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CRITICAL GROUP IDENTIFICATION VIA A RADIOLOGICAL HABIT STUDY OF MEMBERS OF THE PUBLIC POTENTIALLY EXPOSED TO RADIATION FROM THE KOEBERG NUCLEAR POWER STATION

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A Research Report submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science

Johannesburg, 2009

ABSTRACT

The Koeberg Nuclear Power Station is situated on the Cape West Coast, approximately 30 km north of Cape Town and is licensed by the National Nuclear Regulator of South Africa (NNR). The NNR authorises internationally acceptable annual discharges of radioactive effluent from the plant, under controlled conditions via approved liquid and gaseous effluent pathways. The radioactivity contained in effluent may migrate into the environment and directly and/or indirectly expose members of the public to radiation and result in public dose. One way of assessing the public dose is to identify the Critical Group, those members of the public who are the most highly exposed. A Critical Group is defined as a small group of people being reasonably homogeneous with respect to its exposure for a given radiation source and given exposure pathway. The identification of the Critical Group is motivated by the need to demonstrate compliance with international and national radiological safety requirements and to safeguard potentially exposed individuals in the vicinity of the Koeberg Nuclear Power Station. A radiological habit survey was designed and implemented. Data were obtained from members of the public relating to their eating and recreational habits which may result in potential exposure. Recent radiological environmental-surveillance data and radiological monitoring data were combined with the radiological habit survey data taking the aquatic, terrestrial, direct radiation and combined pathways into account in order to calculate Retrospective Public Doses. A pathway habit-profiling method was applied to derive profiles of habit rates for each pathway. Individuals with the highest consumption rates, occupancy or doses were identified and a "cut-off" method was applied to select the Critical Groups and Critical Group rates for each pathway. Habit profiles, source terms and dose rates measured during fieldwork were applied to calculate effective doses. The pathway which gave rise to the highest Critical Group dose was used to identify the Critical Group for the Koeberg Nuclear Power Station. The highest Critical Group dose was used for comparison with the national annual dose limit and dose constraint.

DECLARATION

I declare that this Research Report is my own, unaided work. It is being submitted for the Degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Marc Maree January 2009

DEDICATION

In memory of my father

James John Maree

1935-2008

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Glory, honour and praise to God our Father and to our Lord Jesus Christ for all wisdom and knowledge. I would like to thank my loving wife Benita, my daughter Marcita and son, Jean-Marc for patient endurance, love and support rendered during my studies.

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CHAPTER 1

INTRODUCTION AND CONTEXT

"For the purpose of protection of the public against radiation, the International Commission on Radiological Protection has used the 'Critical Group' concept to characterise an individual receiving a dose of radiation that is representative of the more highly exposed individuals in the population" [IC07].

1.1 Introduction

The primary purpose of this work is to identify the Critical Group which received the highest effective dose during 2006 due to radioactive sources and pathways from the Koeberg Nuclear Power Station. The Critical Group is identified via retrospective application of environmental-surveillance data, site-specific radiological habit survey data and radiological surveillance data. Appendix A contains radiological protection definitions and glossary relating to terminology used in this work.

Information in this chapter is organised in three sections. The first aspect is the identification of the Critical Group, the 2nd aspect is the methodology applied and the 3rd aspect outlines the format of this report.

1.2 Identification of the Critical Group

A Critical Group is defined as: "*A small group of the public who is representative of those receiving the highest doses of radiation due to a particular radiation source or a number of radiation sources*" [HU04]. The identification of the Critical Group for the Koeberg Nuclear Power Station is motivated by the need to demonstrate compliance with international and national Critical Group requirements, dose limits and dose constraints.

For the purposes of protection of the public, the International Commission on Radiological Protection (ICRP) has historically recommended application of the "Critical Group" concept to characterise an individual receiving a dose that is

representative of the more highly exposed individuals in the population. A Critical Group is regarded as a small group of individuals representative of those most highly exposed and is characterised by typical habits e.g., consumption of food stuff, breathing rate, location and usage of local resources [IC77]. The identification of the Critical Group for the Koeberg Nuclear Power Station is motivated by the need to demonstrate compliance with the following key ICRP recommendations:

- homogeneity of members of the Critical Group, i.e. the variance of the mean dose must be within a factor of three if the Critical Group dose is greater than a tenth of the dose limit [IC85];
- all pathways including the aquatic, terrestrial, direct radiation and combined pathways must be considered in the dose assessment of the Critical Group [IC91]; and
- mean consumption rates and occupancy rates should be considered to identify the characteristics of the Critical Group [IC07].

The identification of the Critical Group for the Koeberg Nuclear Power Station is also motivated by the need to demonstrate compliance with the following statutory and regulatory dose limits and dose constraints from the Department of Minerals and Energy of South Africa (DME) and the National Nuclear Regulator of South Africa (NNR):

- an annual average effective dose limit of 1 mSv y^{-1} is applicable to Critical Groups [DM99]; and
- a public dose constraint of 0.25 mSv y^{-1} is applicable to Critical Groups [NN01, NN04].

Identification of the Critical Group for the Koeberg Nuclear Power Station has demonstrated compliance with international and national Critical Group requirements, dose limits and dose constraints. This work has identified new information on land-use, demographics, recreational habits and eating habits for future applications in Retrospective and Prospective Public Dose Assessments.

1.3 Methodology

Principles, methodologies and techniques developed by UK scientists and experts, [AL04, LE82, CU05, AL05, BY95, CA02, CU05, HA02, HU82] in the field of Retrospective Public Dose Assessments were reviewed, applied and refined to identify the Critical Group due to radioactive sources and exposure pathways from the Koeberg Nuclear Power Station.

Potential sources of exposure from the Koeberg Nuclear Power Station were assessed in accordance with a Radiological Assessment Exposure Pathways Checklist (RAEPC) [AL04]. Potential release routes, radiation sources, exposure pathways from the Koeberg Nuclear Power Station were identified and rated in order of significance in accordance with the RAEPC. Common and unusual release routes from the Koeberg Nuclear Power Station including air, coastal waters, direct radiation and sewage treatment works were assessed and rated in order of significance.

A radiological habit survey [LE82, CU05] was designed to investigate exposure pathways to the public resulting from radioactive discharges to the aquatic and terrestrial environment and to obtain data on occupancy and consumption rates from which Critical Groups may be identified. Framework Document Report, RP 5.294 listed in Appendix B contains information on preparation, implementation, data collection and data management phases of the radiological habit survey.

Principles for Retrospective Public Dose Assessments [AL05] were applied to ensure alignment of dose assessment methodologies with best practices applied in the UK. The following principles were applied in Retrospective Public Dose Assessments:

- workers who are exposed to discharges of radioactive waste, but do not work directly with ionising radiation were included in the assessment;
- Critical Group average doses were conservatively calculated for the purpose of assessing compliance with the public dose limit and dose constraint;

- significant release routes, sources and exposure pathways of authorised waste discharges and direct radiation were assessed; and
- measured data and results above background ambient radiation levels were applied where available for Retrospective Public Dose Assessments;

A pathway habit-profiling method rated as the best method for application in total Retrospective Public Dose Assessments [CA05] was reviewed and applied. Individuals with the highest consumption rates, occupancy rates or doses were identified. Threshold values were derived by dividing the highest individual consumption rate, occupancy rate or dose by a factor of three as per a "cut-off" method [HU82]. Critical Groups were derived by identifying all individuals with consumption rates, occupancy rates or doses greater than or equal to Threshold values. Critical Group rates were then calculated by assessing the arithmetic mean rates of the Critical Groups [HU82] and were applied in Retrospective Public Dose Assessments.

Radiological environmental-surveillance data addressed in the 2006 Koeberg Radiological Environment Survey Annual Report [AL06] were combined with individual eating and recreational habit data to calculate Retrospective Public Doses [JO04]. Calibrated, portable radiation monitoring instruments were used to measure ambient gamma radiation dose rates and background radiation dose rates in the environment and inside buildings. Committed effective doses were calculated based on potential intakes of radionuclides.

Uncertainty and variability associated with radiological measurements were considered. Uncertainty measures the lack of knowledge of the system under investigation, which in radiation dose assessment terms relate to how well doses of interest may be estimated [ND05].

In addition to the pathway habit-profiling method [CA05], an Individual method was applied to identify the highest exposed individuals via a combined pathway [CA02, HU04]. This method was applied as it was rated as the best method for

Retrospective Dose Assessments [CA02] based on ease of application and meeting the ICRP concept of homogeneity in Critical Groups [IC85]. Summation of Critical Group dose in Retrospective Public Dose Assessments is not a requirement in the South African systems of radiological control. However, doses were calculated for each individual using habit data for that individual and concentration and dose data relevant to the pathways for which habits data were available for that individual.

Pathways, which gave rise to the highest Critical Group dose, were used to identify the Critical Group for the Koeberg Nuclear Power Station and the set of radiological habit survey data which gave rise to the highest Critical Group dose was analysed to determine the homogeneity of the Critical Group [HU04]. Highest Critical Group doses were used for comparison with the national public dose limit. Aquatic pathway consumption and occupancy rates were used for comparison with the consumption rates derived in 1989 [BA89].

The main advantages of the application of the above framework were to identify a small group of the public representing those who may have received the highest dose during 2006 due to sources and pathways from the Koeberg Nuclear Power Station via methodologies applied in the UK systems of radiological control.

This framework may be applied to identify Critical Groups via Retrospective Public Dose Assessments and may be used to benchmark, assess and improve existing environmental and radiological surveillance programmes. This framework may also be applied for identification of relevant radiological information for communication to members of the public.

1.4 Research Report structure and chapter outline

The layout of this Research Report is as follows:

- Chapter 2 describes the theoretical consideration and methods used for identification of the Critical Group due to sources and pathways from the Koeberg Nuclear Power Station;

- Chapter 3 presents the results and discussion of the radiological habit survey and the dose assessments for identification of the Critical Group due to sources and pathways from the Koeberg Nuclear Power Station; and
- Chapter 4 presents the conclusions.

CHAPTER 2

THEORETICAL CONSIDERATION AND METHODS

"It would be desirable to examine the results of each integrated assessment to see what is revealed in detail about the important pathways and radionuclides at each site with a view to targeting surveillance and further habit surveys" [CA02].

2.1 Introduction

In this chapter the theoretical consideration and methods addressed in the framework presented in Chapter 1 for the identification of the Critical Group due to sources and pathways of exposure from the Koeberg Nuclear Power Station are discussed. Development of the Critical Group concept is discussed in Section 2.2. Application of the Critical Group concept in the UK is discussed in Section 2.3. Pathways from the Koeberg Nuclear Power Station are discussed in Section 2.4. Sources near the Koeberg Nuclear Power Station are discussed in Section 2.5. Radiation detection and measurement is discussed in Section 2.6. Environmental sample preparation and analysis is discussed in Section 2.7. The radiological habit survey is discussed in Section 2.8. Principles for dose assessment are presented in Section 2.9. Uncertainty and variability requirements are discussed in Section 2.10 and dose assessment methods are discussed in Section 2.11.

2.2 Development of the Critical Group concept

A Critical Group is defined as a group of members of the public which is reasonably homogeneous with respect to its exposure for a given radiation exposure pathway and is typical of individuals receiving the highest effective dose or equivalent dose (as applicable) by the given exposure pathway from a given source. ICRP recommends the selection of appropriate Critical Groups as a basis for assessment of dose to individual members of the public. Methodologies recommended by ICRP for selection of Critical Groups have developed significantly since the 1960's. In 1966 ICRP recommended application of appropriate homogeneity of habits with respect to age, diet, pathways and sources of exposure when determining the Critical Group. In 1977 ICRP recommended

that doses from different pathways be added together when determining the Critical Group [IC77]. In 1985 ICRP clarified the homogeneity requirement relating to Critical Groups by recommending that the variance of the dose for members of the Critical Group be within a factor of ten. However, when the mean dose is greater than a tenth of the dose limit, the range should be within a factor of three [IC85]. In 1990 ICRP recommended that all contributing pathways be considered for the Critical Group dose assessments [IC91]. All of the above Critical Group requirements were applied in the identification of the Critical Group potentially exposed to radiation during 2006 due to operation of the Koeberg Nuclear Power Station.

