	7.1×10^{-3}	1.7×10^{-4}	2.4×10^{-2}
		Clay	10	4.1×10^{-4}	2.3×10^1	4.9×10^{-2}	1.5×10^{-1}	2.5×10^{-5}	4.8×10^{-1}
		Organic	4	4.5×10^{-4}	7.6	1.4×10^{-3}	1.9×10^{-3}	8.0×10^{-5}	4.0×10^{-3}
Leguminous Vegetable	Stems and shoots	All	7	4.3×10^{-3}	4.0	8.5×10^{-3}	9.1×10^{-3}	5.3×10^{-4}	2.4×10^{-2}

Soil to plant transfer factor values for **thorium** (continued)

Plant group	Plant compartment	Soil	N	GM	GSD	AM	SD	Min	Max
Root crops	Roots	All	33	8.0×10^{-4}	1.3×10^1	9.3×10^{-3}	2.0×10^{-2}	8.2×10^{-6}	9.5×10^{-2}
		Loam	14	1.1×10^{-3}	1.6×10^1	9.1×10^{-3}	1.5×10^{-2}	8.2×10^{-6}	5.3×10^{-2}
		Clay	14	2.6×10^{-4}	5.4	2.0×10^{-3}	6.1×10^{-3}	4.5×10^{-5}	2.3×10^{-2}
Tubers	Stems and shoots	All	8	8.7×10^{-3}	4.4	2.1×10^{-2}	2.8×10^{-2}	2.1×10^{-3}	7.8×10^{-2}
	Tubers	All	24	2.0×10^{-4}	9.9	1.6×10^{-3}	3.7×10^{-3}	1.3×10^{-5}	1.8×10^{-2}
		Loam	10	2.5×10^{-4}	6.4	8.3×10^{-4}	1.2×10^{-3}	1.3×10^{-5}	3.6×10^{-3}
		Clay	12	9.6×10^{-5}	1.1×10^1	1.7×10^{-3}	5.0×10^{-3}	1.3×10^{-5}	1.8×10^{-2}
	Stems and shoots	All	2			1.9×10^{-2}	1.9×10^{-2}	4.8×10^{-3}	3.2×10^{-2}
Fruit	Fruit	All	2			6.3×10^{-3}	5.3×10^{-3}	2.5×10^{-3}	1.0×10^{-2}
Other crops	Tea Leaves		1			3.4×10^{-3}			
Grasses	Stems and shoots	All	64	4.2×10^{-2}	3.1	7.4×10^{-2}	1.0×10^{-1}	7.4×10^{-4}	6.5×10^{-1}
Pasture (Natural)	Stems and shoots	All	36	9.9×10^{-2}	5.5	3.7×10^{-1}	6.4×10^{-1}	2.9×10^{-3}	2.7
Fodders	Stems and shoots	All	5	2.6×10^{-3}	1.6	2.8×10^{-3}	1.2×10^{-3}	1.5×10^{-3}	4×10^{-3}

Soil to plant transfer factor values for **potassium**

Plant group	Plant compartment	Soil	N	GM	GSD	AM	SD	Min	Max
Cereals	Grain	All	2			7.4×10^{-1}	3.3×10^{-3}	7.3×10^{-1}	7.4×10^{-1}
Leafy Vegetables	Leaves	All	2			1.3	1.2×10^{-1}	1.2	1.3
Pasture	Stems and shoots	All	1			7.3×10^{-1}			
Cereals	Stems and shoots	All	2			1.1	2.0×10^{-1}	9.3×10^{-1}	1.2

Compiled from the IAEA-TECDOC-1616 ⁽³¹⁾

Soil to plant transfer factor values for **radium**

Plant group	Plant compartment	Soil	N	GM	GSD	AM	SD	Min	Max
All		All	561	4.0×10^{-2}	8.6	6.9×10^{-1}	6.1	1.1×10^{-5}	1.3×10^{-2}
Cereals	Grain	All	24	1.7×10^{-2}	1.20×10^{-2}	1.1×10^{-1}	1.9×10^{-1}	8.0×10^{-5}	6.7×10^{-1}
		Loam	7	2.9×10^{-2}	9.70	1.6×10^{-1}	2.6×10^{-1}	8×10^{-4}	6.7×10^{-1}
		Clay	10	3.9×10^{-2}	9.88	1.3×10^{-1}	1.8×10^{-1}	2.40×10^{-4}	5.00×10^{-1}
		Stems and shoots	All	3.6×10^{-2}	4.78	9.4×10^{-2}	1.3×10^{-1}	1.60×10^{-3}	4.3×10^{-1}
Maize	Grain	Loam	10	5.2×10^{-2}	4.44	1.3×10^{-1}	1.6×10^{-1}	7.20×10^{-3}	4.3×10^{-1}
		All	28	2.4×10^{-3}	5.43	1.1×10^{-2}	2.3×10^{-2}	1.2×10^{-4}	1.1×10^{-1}
		Loam	4	1.7×10^{-3}	1.78	1.9×10^{-3}	1.0×10^{-3}	9.0×10^{-4}	3.0×10^{-3}
		Clay	16	1.4×10^{-3}	4.81	9.2×10^{-3}	2.8×10^{-2}	1.2×10^{-4}	1.1×10^{-1}
Leafy Vegetables	Stems and shoots	All	6	1.8×10^{-2}	5.24	3.7×10^{-2}	3.3×10^{-2}	9.6×10^{-4}	8.5×10^{-2}
		Leaves	All	9.1×10^{-2}	6.7	2.6	1.5×10^{-1}	1.8×10^{-3}	1.3×10^{-2}
		Loam	10	1.2×10^{-1}	2.5	1.6×10^{-1}	1.2×10^{-1}	1.6×10^{-2}	4.44×10^{-1}
		Clay	20	4.0×10^{-2}	4.5	9.2×10^{-2}	1.1×10^{-1}	1.8×10^{-3}	4.2×10^{-1}
Non-Leafy Vegetables	Fruits, heads, berries, buds	Organic	9	4.9×10^{-2}	2.1	6.2×10^{-2}	4.60×10^{-2}	2.0×10^{-2}	1.4×10^{-1}
		All	44	1.7×10^{-2}	8.4	2.6×10^{-1}	1.0	2.4×10^{-4}	6.3
		Sand	3	2.2×10^{-3}	2.1	2.70×10^{-3}	2.0×10^{-3}	1.10×10^{-3}	5.00×10^{-3}
		Loam	4	4.8×10^{-2}	5.6	1.2×10^{-1}	1.5×10^{-1}	6.9×10^{-3}	3.40×10^{-1}
Leguminous Vegetable	Stems and shoots	Clay	17	2.2×10^{-2}	2.8	4.1×10^{-2}	6.00×10^{-2}	3.9×10^{-3}	2.10×10^{-1}
		All	13	6.1×10^{-2}	6.4	3.1×10^{-1}	5.7×10^{-1}	6.7×10^{-3}	1.8
	Pots	All	40	1.4×10^{-2}	8.2	2.4×10^{-1}	1.0	3.20×10^{-4}	6.2
		Loam	12	9.8×10^{-3}	4.5	2.2×10^{-2}	2.6×10^{-2}	4.80×10^{-4}	8.7×10^{-2}
	Stems and shoots	Clay	15	9.3×10^{-3}	4.2	2.2×10^{-2}	3.0×10^{-2}	8×10^{-4}	1.10×10^{-1}
		All	18	2.8×10^{-2}	1.1×10^1	1.4×10^{-1}	3.5×10^{-1}	1.1×10^{-5}	1.50
		Loam	6	1.1×10^{-2}	3.2×10^1	4.8×10^{-2}	4.6×10^{-2}	1.1×10^{-5}	1.10×10^{-1}

Soil to plant transfer factors for **radium** (continued)

Plant group	Plant compartment	Soil	N	GM	GSD	AM	SD	Min	Max
Root crops	Roots	All	60	7 x10 ⁻²	9.2	1.9	7.8	2.0x10 ⁻³	5.6x10 ¹
		Sand	3	4.8x10 ⁻³	2.3	6 x10 ⁻³	4.5x10 ⁻³	2.0x10 ⁻³	1.1x10 ⁻²
		Loam	8	9.1x10 ⁻²	1.9	1.1x10 ⁻¹	5.9x10 ⁻²	2.9x10 ⁻²	2 x10 ⁻¹
		Clay	23	3.9x10 ⁻²	2.9	5.1x10 ⁻²	5.20x10 ⁻²	3.2x10 ⁻³	2.2x10 ⁻¹
	Stems and shoots	All	22	7.1x10 ⁻²	4.6	1.8x10 ⁻¹	2.2x10 ⁻¹	2.5x10 ⁻³	7.1x10 ⁻¹
		Loam	6	1.5x10 ⁻¹	5.6	3.1x10 ⁻¹	2.8x10 ⁻¹	9.6x10 ⁻³	7.1x10 ⁻¹
	Tubers	All	45	1.1x10 ⁻²	6.8	1.4x10 ⁻¹	5.9x10 ⁻¹	2.40x10 ⁻⁴	3.9
		Loam	8	1.20x10 ⁻²	1.1x10 ¹	9.2x10 ⁻²	2.1x10 ⁻¹	2.40x10 ⁻⁴	6.20x10 ⁻¹
Clay		24	5.40x10 ⁻³	2.5	9.5x10 ⁻³	1.6x10 ⁻²	1.3x10 ⁻³	8.00x10 ⁻²	
	Shoots	All	6	1.6x10 ⁻¹	2.2	1.9x10 ⁻¹	1.1x10 ⁻¹	4.3x10 ⁻²	3.3x10 ⁻¹
	Herbs	All	20	6.9x10 ⁻²	4.2	2.6x10 ⁻¹	7.3x10 ⁻¹	5.30x10 ⁻³	3.3
Fruit	Fruit	All	12	1.2x10 ⁻²	3.7	2.7x10 ⁻²	4.6x10 ⁻²	1.4x10 ⁻³	1.7x10 ⁻¹
Other crops	Sunflower-3/ peanut-1	All	4	4.2x10 ⁻¹	3.0	5.8x10 ⁻¹	4.2x10 ⁻¹	8.50x10 ⁻²	1.10
	Tea Leaves	All	1			3.3x10 ⁻²			
Grasses	Stems and shoots	All	62	1.3x10 ⁻¹	4	2.6x10 ⁻¹	3.20x10 ⁻¹	3.6x10 ⁻³	1.6
		Sand	24	1.4x10 ⁻¹	4.2	3.1x10 ⁻¹	4 x10 ⁻¹	5.4x10 ⁻³	1.6
		Loam	14	2.6x10 ⁻¹	2.00	3.2x10 ⁻¹	2.1x10 ⁻¹	9.6x10 ⁻²	7.2x10 ⁻¹
		Clay	3	4.20x10 ⁻²	1.5	4.4x10 ⁻²	1.70x10 ⁻²	2.70x10 ⁻²	6.1x10 ⁻²
Pasture (Natural)	Stems and shoots	All	42	7.10x10 ⁻²	7.6	1.9x10 ⁻¹	2.8x10 ⁻¹	5.1x10 ⁻⁵	1.60
		Sand	3	8 x10 ⁻³	3.8	1.2x10 ⁻²	1.1x10 ⁻²	1.80x10 ⁻³	2.3x10 ⁻²
		Loam	6	8.8x10 ⁻³	1.9x10 ¹	3.9x10 ⁻²	4 x10 ⁻²	5.1x10 ⁻⁵	1.1x10 ⁻¹
Fodders Leguminous	Stems and shoots	All	16	1.7x10 ⁻¹	3.1	3.0x10 ⁻¹	3.70x10 ⁻¹	3.40x10 ⁻²	1.5
		Sand	5	1.70x10 ⁻¹	2.5	2.4x10 ⁻¹	2.20x10 ⁻¹	8.00x10 ⁻²	5.7x10 ⁻¹
		Loam	8	1.2x10 ⁻¹	3.9	3.1x10 ⁻¹	5.1x10 ⁻¹	3.40x10 ⁻²	1.5

Compiled from the IAEA-TECDOC-1616 as a reliable source⁽³¹⁾.