2.3 Application of the Critical Group concept in the UK

The UK has applied some of the ICRP recommendations on Critical Groups for Retrospective Public Dose Assessments since the 1960's. In 1994, a study was undertaken to assess Critical Group doses from nuclear sites in England and Wales taking into account all ICRP recommendations [BY05]. The approach adopted was to calculate doses to the group of people most exposed to aquatic discharges, consumption of terrestrial foods, atmospheric pathways and direct exposure and a combination of pathways. The study showed that whilst existing methods for identifying the Critical Groups were largely adequate, habit surveys should be designed to obtain information on combined exposure pathways. As a result of this study, habit surveys and methodologies for Retrospective Public Dose Assessments have developed significantly in the UK over the last decade.

Principles, methodologies and techniques developed by UK scientists and experts, [AL05, BY95, CA02, CU05, IA96, HA02 and HU82] in the field of Retrospective Public Dose Assessments were reviewed, applied and refined to identify the Critical Group due to radioactive sources and exposure pathways from the Koeberg Nuclear Power Station.

2.4 Pathways from the Koeberg Nuclear Power Station

The Koeberg Nuclear Power Station is situated in Melkbosstrand, on the Cape West Coast, approximately 30 km north of Cape Town. The location of the Koeberg Nuclear Power Station is depicted on a map in Fig. 2.1.

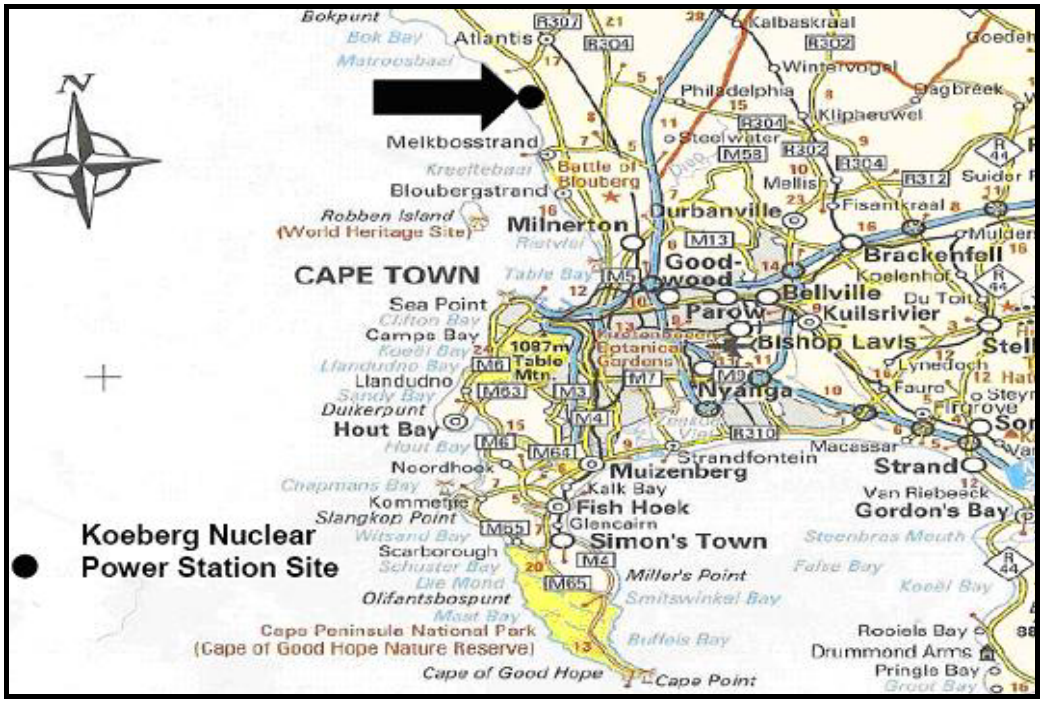

Figure 2.1 Map depicting location of the Koeberg Nuclear Power Station.

The power station is operated by Eskom, Generation under Nuclear Licence No.1 issued by the National Nuclear Regulator of South Africa in accordance with provisions addressed in the National Nuclear Regulator Act, 1999 (Act No. 47 of 1999). During operation Koeberg Nuclear Power Station may discharge liquid and gaseous effluent containing activity in accordance with Annual Authorised Discharge Quantities (AADQ) extracted from [OP01] and listed in Table 2.1.

Table 2.1 List of Annual Authorised Discharge Quantities (AADQ) for the Koeberg Nuclear Power Station.

Radionuclide	AADQ for liquid discharges (Bq)	AADQ for Gaseous discharges (Bq)	Method of detection employed at Koeberg
^{110m}Ag	4.62×10^{9}	4.12×10^{6}	Gamma spectrometry
^{41}Ar		4.79×10^{13}	Gamma spectrometry
^{139}Ba	2.72×10^{5}		Gamma spectrometry
^{140}Ba	2.37×10^{9}	2.68×10^{6}	Gamma spectrometry
^{7}Be	1.04×10^{10}	9.72×10^{6}	Gamma spectrometry
^{82}Br	1.29×10^{9}	1.02×10^{8}	Gamma spectrometry
^{84}Br	2.64×10^{7}	9.67×10^{7}	Gamma spectrometry
^{141}Ce	3.10×10^{8}	3.01×10^{5}	Gamma spectrometry
^{144}Ce	2.87×10^{8}	2.56×10^{5}	Gamma spectrometry
^{57}Co	1.26×10^{8}	1.12×10^{5}	Gamma spectrometry
^{58}Co	5.22×10^{10}	4.82×10^{7}	Gamma spectrometry
^{60}Co	2.47×10^{10}	2.19×10^{7}	Gamma spectrometry
^{51}Cr	3.09×10^{10}	3.05×10^{7}	Gamma spectrometry
^{134}Cs	1.40×10^{12}	1.24×10^{9}	Gamma spectrometry
^{136}Cs	3.75×10^{11}	4.20×10^{8}	Gamma spectrometry
^{137}Cs	6.94×10^{11}	6.10×10^{8}	Gamma spectrometry
^{138}Cs	7.20×10^{7}	1.37×10^{7}	Gamma spectrometry
^{59}Fe	1.46×10^{9}	1.38×10^{6}	Gamma spectrometry
^{3}H	5.73×10^{14}	5.72×10^{14}	Liquid scintillation
^{130}I	7.64×10^{8}	4.36×10^{8}	Gamma spectrometry
^{131}I	1.52×10^{12}	2.37×10^{10}	Gamma spectrometry
^{132}I	8.36×10^{10}	4.38×10^{9}	Gamma spectrometry
^{133}I	9.90×10^{10}	2.49×10^{10}	Gamma spectrometry
^{134}I	8.38×10^{8}	4.00×10^{9}	Gamma spectrometry
^{135}I	1.47×10^{10}	1.08×10^{10}	Gamma spectrometry
^{85}Kr		3.57×10^{14}	Gamma spectrometry
^{85m}Kr		1.39×10^{13}	Gamma spectrometry
^{87}Kr		9.71×10^{12}	Gamma spectrometry
^{88}Kr		2.30×10^{13}	Gamma spectrometry
^{140}La	2.84×10^{9}	5.33×10^{6}	Gamma spectrometry
^{54}Mn	5.72×10^{9}	5.09×10^{6}	Gamma spectrometry
^{56}Mn	1.04×10^{8}	1.48×10^{7}	Gamma spectrometry
^{99}Mo	2.66×10^{11}	7.35×10^{8}	Gamma spectrometry
^{24}Na	1.39×10^{9}	1.01×10^{8}	Gamma spectrometry
^{94}Nb	4.62×10^{6}		Gamma spectrometry
^{95}Nb	3.02×10^{8}	2.91×10^{5}	Gamma spectrometry
^{147}Nd	1.36×10^{8}	1.60×10^{5}	Gamma spectrometry

Table 2.1 (cont.)

Radionuclide	AADQ for liquid discharges (Bq)	AADQ for Gaseous discharges (Bq)	Method of detection employed at Koeberg
^{239}Np	1.39 x 10^{8}	4.64 x 10^{5}	Gamma spectrometry
^{144}Pr	2.83 x 10^{8}	2.62 x 10^{5}	Gamma spectrometry
^{88}Rb	2.55 x 10^{8}	2.30 x 10^{13}	Gamma spectrometry
^{89}Rb	6.22 x 10^{6}	1.21 x 10^{6}	Gamma spectrometry
^{105}Rh	2.84 x 10^{7}	2.08 x 10^{5}	Gamma spectrometry
^{103}Ru	3.60 x 10^{8}	3.43 x 10^{5}	Gamma spectrometry
^{105}Ru	2.53 x 10^{5}		Gamma spectrometry
^{122}Sb	2.05 x 10^{9}	5.77 x 10^{6}	Gamma spectrometry
^{124}Sb	1.92 x 10^{9}	1.78 x 10^{6}	Gamma spectrometry
^{125}Sb	7.68 x 10^{8}	6.78 x 10^{5}	Gamma spectrometry
^{113}Sn	1.05 x 10^{7}		Gamma spectrometry
^{89}Sr	8.96 x 10^{8}	8.40 x 10^{5}	Beta spectrometry
^{90}Sr	1.97 x 10^{8}	1.77 x 10^{5}	Beta spectrometry
^{91}Sr	2.73 x 10^{6}	3.68 x 10^{5}	Beta spectrometry
^{92}Sr	5.65 x 10^{5}	7.97 x 10^{4}	Beta spectrometry
^{99m}Tc	2.35 x 10^{11}	9.72 x 10^{8}	Gamma spectrometry
^{237}U	2.49 x 10^{7}		Gamma spectrometry
^{187}W	5.48 x 10^{8}	1.04 x 10^{7}	Gamma spectrometry
^{131m}Xe		7.75 x 10^{13}	Gamma spectrometry
^{133}Xe		5.42 x 10^{15}	Gamma spectrometry
^{133m}Xe		6.50 x 10^{13}	Gamma spectrometry
^{135}Xe		8.24 x 10^{13}	Gamma spectrometry
^{135m}Xe		5.80 x 10^{13}	Gamma spectrometry
^{138}Xe		7.23 x 10^{12}	Gamma spectrometry
^{92}Y	1.56 x 10^{5}		Gamma spectrometry
^{65}Zn	1.81 x 10^{9}	1.61 x 10^{6}	Gamma spectrometry
^{95}Zr	3.16 x 10^{8}	2.92 x 10^{5}	Gamma spectrometry
^{97}Zr	6.35 x 10^{7}	1.60 x 10^{5}	Gamma spectrometry
other nuclides	5.00 x 10^{5}	1.00 x 10^{6}	Gamma spectrometry

The NNR developed the AADQ and regulates the Koeberg Nuclear Power Station discharges in accordance with the AADQ. Liquid and gaseous effluents, which contain activity that may originate from radioactive fuel or activation of corrosion products or activation of chemicals added to plant systems or activation of air and water in plant systems, are generated as a by-product during operations of a nuclear power plant. Under planned and controlled conditions, effluents may be discharged in the environment should the activity in the effluent be below the

AADQ. The activity in the liquid and gaseous discharges migrate into the environment and directly and/or indirectly expose members of the public to radiation and may result in a public dose.

2.5 Sources near the Koeberg Nuclear Power Station

The NNR has regulated the Koeberg Environmental-surveillance Programme since 1984. Radiological environmental surveys are performed routinely in the aquatic and terrestrial environment in the vicinity of the Koeberg Nuclear Power Station and the results are reported to the NNR quarterly and annually. Sampling data contained in the 2006 Koeberg Annual Radiological Survey Report [AL06] and listed in Table 2.4, were used to identify potential sources and pathways of public exposure due to operation of the Koeberg Nuclear Power Station.

Potential sources of exposure from the Koeberg Nuclear Power Station were assessed in accordance with a Radiological Assessment Exposure Pathways Checklist (RAEPC) [AL04]. Potential release routes, radiation sources, exposure pathways from the Koeberg Nuclear Power Station including air, freshwater rivers and dams, coastal waters, sewer and sewer treatment works, ground water and direct radiation were identified and rated in order of significance in accordance with the RAEPC [AL04]. Main sources of potential exposure from the Koeberg Nuclear Power Station were identified as coastal waters, sewage from the local sewage treatment works and direct radiation.

Environmental samples are collected from the aquatic and terrestrial areas in the vicinity of Koeberg Nuclear Power Station in accordance with procedures approved by the NNR. Table 2.2 contains information on potential exposure pathways, types of samples collected, sampling and collection frequency and the types of analyses performed.

Table 2.2 Exposure pathways, sampling and collection frequency and types of sample analysis.

Exposure pathway and/or sample	Sampling and collection frequency	Type, frequency and analysis
Radioiodine and particulate	Continuous sampler operation with sample collection weekly	Radioiodine Canister: analyse weekly for I-131. Particulate Sampler: gamma isotopic activity following filter change
Direct Radiation	Monthly on public exclusion boundary, with the rest quarterly.	Gamma exposure: Analyse monthly or quarterly.
Sea Water	Composite sample over a one-month period from weekly grab sample	Gamma isotopic analysis: monthly. Composite for tritium analysis: quarterly.
Soil	Annually	Gamma isotopic analysis
Drinking or surface fresh water	Weekly samples for monthly composite Monthly	Composite for gamma isotopic analysis: monthly. Composite for tritium analysis: quarterly.
Sediment from shoreline	Semi-annually	Gamma isotopic analysis semi-annually.
Milk	Semi-monthly animals are on pasture, monthly at other times.	Gamma isotopic and I-131 analysis: semi-monthly when animals are on pasture; monthly at other times
Fish and Invertebrates	Sample semi-annually.	Gamma isotopic analysis: On edible portions.
Food products	At time of harvest	Gamma isotopic analysis: On edible portions.
Broad Leaf Vegetation	Monthly when available	Gamma isotopic analysis: On leaves.
Sewage	Monthly sample	Gamma isotopic analysis of sludge: Monthly. H-3 analysis of liquid: Quarterly composite.

2.6 Radiation detection and measurement

Retrospective Public Dose Assessments for Sub-critical Groups were performed via assessment of radionuclide activity in locally harvested aquatic and terrestrial food samples and dose rates measured directly in the environment.

Radionuclide analysis was carried out on local aquatic and terrestrial samples at the Koeberg Environmental-surveillance Laboratory (KESL) in accordance with standards approved by the NNR. The KESL is fully equipped to detect and measure the gamma emitting radionuclides listed in Table 2.1. Analyses that are carried out on local aquatic and terrestrial samples vary according to the nature of the radionuclide under investigation. Gamma-ray spectrometry is performed on local aquatic and terrestrial samples at the KESL to detect and measure radionuclide activity.

2.6.1 Gamma-ray spectrometry

Gamma-ray spectrometry is a cost-effective method of detecting gamma emitting radionuclides [KN99]. X-rays or gamma-ray photons are carriers of the electric field and they produce direct ionisation (through the photoelectric effect) in any material that they traverse. There is also extensive secondary ionisation produced by the high energy secondary electrons from the primary gamma-ray interactions. The detection of gamma rays is therefore dependent on causing the gamma-ray photon energy to undergo an interaction that transfers all or part of the photon energy to an electron in the detector material. Three major types of interactions play an important role in gamma radiation measurement and detection:

- photoelectric absorption;
- Compton scattering; and
- pair production.

2.6.1.1 Gamma-radiation interactions with matter

Photoelectric effect

In the photoelectric absorption process, a photon undergoes an interaction with an absorber atom in which the photon completely disappears. In its place, an

energetic photoelectron is ejected by the atom from one of its bound shells. The interaction is with the atom as a whole and cannot take place with free electrons. For gamma-ray energies of more than a few hundred keV, the photoelectron carries off the majority of the original photon energy. In addition to the photoelectron, the interaction also creates an ionised absorber atom with a vacancy in one of its bound shells. This vacancy is quickly filled through capture of a free electron from the medium and/or rearrangement of electrons from other shells of the atom. Therefore, one or more characteristic X-ray photons may be generated. Although in most cases these X-rays are reabsorbed close to the original site through photoelectric absorption involving less tightly bound shells, their migration and possible escape from radiation detectors can influence their response. Figure 2.2 depicts a schematic representation of the photoelectric absorption interaction.

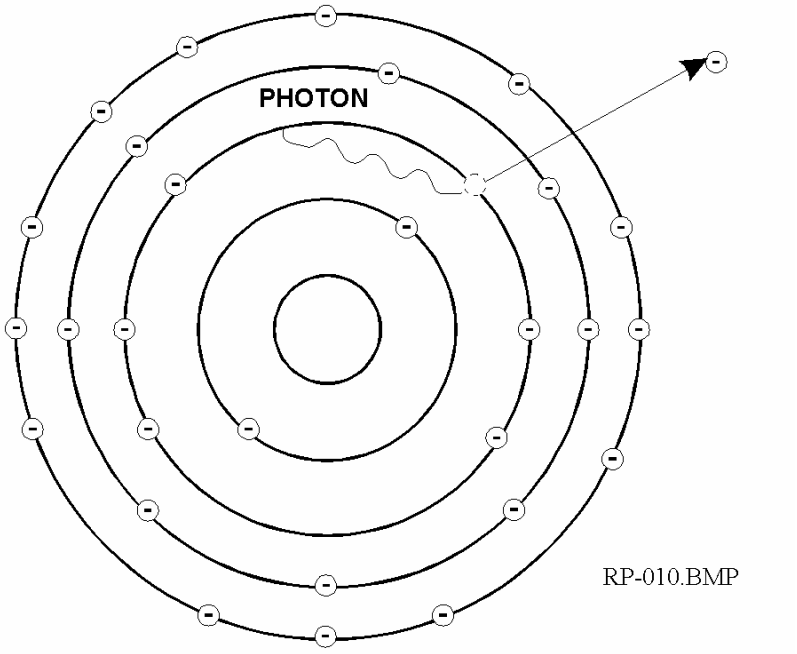

Figure 2.2 Schematic representation showing a photon interaction with an electron in which the photon completely disappears and a photoelectron is ejected.

Compton scattering

Compton scattering takes place between the incident gamma ray photon and an electron in the absorbing material. It is most often the predominant interaction mechanism for gamma-ray energies typical of radioisotope sources. In Compton scattering, the incoming gamma-ray photon is deflected through an angle with respect to its original direction. The photon transfers a portion of its energy to the electron (assumed to be initially at rest), which is then known as a recoil electron. Figure 2.3 depicts a schematic representation of the Compton scattering interaction.

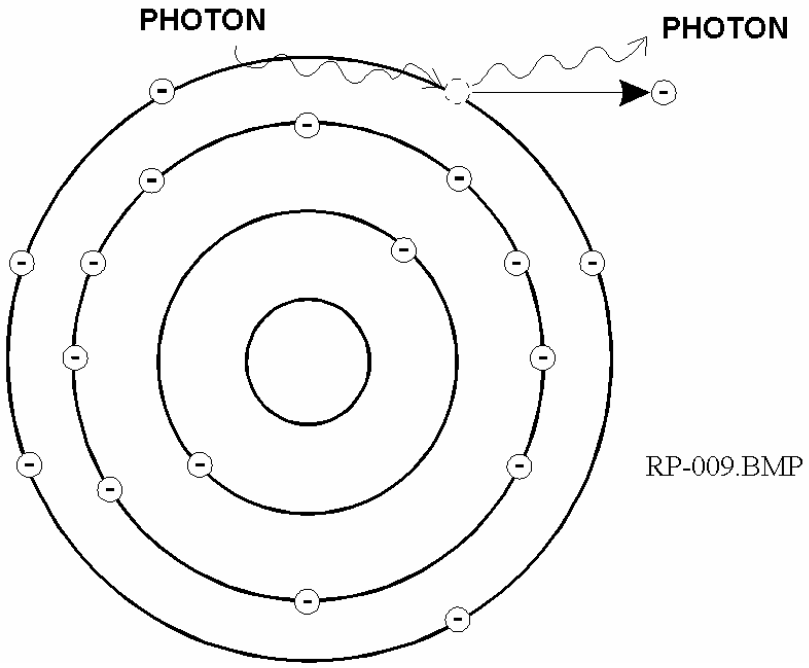

Figure 2.3 Schematic representation showing a photon interaction with an electron in which the photon is deflected and a portion of the photon energy is transferred to the electron.

Pair production

Pair production is energetically possible when the incident gamma-ray energy exceeds twice the rest-mass energy of the electron (1.02 MeV). In the interaction (which must take place in the Coulomb field of a nucleus), the gamma-ray photon disappears and is replaced by an electron-positron pair. All the excess energy carried in the photon above the 1.02 MeV required to create the pair goes into kinetic energy shared by the positron and the electron. The positron will subsequently annihilate or combine with an electron after slowing down in the detector material. At this point both the positron and electron disappear and two annihilation photons of energy 0.511 MeV each are normally produced as secondary products of the interaction. The subsequent fate of this annihilation radiation has an important effect on the response of gamma-ray detectors. Figure 2.4 depicts a schematic representation of the pair production interaction.

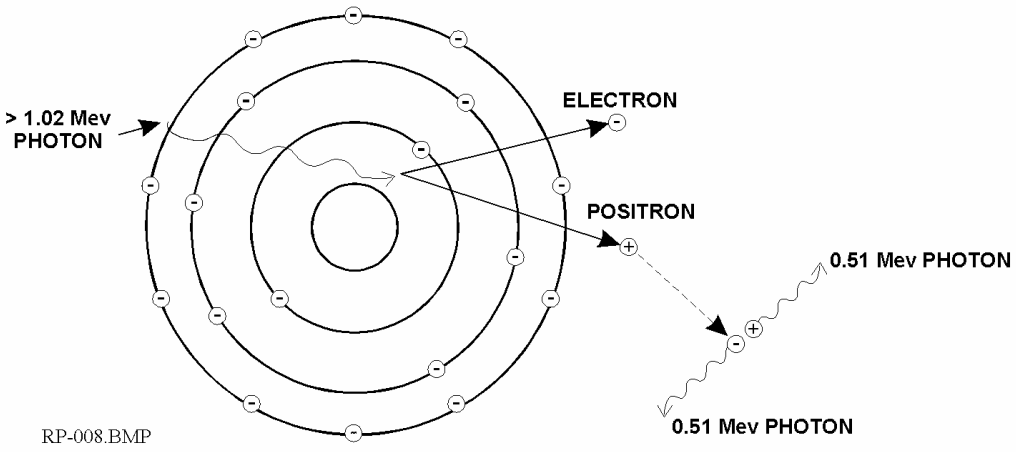

Figure 2.3 Schematic representation of pair production interaction.