Soil to plant transfer factor values for **lead**

Plant group	Plant compartment	Soil	N	GM	GSD	AM	SD	Min	Max
All		All	208	2.0×10^{-2}	1.4×10^1	6.3×10^{-1}	2.9	1.5×10^{-4}	2.5×10^1
Cereals	Grain	All	9	1.1×10^{-2}	3.6	1.8×10^{-2}	1.6×10^{-2}	1.9×10^{-3}	4.8×10^{-1}
	Stems and shoots	All	4	2.3×10^{-2}	3.5	3.8×10^{-2}	4.1×10^{-2}	5.1×10^{-3}	9.6×10^{-2}
Maize	Grain	All	9	1.2×10^{-3}	2.3	1.7×10^{-3}	1.4×10^{-3}	5.2×10^{-4}	3.8×10^{-3}
	Stems and shoots	All	3	2.8×10^{-3}	6.6	8.5×10^{-3}	1.3×10^{-2}	6.0×10^{-4}	2.3×10^{-2}
Leafy Vegetables	Leaves	All	31	8.0×10^{-2}	1.3×10^1	2.1	6.1	3.2×10^{-3}	2.5×10^1
		Sand	4	7.3×10^{-2}	1.5	7.8×10^{-2}	3.3×10^{-2}	4.9×10^{-2}	1.1×10^{-1}
		Loam	3	8.2×10^{-1}	1.0	8.2×10^{-1}	3.5×10^{-2}	7.9×10^{-1}	8.6×10^{-1}
		Clay	7	2.8×10^{-2}	4.1	5.1×10^{-2}	4.8×10^{-2}	4.1×10^{-3}	1.2×10^{-1}
Non-Leafy Vegetables	Fruits, heads, berries, buds	All	5	1.5×10^{-2}	2.6×10^1	7.8×10^{-1}	1.7	1.5×10^{-3}	3.9
	Stems and shoots	All	2			8.8×10^{-3}	4.2×10^{-3}	5.8×10^{-3}	1.2×10^{-2}
Leguminous Vegetable	Pods	All	17	5.3×10^{-3}	1.2×10^1	3.3×10^{-1}	1.20	4.4×10^{-6}	4.9
		Sand	3	2.7×10^{-3}	3.2	4.2×10^{-3}	3.4×10^{-3}	6.5×10^{-4}	8.9×10^{-3}
		Loam	5	1.4×10^{-3}	4.4	4.2×10^{-3}	3.4×10^{-3}	6.5×10^{-4}	8.9×10^{-3}
		Clay	4	8.0×10^{-4}	1.0	3.3×10^{-3}	4.7×10^{-3}	4.6×10^{-4}	1.0×10^{-2}
Root crops	Stems and shoots	All	1			8.0×10^{-4}			
		All	27	1.5×10^{-2}	1.6×10^1	4.1×10^{-1}	9.8×10^{-1}	2.4×10^{-4}	3.3
		Sand	5	6.4×10^{-2}	1.6	7.3×10^{-2}	3.4×10^{-2}	4.2×10^{-2}	1.2×10^{-1}
		Loam	5	2.3×10^{-3}	4.7	5.0×10^{-3}	6.8×10^{-3}	2.4×10^{-4}	1.7×10^{-2}
Tubers	Tubers	All	12	6.3×10^{-2}	1.5×10^1	2.5	5.7	3×10^{-3}	1.6×10^1
		All	30	1.5×10^{-3}	7.4	9.1×10^{-2}	4.8×10^{-1}	1.5×10^{-4}	2.6
		Sand	5	6.4×10^{-3}	3.5	1.2×10^{-2}	1.6×10^{-2}	1.6×10^{-3}	3.9×10^{-2}
		Loam	17	5.20×10^{-4}	2.4	7.3×10^{-3}	6.2×10^{-4}	1.5×10^{-4}	2.3×10^{-3}
Fruits	Fruits	All	5	7.7×10^{-3}	2.6	1.0×10^{-2}	6×10^{-3}	1.5×10^{-3}	1.7×10^{-2}
	Leaves	All	1			2.5×10^{-1}			

Compiled from the IAEA-TECDOC-1616 as a reliable source ⁽³¹⁾.

Soil to plant transfer factor values for lead (continued)

Plant group	Plant compartment	Soil	N	GM	GSD	AM	SD	Min	Max
Grasses	Stems and shoots	All	17	3.1×10^{-1}	1.8	3.6×10^{-1}	2.2×10^{-1}	1.1×10^{-1}	1.0
Pasture (Natural)	Stems and shoots	All	34	9.2×10^{-2}	4.8	2.3×10^{-1}	2.9×10^{-1}	2.2×10^{-3}	10
Fodders	Stems and shoots	All	1			1.6×10^{-2}			

Compiled from the IAEA-TECDOC-1616 as a reliable source ⁽³¹⁾.