2.6.1.2 Germanium-Lithium spectrometers

In order for a detector to serve as a gamma spectrometer, it must carry out two distinct functions. Firstly, it must act as a conversion medium in which incident gamma rays have a reasonable probability of interacting to yield one or more fast electrons and secondly, it must function as a conventional detector for those

secondary electrons. At the KESL, Germanium-Lithium (GeLi) gamma-ray spectrometers are used to detect and measure radionuclide activity in local aquatic and terrestrial samples.

A GeLi detector includes three basic components i.e. detector, amplifier and measuring device. A power supply provides a high voltage differential across the electrodes in the detector. In addition, the system usually includes a minicomputer and other complex electronic hardware. Figure 2.5 depicts a schematic representation of a GeLi detector.

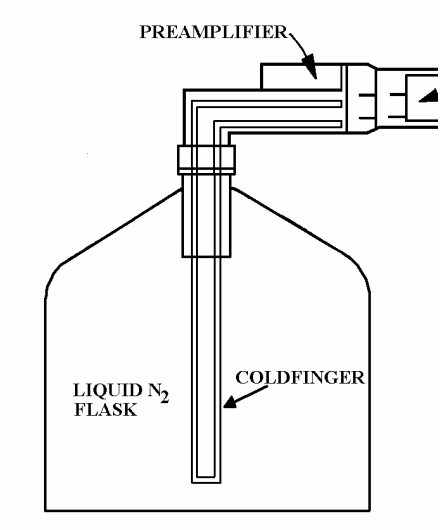

Figure 2.4 Schematic representation of a Germanium-Lithium (GeLi) detector.

Germanium detectors are semiconductor diodes having a P-I-N structure in which the Intrinsic (I) region is sensitive to ionizing radiation, particularly X-rays and gamma rays. Under reverse bias, an electric field extends across the intrinsic or depleted region. When photons interact with the material within the depleted volume of a detector, charge carriers (holes and electrons) are produced and are swept by the electric field to the P and N electrodes. This charge, which is in proportion to the energy deposited in the detector by the incoming photon, is converted into a voltage pulse by an integral charge sensitive preamplifier. Germanium has a relatively low band gap thus these detectors must be cooled in order to reduce the thermal generation of charge carriers (thus reverse leakage

current) to an acceptable level. Liquid nitrogen is used for cooling germanium detectors. The detector is mounted in a vacuum chamber which is attached to or inserted into a dewar or an electrically powered cooler. The sensitive detector surfaces are thus protected from moisture and condensable contaminants. Figure 2.6 shows the environmental depicts a schematic representation of a GeLi detector.



Figure 2.6 The GeLi gamma-ray spectrometer system at the KESL

2.6.1.3 Multi-channel analysers

GeLi detectors used at the KESL are connected to multi-channel analysers based on advanced digital signal processing techniques. The multi-channel analysers count the pulses from the GeLi detectors and classify them by pulse size, or radiation energy into different channels in a multi-channel analyser. A number, known as the channel address, is generated in response to each input pulse. These numbers are derived from the pulse heights (voltage). A specific value of energy per channel is assigned. The channel number is proportional to the magnitude of the input pulse which is proportional to the energy of the detected radiation.

Pulses are collected and stored in the appropriate channels for display of a gamma spectrum. Figure 2.7 depicts an integrated multi-channel analyser based on advanced digital signal processing techniques.



Figure 2.7 Multi-channel analyser at the KESL

2.6.2 Beta particle detection and spectroscopy

Beta-minus particles (β^-) are relatively high-energy electrons emitted from the nucleus. β^- particles have a negative charge and are more penetrating than the alpha particles. The energy of a β^- particle emitted from a specific radionuclide is not discrete, but varies over a continuous spectrum. β^- emitting radionuclides each have a maximum energy, a property that may be used to identify the nuclide. The shape of the β^- energy-spectrum is such that the average β^- energy is approximately a third of the maximum energy. β^- decay-energy is shared between the β^- particle and an antineutrino, a particle with no charge, and is as a result of a neutron being converted to a proton within the nucleus ($n \rightarrow p + e^- + \overline{\upsilon_e}$). This property gives rise to a continuous β^- energy-spectrum as depicted in Fig. 2.8. Two major types of interactions play an important role in β^- radiation measurement and detection:

- bremsstrahlung; and
- Čerenkov radiation.

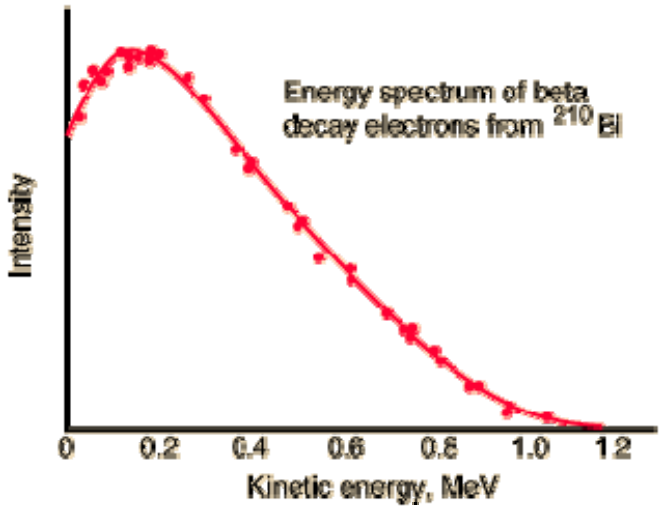

Figure 2.8 Schematic representation of a β^- energy-spectrum.

2.6.2.1 β^- interactions with matter

Bremsstrahlung

Bremsstrahlung is electromagnetic radiation produced by the deceleration (breaking) of a charged particle, such as an electron, when deflected by another charged particle, such as an atomic nucleus. Bremsstrahlung may also be referred to radiation that arises as a result of a charged particle that is free both before and after the deflection (acceleration) that causes the emission. Strictly speaking, bremsstrahlung refers to any radiation due to the acceleration of a charged particle.

When fast electrons, including β^- particles, are accelerated or decelerated a part of their energy is converted into electromagnetic radiation in the form of bremsstrahlung. Should an energetic electron pass close to the nucleus of an atom, the Coulomb forces deflect and accelerate the electron. The electron emits energy in the form of X-rays called bremsstrahlung. The fraction of the electron energy

converted into bremsstrahlung increases with increasing electron energy and is largest for absorbing materials of high atomic number.

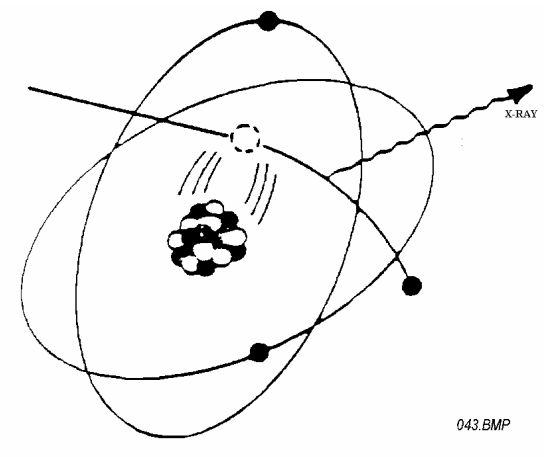

Figure 2.9 Schematic representation of bremsstrahlung.

Čerenkov light

Čerenkov light is emitted whenever the velocity of charged particles, including β^- particles, exceed the velocity of light in the medium through which it is passing. Čerenkov light was discovered by Pavel Cerenkov in 1934, while he was studying the effects of radioactive substances on liquids. He noticed that water surrounding certain radioactive substances emitted a faint blue glow, which is now termed Čerenkov radiation. The threshold energy for the occurrence of Cerenkov light for electron radiation in water (n = 1.33) is 260 keV. High-energy nuclei with a charge greater than or equal to six are capable of producing Čerenkov light. The light observed is frequently attributed to a shock wave phenomenon and has been thought of as an optical analog of the sonic boom; however, this is not entirely correct. What actually happens is that a fast moving charged particle moving through a dielectric medium causes local, non-isotropic polarizations in the atoms of the dielectric. These atoms return to normal states by emitting light. If the velocity of the particle is less than the velocity of light in the medium, the light is destroyed by destructive interference. If the velocity of the particle is greater than the velocity of light in the medium, the light

remains due to constructive interference. Figure 2.10 depicts Čerenkov light in the core of a nuclear reactor.

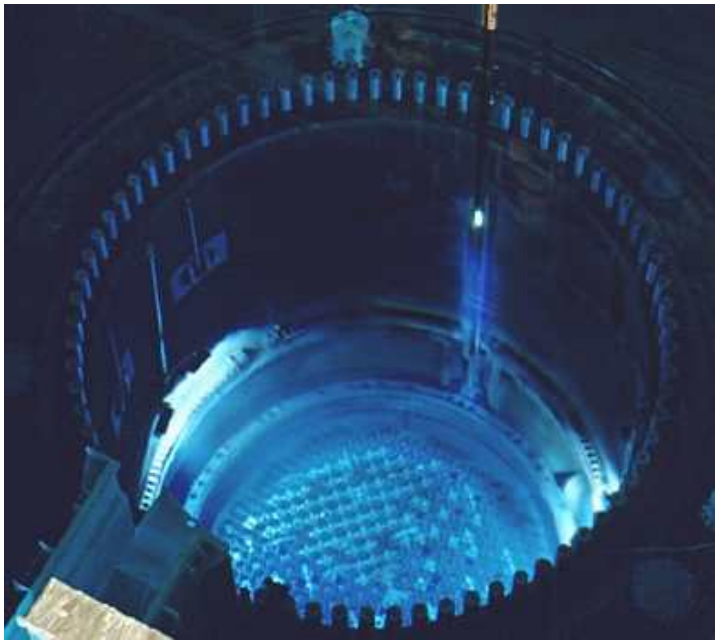

Figure 2.10 Čerenkov light in the core of a nuclear reactor.

Backscattering

Electrons, including β^- particles, can undergo large-angle deflections due to electron-nuclear interactions which can change the electron direction and lead to the phenomenon of backscattering. An electron entering one surface of an absorber may undergo significant deflection so that it re-emerges from the surface through which it entered. These backscattered electrons do not deposit all their energy in the absorbing material and, therefore, can have a significant effect on the response of detectors.

2.6.2.2 Scintillation detectors

The detection of β^- particles via scintillation light in certain materials is one of the most useful techniques [KN99]. β^- radiation from tritium is detected in sample material at the KESL via liquid scintillation since liquid scintillation detectors have high efficiency for detection of low-energy β^- radiation. A sample

of environmental material is dissolved or suspended in a "cocktail" containing an aromatic solvent i.e. benzene or toluene and small amounts of other additives known as fluors. Beta particles emitted from the sample transfer energy to the solvent molecules, which in turn transfer their energy to the fluors; the excited fluor molecules dissipate the energy by emitting light. In this way, each beta emission may result in a pulse of light. Scintillation cocktails often contain additives that shift the wavelength of the emitted light to make it more easily detected.

The samples of environmental material are placed in small transparent or translucent (often glass or plastic) vials that are loaded into an instrument known as a liquid scintillation counter. The counter has two photomultiplier tubes connected in a coincidence circuit. The coincidence circuit assures that genuine light pulses, which reach both photomultiplier tubes, are counted, while spurious pulses (due to line noise, for example), which would only affect one of the tubes, are ignored. Liquid scintillation counter efficiencies at KESL range from about 30% for tritium. Some chemical compounds (notably chlorine compounds) and highly colored samples can interfere with the counting process. This interference, known as "quenching", can be overcome through data correction or through careful sample preparation. Figure 2.11 presents a liquid scintillation counter.



Figure 2.11 Photograph of a liquid scintillation counter.

2.6.2.3 Ionisation chambers

The term ionisation chamber is used for the type of radiation detector in which ion pairs are collected from gasses. As a fast charged particle passes through a gas exited and ionised molecules are formed along its path. After a neutral molecule of gas is ionised, the resulting positive ion and free electron are called an ion pair, which serves as the basic constituent of the electrical signal developed by the ion chamber. Ions can be formed either by direct interaction with the incident particle, or through a secondary process in which some of the particle energy is first transferred to an energetic electron or "delta ray". In the presence of an electric field, the drift of the positive and negative charges represented by ions and electrons constitutes an electric current. If a given volume of gas is undergoing steady-state irradiation, the rate of formation of ion pairs is constant. Measurement of the ionisation current or the rate at which ion pairs are formed within the detector is the basic principle of a portable ion chamber.

Air-filled portable ion chambers are suitable for beta and gamma ambient radiation measurements because exposure is defined in terms of the amount of ionisation charge created in air. Figure 2.12 shows a schematic representation of a portable ion chamber.

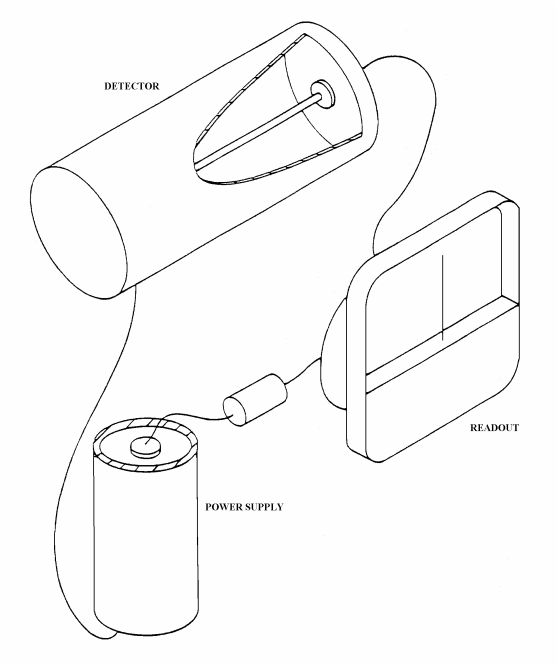

Figure 2.12 Schematic representation of a portable ion chamber.

2.6.2.4 Neutron detectors

Neutrons are generated in the two Koeberg Nuclear Power Station reactors during electricity production and may escape from the reactors during operations. Neutron radiation surveys are routinely performed at the Koeberg Nuclear Power Station to identify and assess potential sources of neutrons radiation in the environment. Neutrons are generally detected through nuclear reactions that result in prompt energetic charged particles such as protons and alpha particles. The cross section for neutron interactions in most materials is a strong function of neutron energy thus different techniques have been developed for neutron detection in different energy regions. At the Koeberg Nuclear Power Station neutron radiation surveys were performed with a portable neutron detector capable of detecting slow neutrons with energies below 0.5 eV. A slow neutron can be absorbed by the nucleus of an atom and a heavy charged particle (alpha or photon) is emitted. The charged particle in turn produces excitation of scintillation which can be measured. Materials with a high slow neutron cross section are used. The $^{10}B(n,\alpha)$, $^{6}Li(n,\alpha)$ and $^{3}He(n,\alpha)$ reactions are the ones commonly employed. On the other hand, a technique that is applied for measuring fast neutrons is to

convert them to slow neutrons, and then measure the slow neutrons. In this technique, a sheet of cadmium is placed on the outside of the detector to absorb any slow neutrons that might be present. Polyethylene may be placed under the cadmium to convert the fast neutrons into slow neutrons. Figure 2.13 depicts a schematic representation of a portable neutron detector capable of measuring fast neutrons.

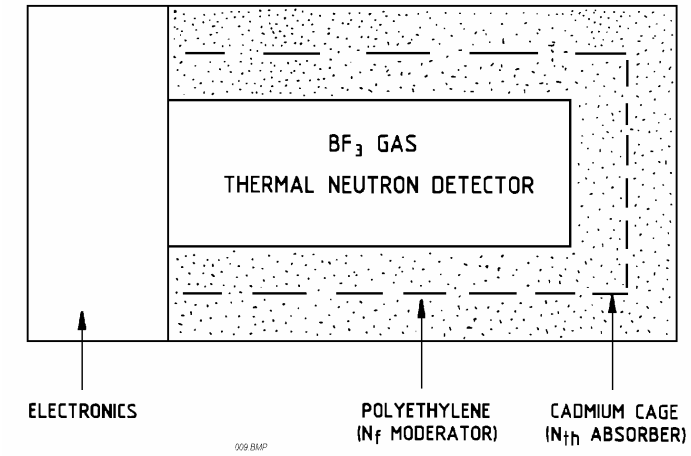

Figure 2.13 Schematic representation of a portable neutron detector capable of measuring fast neutrons.

2.6.3 Limits of detectability

2.6.3.1 Minimum Detectable Amount of activity

One of the most widely used definitions of Minimum Detectable Amount (MDA) of activity was first introduced by Currie [CU68]. The MDA is the activity which, if present in a sample, produces a counting rate that will be detected (i.e. considered to be above background) with a certain level of confidence. The "certain level of confidence" is normally set at 95%, i.e. a sample containing exactly the MDA will, as a result of random fluctuations, be taken to be free of activity 5% of the time. MDA is based on a binary (yes or no) decision whether a given sample contains activity [KN99]. In the simplest case, a counting system is set up to detect the radiation of interest and the total number of counts recorded for equal periods of time as different samples are put in place. Let N_T be the number of counts recorded with an unknown sample and N_B be the number of

recorded counts when a blank sample is substituted to determine the background level. Equal allocation of time to the sample and background is applied to minimize the uncertainty in the net counts when the source is weak compared with background. The net counts, N_S, resulting from the unknown sample are then calculated by:

$$N_S = N_T - N_B. \tag{2.1}$$

To make a decision whether the sample contains activity, N_S is then compared with a critical level L_C. A simple protocol is followed: If N_S is less than L_C, it is concluded that the sample does not contain activity, whereas if N_S exceeds L_C, it is assumed that some real activity is present. In the absence of statistical fluctuations and other instrumental variations, L_C could be set at zero, and any net positive counts could be interpreted as evidence of real activity. With the statistical fluctuations that are in any counting measurement, there will be many instances of positive N_S that will be observed even for samples with no activity. A value of L_C should be high enough to minimize the likelihood of false positives, while being low to reduce the possibility of missing real activity when some is actually present.

If we assume that the counting time is long enough so that the total number of counts recorded in each of these measurements is large (say > 30), then both N_T and N_B should follow Gaussian distributions [KN99]. When these two variables are subtracted to determine N_S, the net counts should also follow a Gaussian whose mean is the true net number of counts, and whose standard deviation can be predicted by:

$$\sigma^2_{N_S} = \sigma^2_{N_T} + \sigma^2_{N_B}. \tag{2.2}$$

If there is no actual activity present in the sample, then the true mean values of N_T and N_B are the same, and the mean value of N_S is zero. Since under these

conditions $\sigma_{N_T} = \sigma_{N_B}$, the standard deviation of the Gaussian distribution for N_S, is given by:

$$\sigma_{N_S} = \sqrt{2\sigma_{N_B}^2} = \sqrt{2}\ \sigma_{N_B}. \tag{2.3}$$

If the only significant fluctuations entering the measurement are from counting statistics, then $\sigma_{N_B} = \sqrt{N_B}$ and $\sigma_{N_S} = \sqrt{2N_B}$. Since no true activity is present, any positive indication will be a false positive and therefore L_C should be set high enough to ensure that, under these conditions, the probability that a particular measurement of N_S exceeds L_C is acceptably small. The probability for a random sample from a Gaussian distribution having a value within the interval of the mean $\pm 1.645\sigma$ is 90% [KN99]. Since only positive deviations from the mean is considered, there is a 95 % probability that a random sample will lie below the mean plus 1.645σ. Thus setting $L_C = 1.645\sigma_{N_S} = 1.645\sqrt{2}\ \sigma_{N_S} = 2.326\ \sigma_{N_B}$ ensures that a false-positive probability will be no larger than 5 %. This choice has become a common basis for setting L_C. The MDA is referred to at the Koeberg Nuclear Power Station as the detection limit or lower limit of detection (LLD). The counting rate from a sample containing the MDA is termed the Minimum Significant Activity (MSA).

2.6.3.2 Minimum Significant Activity

The MSA is the activity which, if present in a sample, produces a counting rate that can be reliably distinguished from background with a certain level of confidence. A sample containing exactly the MSA will, as a result of random fluctuations, be taken to be free of activity 50% of the time, whereas a true background sample will be taken to be free of activity 95% of the time. The MSA is sometimes referred to as the decision limit. The counting rate from a sample containing the MSA is termed the critical level at the Koeberg Nuclear Power Station.

2.6.4 Koeberg Environmental Surveys

Gamma-ray spectrometry results contained in the 2006 Koeberg Annual Radiological Survey Report [AL06] and listed in Table 2.4 were applied in Retrospective Public Dose Assessments. Gamma-ray spectrometry was performed on aquatic and terrestrial sample material at the KESL in accordance with Quality Control Programmes approved by the NNR.

Precision of measurements was achieved via application of a statistical control process to ascertain precision of data and causes for variation. Accuracy of data was achieved by using calibration sources traceable to international standards and participation in inter-laboratory comparison studies. Verification samples are routinely sent to the NNR for verification of precision and accuracy of measurements.

Instrument detection limits or LLD are specified by the NNR for principle gamma emitters selected on their abundance in waste streams, contribution to off-site dose and to be consistent with international practices. The LLD is the smallest concentration of radioactive material in a sample that will yield a net count rate above the system background that may be detected with 95% probability. LLD values represent the intrinsic capability of the measurement system and are verified by counting empty containers in a gamma spectrometer for a specific duration during background radiation checks. All gamma-ray spectrometers used at the KESL comply with the LLD specified by the NNR and calculated in accordance with the methodology outlined in Sub-section 2.6.3.1.

Gamma-ray spectrometry results extracted from the 2006 Koeberg Annual Radiological Survey Report [AL06] and listed in Table 2.4 are the Minimum Significant Activity (MSA) derived for aquatic and terrestrial samples. MSA values represent the smallest concentration of radioactive material in a sample that will yield a net count rate above the actual background in a sample that may be

detected with 95% confidence. MSA values represent the true detection limits for samples analysed.

The following measurement considerations were applied in the assessment of committed effective doses due to potential intakes of radionuclides during the year:

- local foods sampled and analysed for activity are representative of local foods consumed by the public;
- seasonal patterns of local food production and consumption were considered;
- sample preparation was performed in accordance with methods addressed in authorised Koeberg Environmental-surveillance Procedures;
- sample analysis was performed in accordance with methods addressed in authorised Koeberg Environmental-surveillance Procedures; and
- analytical sensitivity of gamma spectrometry instruments meet the minimum detectable limits prescribed by the NNR.

2.6.4.1 Beta and gamma radiation measurements

Gamma and beta radiation surveys were performed to identify direct radiation pathways and monitor ambient direct radiation levels in the vicinity of the Koeberg Nuclear Power Station. The radiation interacts with material in the detector and the output of the detector is amplified and converted into a measurement in mSv h^{-1}. Ionisation chamber type portable gamma and beta radiation instruments were used for monitoring gamma and beta radiation as it is the most sensitive to low levels of radiation. The error associated with a beta and gamma dose rate measurement is 10% based according to information on the instrument calibration certificate.

2.6.4.2 Neutron radiation measurements

Neutron radiation surveys were performed with a portable neutron detector to identify direct radiation pathways and monitor ambient direct radiation levels in the vicinity of the Koeberg Nuclear Power Station. The error associated with a

neutron dose rate measurement is 15% based according to information on the instrument calibration certificate.