Soil to plant transfer factor values for polonium

Plant group	Plant compartment	Soil	N	GM	GSD	AM	SD	Min	Max
All		All	57	5.6×10^{-3}	1.3×10^{-1}	5.6×10^{-2}	1.6×10^{-1}	1.6×10^{-5}	1.0
Cereals	Grain	All	2			2.4×10^{-4}	2.6×10^{-5}	2.2×10^{-4}	2.6×10^{-4}
Maize	Grain	All	2			2.4×10^{-4}	3.2×10^{-4}	1.8×10^{-5}	4.7×10^{-4}
Leafy Vegetables	Leaves	All	12	7.4×10^{-3}	6.9	1.9×10^{-2}	1.7×10^{-2}		
Non-Leafy Vegetables	Stems and shoots	All	2			1.9×10^{-4}	2.5×10^{-4}	1.6×10^{-5}	3.7×10^{-4}
Leguminous Vegetable	Pots	All	4	2.7×10^{-4}	3.9	4.8×10^{-4}	4.6×10^{-4}	6.0×10^{-5}	1.0×10^{-3}
Root crops	Roots	All	10	5.80×10^{-3}	4.3	1.2×10^{-2}	1.7×10^{-2}	2.4×10^{-8}	4.9×10^{-2}
	Stems and shoots	All	2			7.7×10^{-2}	2.7×10^{-2}	5.8×10^{-2}	9.7×10^{-2}
Tubers	Tubers	All	9	2.7×10^{-3}	5.8	8.0×10^{-3}	1.2×10^{-2}	1.4×10^{-4}	3.4×10^{-2}
Pasture (Natural)	Stems and shoots	All	10	1.2×10^{-1}	4.2	2.6×10^{-1}	3.2×10^{-1}	2.2×10^{-2}	1.0
Fodder Leguminous	Stems and shoots	All	2			1.1×10^{-2}	2.0	2.6×10^{-5}	2.2×10^{-4}

Compiled from the IAEA-TECDOC-1616 as a reliable source ⁽³¹⁾.

Annexure 2 Data base of crops⁽⁵²⁾

ALPHABETICAL LIST OF CROPS WITH BOTANICAL NAME AND CROP CODE

Crop name	Botanical name	ICC code	Previous code ¹
Abaca (Manila hemp)	<i>Musa textilis</i>	9213	2.2.4.1
Alfalfa for fodder	<i>Medicago sativa</i>	911	1.7.1.1
Alfalfa for seed	<i>Medicago sativa</i>	911	1.8.2
Almond	<i>Prunus dulcis</i>	361	2.1.7.1
Anise seeds	<i>Pimpinella anisum</i>	6212	1.4.3.4
Apple	<i>Malus sylvestris</i>	351	2.1.2.1
Apricot	<i>Prunus armeniaca</i>	352	2.1.3.1
Areca (betel nut)	<i>Areca catechu</i>	992	2.2.7.6
Arracha	<i>Arracacia xanthorrhiza</i>	59	1.2.9
Arrowroot	<i>Maranta arundinacea</i>	59	1.2.5
Artichoke	<i>Cynara scolymus</i>	211	1.5.1.0.1
Asparagus	<i>Asparagus officinalis</i>	212	1.5.1.0.2
Avocado	<i>Persea americana</i>	311	2.1.6.0.1
Bajra (Pearl millet)	<i>Pennisetum americanum</i>	18	1.1.5.1.2
Bambara groundnut	<i>Vigna subterranea</i>	79	1.3.9
Banana	<i>Musa paradisiaca</i>	312	2.1.6.0.2
Barley	<i>Hordeum vulgare</i>	15	1.1.4
Beans, dry, edible, for grains	<i>Phaseolus vulgaris</i>	71	1.3.1
Beans, harvested green	<i>Phaseolus and Vigna spp.</i>	71	1.5.4.1
Beet, fodder (mangel)	<i>Beta vulgaris</i>	81	1.7.5.0.5
Beet, red	<i>Beta vulgaris</i>	81	1.5.3.5
Beet, sugar	<i>Beta vulgaris</i>	81	1.4.1.2
Beet, sugar for fodder	<i>Beta vulgaris</i>	81	1.7.5.0.6
Beet, sugar for seeds	<i>Beta vulgaris</i>	81	1.8.1
Bergamot	<i>Citrus bergamia</i>	329	2.1.1.6
Betel nut	<i>Areca catechu</i>	992	2.2.7.6
Black pepper	<i>Piper nigrum</i>	6221	2.2.3.1
Black wattle	<i>Acacia mearnsii</i>	992	2.2.5.2
Blackberries of various species	<i>Rubus spp.</i>	349	2.1.5.7
Blueberry	<i>Vaccinium spp.</i>	346	2.1.5.1
Brazil nut	<i>Bertholletia excelsa</i>	369	2.1.7.6
Breadfruit	<i>Artocarpus altilis</i>	319	2.1.6.0.3
Broad bean, dry	<i>Vicia faba</i>	72	1.3.2
Broad bean, harvested green	<i>Vicia faba</i>	72	1.5.4.3
Broccoli	<i>Brassica oleracea var. botrytis</i>	214	1.5.5.1
Broom millet	<i>Sorghum bicolor</i>	18	1.4.5.4
Broom sorghum	<i>Sorghum bicolor</i>	14	1.4.5.4
Brussels sprouts	<i>Brassica oleracea var. gemmifera</i>	219	1.5.1.0.3
Buckwheat	<i>Fagopyrum esculentum</i>	192	1.1.9
Cabbage (red, white, Savoy)	<i>Brassica oleracea var. capitata</i>	213	1.5.1.0.4
Cabbage, Chinese	<i>Brassica chinensis</i>	213	1.5.1.0.7
Cabbage, for fodder	<i>Brassica spp.</i>	213	1.7.5.0.1
Cacao (cocoa)	<i>Theobroma cacao</i>	614	2.2.1.2
Cantaloupe	<i>Cucumis melo</i>	225	1.5.2.0.1
Caraway seeds	<i>Carum carvi</i>	6219	1.4.3.4
Cardamom	<i>Elettaria cardamomum</i>	6222	2.2.3.7
Cardoon	<i>Cynara cardunculus</i>	219	1.5.1.1.5
Carob	<i>Ceratonia siliqua</i>	39	2.1.6.1.5
Carrot, edible	<i>Daucus carota ssp. sativa</i>	231	1.5.3.1
Carrot, for fodder	<i>Daucus carota ssp. sativa</i>	231	1.7.5.1.0
Cashew nuts	<i>Anacardium occidentale</i>	362	2.1.7.2
Cassava (manioc)	<i>Manihot esculenta</i>	53	1.2.3