2.6.4.3 Koeberg Nuclear Power Station radiation surveys

The following measurement considerations were applied in the assessment of annual effective doses due to external radiation measured near Koeberg Nuclear Power Station:

- calibrated portable radiation monitoring instruments were used to measure ambient gamma-radiation dose rates in the environment and inside buildings; and
- calibrated portable radiation monitoring instruments were used to measure background ambient gamma-radiation dose rates from terrestrial sources in the environment and inside buildings.

The radiological measurements were applied for Retrospective Public Dose Assessments using portable, calibrated radiation monitoring instruments [JO04]. Gamma dose rates were measured in air at various locations near the Koeberg Nuclear Power Station. Background radiation due to cosmic rays, natural terrestrial radiation and intrinsic instrument responses were recorded. No beta or neutron radiation was detected during radiological surveillance.

2.7 Environmental sample preparation and analysis

Environmental samples are prepared and analysed in accordance with procedures approved by the NNR.

2.7.1 Environmental sample preparation

Environmental samples are collected routinely as outlined in Table 2.2 by trained environmental laboratory personnel. Table 2.3 contains information on the environmental sample sizes and sample preparation processes employed at the Koeberg Nuclear Power Station.

Table 2.3 Preparation processes for environmental samples.

Environmental sample	Size of samples	Preparation process
Radioiodine and particulate	The volume of air that passed through the air sample filter	Place filter paper in 50mm stainless steel planchet. No additional preparation required for iodine cartridges.
Direct Radiation	Not applicable.	Dose rates recorded via TLD's
Sea Water	15 litre	Dry sample in dishes via lamps in fume-hood until sediment is formed.
Soil	1 kg	Grind sample into a fine powder.
Drinking or surface fresh water	10 litre	Dry sample in dishes via lamps in fume-hood until sediment is formed. For tritium analysis, 50ml from monthly composite samples are used to analyse a quarterly volume of 250ml.
Sediment from shoreline	1 kg	Grind sample into a fine powder.
Milk	3 litre	Add 100ml glacial acetic acid to sample. Dry sample in oven at 150 ^{o}C until solid material is formed. Add 80g of activated anion exchange resin for iodine analyses.
Fish and Invertebrates	1 kg	Dry sample in dishes via lamps in fume-hood. Place sample in furnace at 100 ^{o}C and increase temperature to 450 ^{o}C until ash is formed.
Food products		
Broad Leaf Vegetation		
Sewage		

2.7.2 Environmental sample analysis

Samples are then weighed, sample mass is calculated and placed in the appropriate holders and geometry in readiness for spectrometry analysis.

2.7.2.1 Calibration of environmental surveillance instrumentation

Environmental laboratory spectrometry equipment is routinely calibrated. Mixed gamma radioactive sources i.e. cobalt, barium, europium and cesium with known gamma-ray energies and activity are used for efficiency and energy calibration purposes. Figure 2.14 depicts an efficiency calibration display and Fig. 2.15 depicts an energy calibration display for gamma spectrometry equipment used at the KESL.

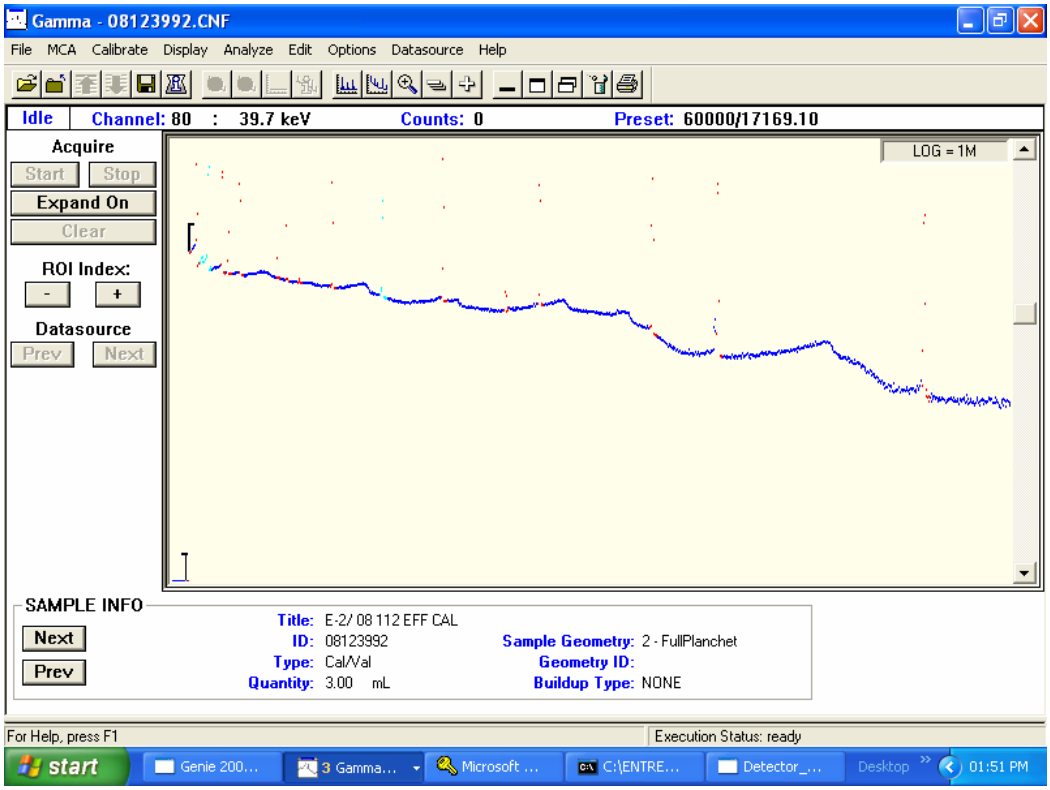

Figure 2.14 Efficiency calibration display for gamma spectrometry equipment used at the KESL.

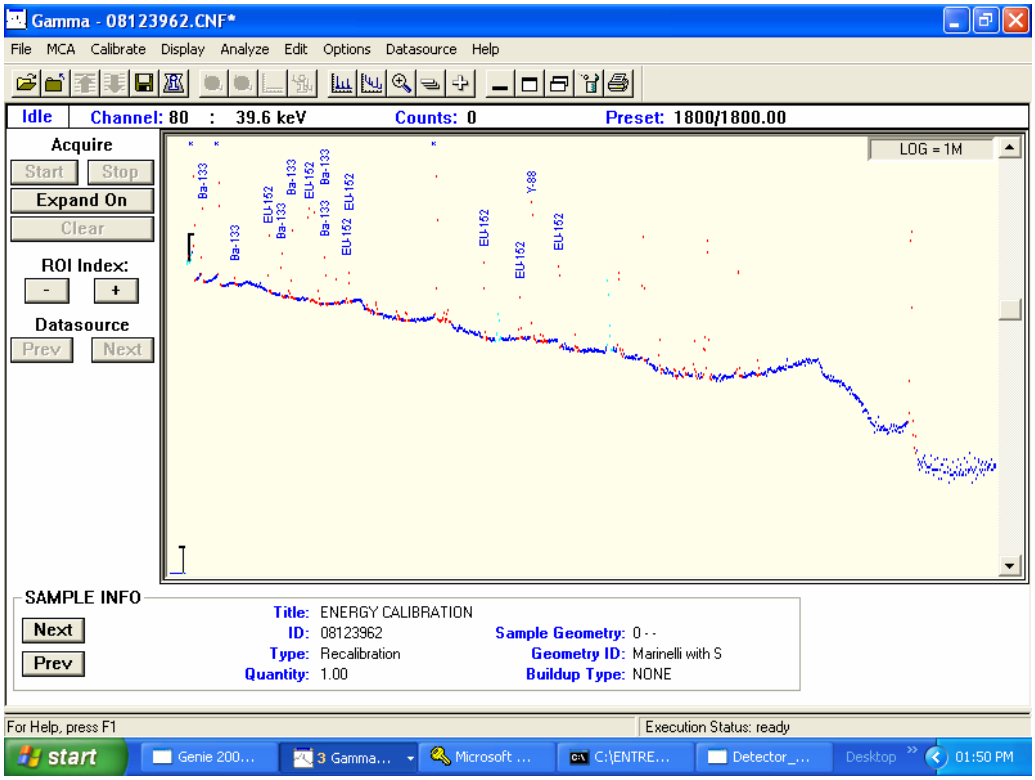

Figure 2.15 Energy calibration display for gamma spectrometry equipment used at the KESL.

2.7.2.2 Detection of activity in environmental samples

Detection limits for environmental surveillance equipment in use at the Koeberg Nuclear Power Station are prescribed by the NNR. The LLD is defined as the smallest concentration of radioactive material in a sample that will yield a net count, above system background, that will be detected with 95% probability concluding that a blank observation represents a "real" signal. The LLD is defined as a limit representing the intrinsic capability of a measurement system and not as a limit for a particular measurement. LLD determinations for gamma spectrometry are based on background counts of the same duration as those applied to real samples and no decay correction is applied. Instrument compliance to the LLD is reconfirmed once a quarter.

Radiological environmental-surveillance data addressed in the 2006 Koeberg Radiological Environment Survey Annual Report [AL06] and the LLD values of environmental surveillance equipment used at the KESL are listed in Table 2.4.

Table 2.4 Radiological environmental-surveillance data addressed in the 2006 Koeberg Radiological Environment Survey Annual Report [AL06] and the LLD values of environmental surveillance equipment used at the KESL

Potential sources of exposure	LLD values	Specific activity
fish	^{137}Cs (0.13 Bq kg^{-1})	^{137}Cs (0.18 ± 0.02 Bq kg^{-1})
crayfish	^{110m}Ag (0.54 Bq kg^{-1})	^{110m}Ag (0.63 ± 0.06 Bq kg^{-1})
abalone	^{58}Co (0.1 Bq kg^{-1}) ^{110m}Ag (0.62 Bq kg^{-1})	^{58}Co (0.12 ± 0.01 Bq kg^{-1}) ^{110m}Ag (0.70 ± 0.07 Bq kg^{-1})
mussels	^{58}Co (0.1 Bq kg^{-1}) ^{60}Co (0.13 Bq kg^{-1}) ^{110m}Ag (0.62 Bq kg^{-1})	^{58}Co (1.12 ± 0.12 Bq kg^{-1}) ^{60}Co (0.22 ± 0.02 Bq kg^{-1}) ^{110m}Ag (12 ± 1.20 Bq kg^{-1})
seawater	^{58}Co (0.02 Bq l^{-1}) ^{60}Co (0.02 Bq l^{-1})	^{58}Co (0.03 ± 0.01 Bq l^{-1}) ^{60}Co (0.026 ± 0.01 Bq l^{-1})
sewage sludge	^{58}Co (0.1Bq kg^{-1}) ^{60}Co (0.13 Bq kg^{-1}) ^{137}Cs (0.13 Bq kg^{-1})	^{58}Co (3.11 ± 0.31 Bq kg^{-1}) ^{60}Co (2.41 ± 0.24 Bq kg^{-1}) ^{137}Cs (0.87 ± 0.09 Bq kg^{-1})

2.8 Radiological habit survey

Information on the sources and pathways of exposure were applied to develop a radiological habit survey for collection of information on eating and recreational habits, i.e. occupancy and consumption rates which may result in public exposure. Framework Document Report listed as Appendix B on pathways and sources near the Koeberg Nuclear Power Station describes the preparation, implementation, data collection and data management phases of the radiological habit survey.

2.8.1 Preparation phase

A preliminary desk study was undertaken to identify areas in the vicinity of the Koeberg Nuclear Power Station which may be affected by liquid and gaseous effluent discharges. Data contained in various Koeberg environmental-surveillance reports, effluent management reports and radiation protection reports were reviewed and applied to identify the aquatic and terrestrial pathways [LE81, CU05]. Recommendations from people with useful local knowledge were applied to demarcate sub-areas on a map depicted in Fig. 2.14. Three sub-areas were identified in the vicinity of the Koeberg Nuclear Power Station namely the aquatic (sea) survey area, the terrestrial (land) survey area and the external exposure (direct radiation or non-food) survey area. Aquatic, terrestrial, and direct radiation survey areas were visited where relevant recreational and commercial activities occur.

The terrestrial pathway includes the main areas of potential gaseous effluent deposition within the radiological habit survey area, including areas where the sewage sludge may be used as fertilizer. The following food categories which may be affected by radioactive contaminants were identified during the design of the radiological habit survey [BY95]:

- root vegetables including beetroot, parsley, herbs, celery, onions and carrots);
- broad leaf vegetables including cabbage, lettuce and spinach;
- other domestic vegetables including tomatoes, beans and peas;
- domestic fruit including apples and berries;
- potatoes include mash, boiled and fried potatoes and sweet-potatoes;
- beef including all beef products; and
- milk which includes all milk products.

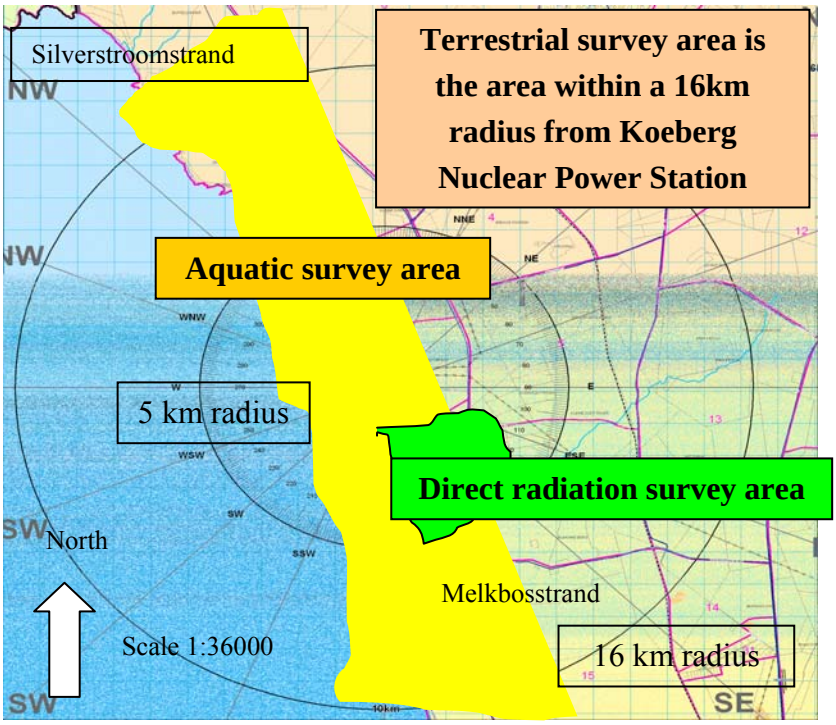

Figure 2.16 Map depicting demarcated aquatic, terrestrial and direct radiation survey areas (taken from Koeberg Site Safety Analysis Report).

The aquatic pathway includes the main areas of potential gaseous and liquid effluent deposition within the radiological habit survey area including the coastline and intertidal areas. The following seafood categories which may be affected by radioactive contaminants were identified during the design of the radiological habit survey [BY95]:

- mollusc including white and black mussels;
- shellfish including crayfish and abalone; and
- fish including all fish.

The direct exposure pathway includes the areas of potential gaseous and liquid effluent deposition within the radiological habit survey. The following recreational activities which may result in direct radiation exposure were identified during the preparation phase [CU05]:

- activities on water including boating and kite-surfing;

- activities in water including diving, board-surfing and swimming;
- handling and processing of sewage sludge;
- work activities in direct radiation areas; and
- recreational activities including hiking and cycling.

2.8.2 Implementation phase

The radiological habit survey was directed at adults with the view of applying scaling factors for future derivation of consumption and occupancy rates for teens, children and infants based on national consumption rates [NE02]. The following potentially exposed persons or Sub-critical Groups were identified: commercial fisherman, mussel collectors, bait diggers, boat owners, farmers, people living and/or working on or near the Koeberg Nuclear Power Station site, commercial and recreational divers, sewage plant operators, hikers, birdwatchers and gardeners.

People within the identified Sub-critical Groups were interviewed or were requested via electronic mail to answer questions relating to the questionnaire on all potential exposure pathways. The responses to the questions were recorded in a spreadsheet. Each individual from whom information was obtained was given a unique identifier number to assist in maintaining data quality. Follow-up telephonic calls were made to clarify some responses. Responses provided sufficient information to determine the individual's consumption rates of locally grown terrestrial foods, locally harvested seafood, and their outdoor recreational activities in the radiological habit survey area relevant to external exposure and occupancy in the direct radiation pathway.

During the radiological habit survey, a total of 352 responses were collected, received, reviewed and processed. Data were personally collected from a group of randomly selected people who live and work close to the Koeberg Nuclear Power Station in the areas of Table View, Duynefontein and Melkbosstrand. The following information was collected and recorded:

- hours spent outdoors;

- hours spent on the beach and in seawater;
- seafood harvested or caught locally for local consumption;
- terrestrial food grown locally for local consumption; and
- other relevant information for application in dose assessment calculations.

2.8.3 Data analyses phase

Data were reviewed, managed and controlled in accordance with the quality control programme developed for the radiological habit survey as addressed in Framework Document Report given as Appendix B of this report.

The radiological measurements were applied for Retrospective Public Dose Assessments. Ambient radiation levels measured in the radiological survey area were plotted on a map as a coarse indication of the potential dose distribution due to direct radiation pathways.

Data were evaluated via application of basic statistical functions to identify the highest individual rates, Threshold values, 97.5 percentile rates and the Critical Group rates. Individuals with the highest consumption rates, occupancy rates or dose were identified. Threshold values were derived by dividing the highest individual consumption rate or occupancy rate or dose by a factor of three as per the “cut-off” method [HU82]. Critical Groups were identified as all individuals with consumption rates, occupancy rates or doses greater and equal to the Threshold value. Critical Group rates were derived by calculating the arithmetic mean consumption rates, occupancy rates or doses of all members in the Critical Groups. Critical Group rates were then applied in Retrospective Public Dose Assessments. The frequency was determined from Critical Group data and graphs and tables were derived.

2.9 Principles for dose assessments

Some of the principles [AL05] were applied to develop Retrospective Public Dose Assessment methodologies to identify the Critical Group due to sources and pathways from the Koeberg Nuclear Power Station. Data were managed in a

suitable form so that the assessment was easy to present, understand and replicate. Workers who may have been potentially exposed to effluent discharges from the Koeberg Nuclear Power Station, but do not work directly with ionising radiation, were included in the dose assessments. The Critical Group dose was used for the purpose of assessing compliance with the public dose limit. This principle recommended by [AL05] is applied internationally and it is aligned with the ICRP recommendations for assessing dose of the representative person [IC05]. Doses to the most exposed age groups (adults, teenagers, children and infants) present in the affected population, were assessed for the purpose of determining compliance with the dose limit. All significant sources and exposure pathways of authorized radioactive waste discharges and direct radiation was assessed and the highest Critical Group dose was compared with the dose limit. Positive monitoring results were used where available for Retrospective Dose Assessment. Conservative assumptions, i.e. assuming that all the activity measured in terrestrial sample material are ingested, were applied in calculations as far as possible. The Critical Groups were selected so that the radiological habit survey data and the doses of members of the Critical Groups were homogeneous within a factor of three. The 'cut-off' method described by [HU82] was used since this method is arguably the best method and has been applied to identify Critical Groups via radiological habit surveys in studies conducted by [LE81, SM89, SM99, MC06].

The highest individual consumption rate or occupancy rate was identified and divided by a factor of 3 in accordance with recommendations addressed in [IC85] and as per the "cut-off" method developed by [HU82]. Critical Groups were derived by identifying all individuals with consumption rates, occupancy rates or doses greater than or equal to the Threshold value. Critical Group rates were derived by calculating the average consumption rates, occupancy rates or doses of all members in the Critical Groups. Critical Group rates were then applied in Retrospective Public Dose Assessments. The pathway which gave rise to the highest Critical Group dose was used for comparison with the public dose limits and dose constraint.

Pathways which gave rise to the highest Critical Group dose were used to identify the Critical Group for the Koeberg Nuclear Power Station, and the set of radiological habit survey data which gave rise to the highest Critical Group dose was analysed to determine the homogeneity of the Critical Group as discussed by [HU04]. Highest Critical Group doses were used for comparison with the national public dose limit. Aquatic pathway consumption and occupancy rates were used for comparison with the rates derived by [BA89].

2.10 Uncertainty and variability

Uncertainty and variability associated with radiological measurements were accounted for based on recommendations made by [ND05]. Uncertainty measures the lack of knowledge of the system under investigation, which in radiation dose assessment terms relate to how well doses of interest can be estimated. Sources of uncertainty were grouped into the following categories:

- measurement uncertainty was applied in the field of laboratory data relating to the preparation and measurement of activity in environmental samples. Potential sampling and analysis errors, lack of precision and inaccuracy of measurements were considered;
- parameter value uncertainty was applied in the Retrospective Public Dose Assessments where the most appropriate values used in assumptions were unknown due to a lack of data;
- scenario uncertainty was applied in some of the assumptions made in the habit survey about the habits of animals and human behaviour where a range of outcomes were evaluated;
- expert judgement and formal elicitation procedures were used to interpret available qualitative and quantitative information in the context of radiological assessments; and
- variability was considered during analysis of habits data to determine the differences between individuals in a group relating to occupancy and eating habits.

The uncertainty and variability in dose assessments presented in this report are indicative based on best estimates.

2.11 Dose assessment methods

Retrospective Public Dose Assessments due to sources and pathways from the Koeberg Nuclear Power Station were based on environmental-surveillance data, radiological monitoring data and radiological habit survey data. Effective doses were assessed due to ingestion of potentially contaminated food and liquids, inhalation and ingestion of potential contamination and external exposure due to direct radiation. Mathematical expressions used in radiation protection were developed and used in the report for determining the effective dose to members of the public from:

(a) internal exposure due to ingestion of seafood (Sub-sec. 2.11.1);
(b) internal exposure due to ingestion of terrestrial food (Sub-sec. 2.11.2);
(c) internal exposure due to ingestion of liquid (Sub-sec. 2.11.3);
(d) internal exposure due to inhalation of dust (Sub-sec. 2.11.4);
(e) external exposure due to immersion in water (Sub-sec. 2.11.5);
(g) external exposure due to standing on sludge (Sub-sec. 2.11.6);
(h) external exposure due to direct radiation (Sub-sec. 2.11.7); and
(i) individual collective dose assessment (Sub-sec. 2.11.8).

2.11.1 Internal exposure due to the ingestion of seafood

The dose from the consumption of seafood, i.e. fish, mussels, crayfish and abalone was calculated from the measured activity in seafood and multiplied by appropriate dose conversion factors and consumption rates given by:

$$E_{\text{seafood}} = \sum_{j} e(g)_{j,\text{ing}}\, A_{j,\text{seafood}}\, I_{j.\text{ing}}, \qquad (2.4)$$

E_{seafood} Effective dose per year due to activity in seafood (Sv y^{-1})

$\sum_{j} e(g)_{j,\text{ing}}$ Committed effective dose conversion factor due to activity in fish for radionuclide j by the group of age g per year as per [IC96] (Sv Bq^{-1})

$A_{j,\text{seafood}}$ Activity in seafood of radionuclide j per year (Bq kg^{-1})

$I_{j.\text{ing}}$ Intakes via ingestion of radionuclide j per year (kg y^{-1}).