1. Crop codes used in 2000 agricultural census programme.

Crop name	Botanical name	ICC code	Previous code ¹
Castor bean	<i>Ricinus communis</i>	431	1.4.2.1.0
Cauliflower	<i>Brassica oleracea</i> var. <i>botrytis</i>	214	1.5.5.1
Celeriac	<i>Apium graveolens</i> var. <i>rapaceum</i>	239	1.5.3.8
Celery	<i>Apium graveolens</i>	219	1.5.1.0.5
Chayote	<i>Sechium edule</i>	229	1.5.2.1.2
Cherry (all varieties)	<i>Prunus</i> spp.	353	2.1.3.2
Chestnut	<i>Castanea sativa</i>	363	2.1.7.4
Chickpea (gram pea)	<i>Cicer arietinum</i>	73	1.3.4
Chicory	<i>Cichorium intybus</i>	217	1.4.5.2
Chicory for greens	<i>Cichorium intybus</i>	217	1.5.1.0.6
Chili, dry (all varieties)	<i>Capsicum</i> spp. (annuum)	6211	1.4.3.1
Chili, fresh (all varieties)	<i>Capsicum</i> spp. (annuum)	6211	1.5.2.0.2
Cinnamon	<i>Cinnamomum verum</i>	6223	2.2.3.2
Citron	<i>Citrus medica</i>	329	2.1.1.6
Citronella	<i>Cymbopogon citrates/ Cymbopogon nardus</i>	992	2.2.7.1
Clementine	<i>Citrus reticulata</i>	324	2.1.1.2
Clove	<i>Eugenia aromatica</i> (<i>Syzygium aromaticum</i>)	6224	2.2.3.3
Clover for fodder (all varieties)	<i>Trifolium</i> spp.	911	1.7.1.2
Clover for seed (all varieties)	<i>Trifolium</i> spp.	911	1.8.3
Cocoa (cacao)	<i>Theobroma cacao</i>	614	2.2.1.2
Coconut	<i>Cocos nucifera</i>	441	2.2.2.1
Cocoyam	<i>Colocasia esculenta</i>	59	1.2.8
Coffee	<i>Coffea</i> spp.	611	2.2.1.1
Cola nut (all varieties)	<i>Cola acuminata</i>	619	2.2.1.6
Colza (rapeseed)	<i>Brassica napus</i>	435	1.4.2.0.5
Corn (maize), for cereals	<i>Zea mays</i>	12	1.1.3
Corn (maize), for silage	<i>Zea mays</i>	12	1.7.3.1
Corn (sweet), for vegetable	<i>Zea mays</i>	12	1.5.5.2
Corn for salad	<i>Valerianella locusta</i>	219	1.5.1.1.5
Cotton (all varieties)	<i>Gossypium</i> spp.	9211	1.4.4.1
Cottonseed (all varieties)	<i>Gossypium</i> spp.	9211	1.4.2.0.8
Cowpea, for grain	<i>Vigna unguiculata</i>	74	1.3.6
Cowpea, harvested green	<i>Vigna unguiculata</i>	74	1.5.4.3
Cranberry	<i>Vaccinium</i> spp.	349	2.1.5.2
Cress	<i>Lepidium sativum</i>	219	1.5.1.0.8
Cucumber	<i>Cucumis sativus</i>	221	1.5.2.0.3
Currants (all varieties)	<i>Ribes</i> spp.	341	2.1.5.3
Custard apple	<i>Annona reticulata</i>	319	2.1.6.0.4
Dasheen	<i>Colocasia esculenta</i>	59	1.2.8
Dates	<i>Phoenix dactylifera</i>	313	2.1.6.0.5
Drumstick tree	<i>Moringa oleifera</i>	6229	2.2.3.8
Durra (sorghum)	<i>Sorghum bicolor</i>	14	1.1.5.2
Durum wheat	<i>Triticum durum</i>	11	1.1.1.1.1;
Earth pea	<i>Vigna subterranea</i>	79	1.3.9
Edo (eddoe)	<i>Xanthosoma</i> spp.; <i>Colocasia</i> spp.	59	1.2.8
Eggplant	<i>Solanum melongena</i>	222	1.5.2.0.4
Endive	<i>Cichorium endivia</i>	219	1.5.1.0.9
Fennel	<i>Foeniculum vulgare</i>	219	1.5.1.1.5
Fenugreek	<i>Trigonella foenum-graecum</i>	79	1.3.9
Fig	<i>Ficus carica</i>	314	2.1.6.0.6
Filbert (Hazelnut)	<i>Corylus avellana</i>	364	2.1.7.5
Fique	<i>Furcraea macrophylla</i>	9219	2.2.4.6
Flax for fibre	<i>Linum usitatissimum</i>	9213	1.4.4.2
Flax for oil seed (linseed)	<i>Linum usitatissimum</i>	9213	1.4.2.0.3
Formio (New Zealand flax)	<i>Phormium tenax</i>	9214	2.2.4.4

1. Crop codes used in 2000 agricultural census programme.

Crop name	Botanical name	ICC code	Previous code ¹
Garlic, dry	<i>Allium sativum</i>	233	1.2.7
Garlic, green	<i>Allium sativum</i>	233	1.5.3.2
Geranium	<i>Pelargonium spp.</i> ; <i>Geranium spp.</i>	931	1.4.3.2
Ginger	<i>Zingiber officinale</i>	6225	2.2.3.4
Gooseberry (all varieties)	<i>Ribes spp.</i>	342	2.1.5.4
Gourd	<i>Lagenaria spp.</i> ; <i>Cucurbita spp.</i>	226	1.5.2.0.5
Gram pea (chickpea)	<i>Cicer arietinum</i>	73	1.3.4
Grape	<i>Vitis vinifera</i>	33	2.1.4
Grapefruit	<i>Citrus paradisi</i>	321	2.1.1.4
Grapes for raisins	<i>Vitis vinifera</i>	33	2.1.4.3
Grapes for table use	<i>Vitis vinifera</i>	33	2.1.4.2
Grapes for wine	<i>Vitis vinifera</i>	33	2.1.4.1
Grass esparto	<i>Lygeum spartum</i>	991	1.4.5.4
Grass, orchard	<i>Dactylis glomerata</i>	911	1.7.2.1
Grass, Sudan	<i>Sorghum bicolor</i> var. <i>sudanense</i>	911	1.7.2.1
Groundnut (peanut)	<i>Arachis hypogaea</i>	42	1.4.2.0.1
Guava	<i>Psidium guajava</i>	319	2.1.6.0.7
Guinea corn (sorghum)	<i>Sorghum bicolor</i>	14	1.1.5.2
Hazelnut (filbert)	<i>Corylus avellana</i>	364	2.1.7.5
Hemp fibre	<i>Cannabis sativa</i> ssp. <i>indica</i>	9213	1.4.4.3
Hemp, Manila (abaca)	<i>Musa textilis</i>	922	2.2.4.1
Hemp, sun	<i>Crotalaria juncea</i>	9213	1.4.4.5
Hempseed	<i>Cannabis sativa</i> (marijuana)	439	1.4.2.1.1
Henequen	<i>Agave fourcroydes</i>	922	2.2.4.2
Henna	<i>Lawsonia inermis</i>	911	1.4.5.4
Hop	<i>Humulus lupulus</i>	619	2.2.1.4
Horse bean	<i>Vicia faba</i>	72	1.3.2
Horseradish	<i>Armoracia rusticana</i>	239	1.5.3.8
Hybrid maize	<i>Zea mays</i>	12	1.1.3.1
Indigo	<i>Indigofera tinctoria</i>	991	1.4.5.4
Jasmine	<i>Jasminum spp.</i>	952	2.2.6.2
Jerusalem artichoke	<i>Helianthus tuberosus</i>	211	1.7.5.0.2
Jowar (sorghum)	<i>Sorghum bicolor</i>	14	1.1.5.2
Jute	<i>Corchorus spp.</i> (over 30 sp.)	9212	1.4.4.4
Kale	<i>Brassica oleracea</i> var. <i>acephala</i>	219	1.5.1.1.0
Kapok	<i>Ceiba pentandra</i>	922	2.2.4.3
Kenaf	<i>Hibiscus cannabinus</i>	9212	1.4.4.5
Kohlrabi	<i>Brassica oleracea</i> var. <i>gongylodes</i>	239	1.5.3.6
Lavender	<i>Lavandula spp.</i> (over 15 sp.)	931	1.4.3.2
Leek	<i>Allium ampeloprasum</i> ; <i>Allium porrum</i>	235	1.5.1.1.1
Lemon	<i>Citrus limon</i>	322	2.1.1.3
Lemon grass	<i>Cymbopogon citratus</i>	922	2.2.7.7
Lentil	<i>Lens culinaris</i>	75	1.3.5
Lespedeza (all varieties)	<i>Lespedeza spp.</i>	911	1.7.1.3
Lettuce	<i>Lactuca sativa</i> var. <i>capitata</i>	215	1.5.1.1.2
Lime, sour	<i>Citrus aurantifolia</i>	322	2.1.1.5
Lime, sweet	<i>Citrus limetta</i>	322	2.1.1.6
Linseed (flax for oil seed)	<i>Linum usitatissimum</i>	432	1.4.2.0.3
Liquorice	<i>Glycyrrhiza glabra</i>	931	1.4.3.3
Litchi	<i>Litchi chinensis</i>	319	2.1.6.1.5
Loquat	<i>Eriobotrya japonica</i>	359	2.1.2.5
Lupine (all varieties)	<i>Lupinus spp.</i>	76	1.3.9

1. Crop codes used in 2000 agricultural census programme.

Crop name	Botanical name	ICC code	Previous code ¹
Macadamia (Queensland nut)	<i>Macadamia spp. ternifolia</i>	369	2.1.7.6
Mace	<i>Myristica fragrans</i>	6222	2.2.3.5
Maguey	<i>Agave atrovirens</i>	922	2.2.4.6
Maize (corn)	<i>Zea mays</i>	12	1.1.3
Maize (corn) for silage	<i>Zea mays</i>	12	1.7.3.1
Maize (hybrid)	<i>Zea mays</i>	12	1.1.3.1
Maize, ordinary	<i>Zea mays</i>	12	1.1.3.2
Mandarin	<i>Citrus reticulata</i>	324	2.1.1.2
Mangel (fodder beet)	<i>Beta vulgaris</i>	81	1.7.5.0.5
Mango	<i>Mangifera indica</i>	315	2.1.6.0.8
Manioc (cassava)	<i>Manihot esculenta</i>	53	1.2.3
Maslin (mixed cereals)	<i>Mixture of Triticum spp.; Secale cereale</i>	191	1.1.8
Medlar	<i>Mespilus germanica</i>	359	2.1.2.4
Melon (except watermelon)	<i>Cucumis melo</i>	225	1.5.2.0.1
Millet broom	<i>Sorghum bicolor</i>	18	1.4.5.4
Millet, bajra	<i>Pennisetum americanum</i>	18	1.1.5.1.2
Millet, bulrush	<i>Pennisetum americanum</i>	18	1.1.5.1.1
Millet, finger	<i>Eleusine coracana</i>	18	1.1.5.1.1
Millet, foxtail	<i>Setaria italica</i>	18	1.1.5.1.2
Millet, Japanese	<i>Echinochloa esculenta</i>	18	1.1.5.1.2
Millet, pearl (bajra, bulrush)	<i>Pennisetum americanum</i>	18	1.1.5.1.1
Millet, proso	<i>Panicum miliaceum</i>	18	1.1.5.1.1
Mint (all varieties)	<i>Mentha spp.</i>	6219	1.4.3.2
Mulberry for fruit (all varieties)	<i>Morus spp.</i>	39	2.1.6.1.5
Mulberry for silkworms	<i>Morus alba</i>	39	2.2.7.2
Mushrooms	<i>Agaricus spp.; Pleurotus spp.; Volvariella</i>	24	1.6.2.2
Mustard	<i>Brassica nigra; Sinapis alba</i>	433	1.4.2.0.6
Nectarine	<i>Prunus persica var. nectarina</i>	354	2.1.3.5
New Zealand flax (formio)	<i>Phormium tenax</i>	922	2.2.4.4
Niger seed	<i>Guizotia abyssinica</i>	434	1.4.2.1.1
Nutmeg	<i>Myristica fragrans</i>	6222	2.2.3.5
Oats, for fodder	<i>Avena spp. (about 30 sp.)</i>	17	1.7.3.2
Oats, for grain	<i>Avena spp. (about 30 sp.)</i>	17	1.1.6
Oil palm	<i>Elaeis guineensis</i>	443	2.2.2.2
Okra	<i>Abelmoschus esculentus</i>	229	1.5.2.0.6
Olive	<i>Olea europaea</i>	442	2.2.2.3
Onion seed	<i>Allium cepa</i>	234	1.8.5
Onion, dry	<i>Allium cepa</i>	234	1.2.6
Onion, green	<i>Allium cepa</i>	234	1.5.3.3
Opium	<i>Papaver somniferum</i>	931	1.4.3.3
Orange	<i>Citrus sinensis</i>	323	2.1.1.1
Orange, bitter	<i>Citrus aurantium</i>	323	2.1.1.6
Ornamental plants	<i>Various</i>	951	1.6.1.2
Palm palmyra	<i>Borassus flabellifer</i>	992	2.2.7.4
Palm, kernel oil	<i>Elaeis guineensis</i>	443	2.2.2.2
Palm, oil	<i>Elaeis guineensis</i>	443	2.2.2.2
Palm, sago	<i>Metroxylon sagu</i>	992	2.2.7.3
Papaya (pawpaw)	<i>Carica papaya</i>	316	2.1.6.0.9
Parsnip	<i>Pastinaca sativa</i>	239	1.5.3.8
Pea, edible dry, for grain	<i>Pisum sativum</i>	77	1.3.3
Pea, harvested green	<i>Pisum sativum</i>	77	1.5.4.2
Peach	<i>Prunus persica</i>	354	2.1.3.3
Peanut (groundnut)	<i>Arachis hypogaea</i>	42	1.4.2.0.1
Pear	<i>Pyrus communis</i>	355	2.1.2.2
Pecan nut	<i>Carya illinoensis</i>	369	2.1.7.6

1. Crop codes used in 2000 agricultural census programme.

Crop name	Botanical name	ICC code	Previous code ¹
Pepper, black	<i>Piper nigrum</i>	6221	2.2.3.1
Pepper, dry	<i>Capsicum spp.</i> (over 30 sp.)	6211	1.4.3.1
Persimmon	<i>Diospyros kaki</i> ; <i>Diospyros virginiana</i>	319	2.1.6.1.0
Pigeon pea	<i>Cajanus cajan</i>	78	1.3.7
Pineapple	<i>Ananas comosus</i>	317	2.1.6.1.1
Pistachio nut	<i>Pistacia vera</i>	365	2.1.7.6
Plantain	<i>Musa sapientum</i>	312	2.1.6.1.2
Plum	<i>Prunus domestica</i>	356	2.1.3.4
Pomegranate	<i>Punica granatum</i>	39	2.1.6.1.3
Pomelo	<i>Citrus grandis</i>	321	2.1.1.4
Poppy seed	<i>Papaver somniferum</i>	439	1.4.2.1.1
Potato	<i>Solanum tuberosum</i>	51	1.2.1
Potato, sweet	<i>Ipomoea batatas</i>	52	1.2.2
Prune	<i>Prunus domestica</i>	356	2.1.3.4
Pumpkin, edible	<i>Cucurbita spp.</i> (over 25 sp.)	226	1.5.2.0
Pumpkin, for fodder	<i>Cucurbita spp.</i> (over 25 sp.)	226	1.7.5.0.3
Pyrethrum	<i>Chrysanthemum cinerariaefolium</i>	991	1.4.5.3
Quebracho	<i>Aspidosperma spp.</i> (more than 3 sp.)	992	2.2.5.3
Queensland nut	<i>See Macadamia</i>	369	2.1.7.6
Quince	<i>Cydonia oblonga</i>	355	2.1.2.3
Quinine	<i>Cinchona spp.</i> (more than 6 sp.)	932	2.2.7.5
Quinoa	<i>Chenopodium quinoa</i>	192	1.1.9
Radish	<i>Raphanus sativus</i> (inc. <i>Cochlearia armoracia</i>)	239	1.5.3.4
Ramie	<i>Boehmeria nivea</i>	922	2.2.4.5
Rapeseed (colza)	<i>Brassica napus</i>	435	1.4.2.0.5
Raspberry (all varieties)	<i>Rubus spp.</i> (over 360 sp.)	344	2.1.5.5
Red beet	<i>Beta vulgaris</i>	239	1.5.3.5
Redtop	<i>Agrostis spp.</i>	911	1.7.2.1
Rhea	<i>Boehmeria nivea</i>	922	2.2.4.5
Rhubarb	<i>Rheum spp.</i>	219	1.5.1.1.3
Rice	<i>Oryza sativa</i> ; <i>Oryza glaberrima</i>	13	1.1.2
Rose	<i>Rosa spp.</i>	952	2.2.6.1
Rubber	<i>Hevea brasiliensis</i>	94	2.2.5.1
Rutabaga (swede)	<i>Brassica napus</i> var. <i>napobrassica</i>	239	1.5.3.6
Rye	<i>Secale cereale</i>	16	1.1.7
Ryegrass seed	<i>Lolium spp.</i> (about 20 sp.)	991	1.8.4
Safflower	<i>Carthamus tinctorius</i>	436	1.4.2.0.9
Sainfoin	<i>Onobrychis viciifolia</i>	911	1.7.1.3
Salsify	<i>Tragopogon porrifolius</i>	239	1.5.3.8
Sapodilla	<i>Achras sapota</i>	39	2.1.6.1.4
Satsuma (mandarin/tangerine)	<i>Citrus reticulata</i>	324	2.1.1.2
Scorzonera – black salsify	<i>Scorzonera hispanica</i>	239	1.5.3.8
Sesame	<i>Sesamum indicum</i>	437	1.4.2.0.7
Shea butter (nut)	<i>Vitellaria paradoxa</i>	449	2.2.2.4
Sisal	<i>Agave sisalana</i>	922	2.2.4.2
Sorghum	<i>Sorghum bicolor</i>	14	1.1.5.2
Sorghum, broom	<i>Sorghum bicolor</i>	14	1.4.5.4
Sorghum, durra	<i>Sorghum bicolor</i>	14	1.1.5.2
Sorghum, Guinea corn	<i>Sorghum bicolor</i>	14	1.1.5.2
Sorghum, jowar	<i>Sorghum bicolor</i>	14	1.1.5.2
Sorghum, sweet	<i>Sorghum bicolor</i>	183	1.4.1.3
Soybean	<i>Glycine max</i>	41	1.4.2.0.2
Soybean hay	<i>Glycine max</i>	41	1.7.1.3
Spelt wheat	<i>Triticum spelta</i>	192	1.1.9
Spinach	<i>Spinacia oleracea</i>	216	1.5.1.1.4

1. Crop codes used in 2000 agricultural census programme.

Crop name	Botanical name	ICC code	Previous code ¹
Squash	<i>Cucurbita</i> spp. (over 25 sp.)	226	1.5.2.0.8
Strawberry	<i>Fragaria</i> spp. (over 30 sp.)	345	2.1.5.6
Sugar beet	<i>Beta vulgaris</i>	81	1.4.1.2
Sugar beet for fodder	<i>Beta vulgaris</i>	81	1.7.5.0.6
Sugar beet for seed	<i>Beta vulgaris</i>	81	1.8.1
Sugarcane for fodder	<i>Saccharum officinarum</i>	82	1.7.5.0.7
Sugarcane for sugar or alcohol	<i>Saccharum officinarum</i>	82	1.4.1.1
Sugarcane for thatching	<i>Saccharum officinarum</i>	82	1.4.5.4
Sunflower for fodder	<i>Helianthus annuus</i>	438	1.7.5.0.4
Sunflower for oil seed	<i>Helianthus annuus</i>	438	1.4.2.0.4
Sunhemp	<i>Crotalaria juncea</i>	9213	1.4.4.5
Swede	<i>Brassica napus</i> var. <i>napobrassica</i>	239	1.5.3.6
Swede for fodder	<i>Brassica napus</i> var. <i>napobrassica</i>	239	1.7.5.0.8
Sweet corn	<i>Zea mays</i>	12	1.5.5.2
Sweet lime	<i>Citrus limetta</i>	322	2.1.1.6
Sweet pepper	<i>Capsicum annuum</i>	6211	1.5.2.0.9
Sweet potato	<i>Lopmoea batatas</i>	52	1.2.2
Sweet sorghum	<i>Sorghum bicolor</i>	183	1.4.1.3
Tangerine	<i>Citrus reticulata</i>	324	2.1.1.2
Tannia	<i>Xanthosoma sagittifolium</i>	59	1.2.8
Tapioca (cassava)	<i>Manihot esculenta</i>	53	1.2.3
Taro	<i>Colocasia esculenta</i>	59	1.2.8
Tea	<i>Camellia sinensis</i>	612	2.2.1.3
Tef	<i>Eragrostis abyssinica</i>	192	1.1.9
Timothy	<i>Phleum pratense</i>	911	1.7.2.1
Tobacco	<i>Nicotiana tabacum</i>	96	1.4.5.1
Tomato	<i>Lycopersicon esculentum</i>	223	1.5.2.1.0
Trefoil	<i>Lotus</i> spp. (about 100 sp.)	991	1.8.6
Triticale for fodder	Hybrid of <i>Triticum aestivum</i> and <i>Secale cereale</i>	47	1.7.3.2
Tung tree	<i>Aleurites</i> spp.; <i>Fordi</i>	449	2.2.2.4
Turnip, edible	<i>Brassica rapa</i>	232	1.5.3.7
Turnip, for fodder	<i>Brassica rapa</i>	232	1.7.5.0.9
Urena (Congo jute)	<i>Urena lobata</i>	9214	1.4.4.5
Vanilla	<i>Vanilla planifolia</i>	6226	2.2.3.6
Vetch for grain	<i>Vicia sativa</i>	79	1.3.8
Walnut	<i>Juglans</i> spp. (over 20 sp.), <i>ep. regia</i>	366	2.1.7.3
Watermelon	<i>Citrullus lanatus</i>	224	1.5.2.1.1
Wheat	<i>Triticum aestivum</i>	11	1.1.1
Yam	<i>Dioscorea</i> spp. (over 120 sp.)	54	1.2.4
Yerba mate	<i>Ilex paraguariensis</i>	613	2.2.1.5

1. Crop codes used in 2000 agricultural census programme.

Annexure 3 Anticipated activities and time schedule for experimental phase of the study