2.11.2 Internal exposure due to the ingestion of terrestrial food

The dose from the consumption of terrestrial food, i.e. root vegetables, broad leaf vegetables, other domestic vegetables, potatoes, mushrooms, domestic fruit and beef was calculated from measured activity in waste water sludge in order to ensure conservative dose assessments. The primary reasons for this approach are, firstly, because it is a new pathway identified during the habit survey as waste water sludge containing trace amounts of radioactivity is used as fertilizer by some farmers near Koeberg Nuclear Power Station. Secondly, information on radionuclide migration, transfer rates and bio-accumulation for the Koeberg Nuclear Power Station source-term from sewage sludge into terrestrial foods are not available. The worse case scenario chosen for terrestrial dose assessments provides assurance that compliance to regulatory limits is achieved. Measured activity in waste water sludge is multiplied by appropriate dose conversion factors and consumption rates given by:

$$E_{\text{terrestrial}} = \sum_{j} e(g)_{j,\text{ing}} A_{j,\text{terrestrial}} I_{j.\text{ing}}, \qquad (2.5)$$

$E_{\text{terrestrial}}$	Effective dose per year due to activity in terrestrial food (Sv y^{-1})
$\sum_{j} e(g)_{j,\text{ing}}$	Committed effective dose conversion factor due to activity in terrestrial food for radionuclide j by the group of age g per year as per [IC96] (Sv Bq^{-1})
$A_{j,\text{terrestrial}}$	Activity in terrestrial food of radionuclide j per year (Bq kg^{-1})
$I_{j.\text{ing}}$	Intakes via ingestion of radionuclide j per year (kg y^{-1}).

It should be noted that no activity attributed to the operation of the Koeberg Nuclear Power Station was measured in any of the terrestrial food samples collected and analysed during 2006. However, samples of sewage sludge obtained from the local sewage treatment works contained some radionuclides of low activity which may be attributed to sources and pathways from the Koeberg Nuclear Power Station. For assessment purposes it was conservatively assumed that 100% of the activity measured in the sewage sludge are present in all locally harvested terrestrial foods.

2.11.3 Internal exposure due to the ingestion of liquids

The dose from the ingestion of liquid foods, i.e. wine, milk and water was calculated from measured activity in liquid and multiplied with appropriate dose conversion factors and consumption rates given by:

$$E_{\text{liquid}} = \sum_j e(g)_{j,\text{ing}} A_{j,\text{liquid}} I_{j,\text{ing}}, \tag{2.6}$$

E_{liquid}	Effective dose per year due to activity in liquid food (Sv y^{-1})
$\sum_j e(g)_{j,\text{ing}}$	Committed effective dose conversion factor due to activity in liquid food for radionuclide *j* by the group of age *g* per year as per [IC96] (Sv Bq^{-1})
$A_{j,\text{liquid}}$	Activity in liquid food of radionuclide *j* per year (Bq l^{-1})
$I_{j,\text{ing}}$	Intakes via ingestion of radionuclide *j* per year (l y^{-1}).

Critical group consumption rates were applied to calculate internal exposure due to wine and milk consumption based on the activity measured. It was assumed that 10 ml of seawater is ingested per hour spent in seawater during recreational activities based on interviews with local surfers. Ingestion of larger volumes of seawater may result in nausea and vomiting. Dose assessments due to ingestion of seawater are omitted from UK studies as ingestion doses are regarded as negligible.

2.11.4 Internal exposure due to the inhalation of dust

The dose from the inhalation of dust was calculated from measured activity in the sewage sludge and multiplied by appropriate dose conversion factors, the breathing rate, the exposure time and airborne activity given by:

$$E_{\text{dust}} = \sum_j e(g)_{j,\text{inh}} B_{g,\text{moderate}} TRD\, I_{j,\text{inh}}, \tag{2.7}$$

E_{dust}	Effective dose per year due to activity in dust (Sv y^{-1})
$\sum_j e(g)_{j,\text{inh}}$	Committed effective dose conversion factor due to activity in dust for radionuclide *j* by the group of age *g* per year as per

	[IC96] ($Sv\,Bq^{-1}$)
$B_{g,\text{moderate}}$	Breathing rate for moderate work taken as 1.2 from [IC96] in ($m^3\,h^{-1}$)
T	time exposed to dust per year ($h\,y^{-1}$)
R	Re-suspension factor of 10^{-4} taken from [DO94]
D	Density of sludge taken as 1600 ($kg\,m^{-3}$)
$I_{j,\text{inh}}$	Intakes via inhalation of radionuclide j per year ($Bq\,m^{-3}$).

The following assumptions were made for assessing the internal exposure for workers at the sewage treatment works due to the inhalation of airborne activity caused by possible re-suspension of the activity measured in the sewage: it was assumed that 0.01% of the dry sewage sludge in the ponds becomes airborne due to re-suspension when processed and are inhaled by the workers at a breathing rate of 1.2 $m^3\,h^{-1}$.

2.11.5 External exposure due to immersion in seawater

The dose from the immersion in seawater was calculated from measured activity in seawater and multiplied by appropriate dose conversion factors and occupancy rates given by:

$$E_{\text{emersion}} = \sum_j e(g)_{j,\text{emersion}}\, A_{j,\text{seawater}}\, T, \tag{2.8}$$

E_{emersion}	Effective dose per year due to emersion in seawater activity ($Sv\,y^{-1}$)
$\sum_j e(g)_{j,\text{emersion}}$	Committed effective dose due to emersion in seawater for radionuclide j by the group of age g per year as per [EC93] ($Sv\,h^{-1}$ / $Bq\,l^{-1}$)
$A_{j,\text{seawater}}$	Activity in seawater of radionuclide j per year ($Bq\,l^{-1}$)
T	Time immersed in seawater per year ($h\,y^{-1}$).

2.11.6 External exposure due to standing on sludge

The dose from standing on the sewage sludge was calculated from measured activity in the sewage sludge and multiplied by appropriate dose conversion factors, the density, the thickness of the sludge and the time spent on source given by:

$$E_{\text{sludge}} = \sum_j e(g)_{j,\text{direct}} \Phi T D A_{j,sludge}, \tag{2.9}$$

E_{sludge}	Effective dose per year due to activity in sewage sludge in (Sv y^{-1})
$\sum_j e(g)_{j,\text{direct}}$	Committed effective dose conversion factor for direct exposure due to activity in sewage sludge for radionuclide j by the group of age g per year as per [US77] (Sv h^{-1} / Bq m^{-2})
Φ	Thickness of sludge taken as 10^{-2} m
T	Time exposed to sewage sludge per year (h y^{-1})
D	Density of sewage sludge taken as 1600 (kg m^{-3})
$A_{j,sludge}$	Activity of radionuclide j in sewage sludge (Bq kg^{-1}).

2.11.7 External exposure due to direct radiation

The dose from direct radiation exposure was calculated from measured ambient dose rates using thermoluminescence dosimeters and field measurements using portable radiation instruments given by:

$$H_{\text{T}} = \sum_R \omega_{\text{R}} D_{P,\text{R}} T, \tag{2.10}$$

H_{T}	Equivalent dose in a tissue or organ T from exposure to penetrating radiation (Sv y^{-1})
$\sum_R \omega_{\text{R}} D_{P,\text{R}}$	The absorbed dose $D_{P,\text{R}}$ from radiation R in a tissue or organ P and ω_{R} is the radiation weighting factor of one for exposure to penetrating radiation per year (Sv y^{-1})
T	Exposure time (y).

2.11.8 Individual collective dose assessment

The individual collective dose from ingestion of aquatic and terrestrial foods, inhalation of contamination and exposure to direct radiation was calculated from measured activity and multiplied by appropriate dose conversion factors and consumption rates given by:

$$E = \sum_{R} \omega_{\mathrm{R}} D_{P,\mathrm{R}}\, T + \sum_{j} e(g)_{j,\mathrm{inh}} I_{j,\mathrm{inh}} + \sum_{j} e(g)_{j,\mathrm{ing}} I_{j,\mathrm{ing}}, \qquad (2.11)$$

E	Total effective dose per year (Sv y^{-1})
$\sum_{R} \omega_{\mathrm{R}} D_{P,\mathrm{R}}$	The absorbed dose $D_{P,\mathrm{R}}$ from radiation R in a tissue or organ P and ω_{R} is the radiation weighting factor of one for exposure to penetrating radiation per year (Sv y^{-1})
T	Exposure time (y)
$\sum_{j} e(g)_{j,\mathrm{inh}}$	Committed effective dose conversion factor due to inhalation activity for radionuclide j by the group of age g per year (Sv Bq^{-1})
$I_{j,\mathrm{inh}}$	Intakes via inhalation of radionuclide j per year (Bq m^{-3})
$\sum_{j} e(g)_{j,\mathrm{ing}}$	Committed effective dose conversion factor due to ingestion activity for radionuclide j by the group of age g per year (Sv Bq^{-1})
$I_{j,\mathrm{ing}}$	Intakes via ingestion of radionuclide j per year (Bq m^{-3}).

The results of the dose assessments are addressed in Chapter 3.

CHAPTER 3

RESULTS AND DISCUSSION

"In practice, it is feasible to take account of these sources of variability by the selection of appropriate Critical Groups within the population, provided the Critical Group is small enough to be homogeneous with respect to age, diet and those aspects of behaviour that affect the doses received." [HU04]

3.1 Introduction

In this chapter the results obtained from the methodologies applied in Chapter 2 relating to the identification of the Critical Group will be discussed. Results of the aquatic pathways are presented in Section 3.2. Results of the terrestrial pathways are presented in Section 3.3. Results of the direct radiation pathways are presented in Section 3.4 and the results of the combined pathways are presented in Section 3.5. The Critical Group dose is assessed in Section 3.6 and findings and observations are discussed in Section 3.7.

3.2 Aquatic pathways

The aquatic survey area covers all coastline and intertidal areas between Silverstroomstrand and Melkbosstrand and all waters inshore of the shipping channel (see Fig. 2.16). Silverstroomstrand marked the northern extent and Melkbosstrand marks the southern extent of the aquatic survey area. The shore is sandy with a few rocks at Melkbosstrand. At high tide and low tide the aquatic survey area consists of a flat beach of sand. Beach sports such as walking and angling are popular in this area. The commercial fishing industry in the aquatic survey area is not active in comparison with the fishing industry on the West Coast though shore angling and spear fishing are very popular in the aquatic survey area. The most popular angling locations are at Melkbosstrand. During the radiological habit survey various people were seen fishing daily on the beach and rocks at Melkbosstrand. The majority of the fish and shellfish harvested from the aquatic survey area were for private use. The use of seaweed from the aquatic

survey area was investigated. However, no evidence was found that seaweed may be used for consumption or as fertiliser.

3.2.1 Aquatic pathway internal exposure

The people consuming the greatest quantities of seafood from the aquatic survey area were hobby fishermen and people who enjoyed seafood. The predominant, locally harvested seafood consumed by adults interviewed were fish (snoek, galjoen and harders), white mussels, black mussels and crayfish.

3.2.1.1 Fish consumption

Many of the adults interviewed, 274 out of 352, consume fish caught or purchased from hobby fishermen in the radiological habit survey area. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual consumption rate was 200 ± 10 kg y^{-1}. A Threshold value calculated in accordance with [IC85] for determining the Critical Group was 66.7 ± 3.3 kg y^{-1} and the calculated 97.5 percentile rate based on 274 observations was 50 ± 2.5 kg y^{-1}. Figure 3.1 depicts the consumption rates of fish (for ease of comparison all figures and tables are presented at the end of this chapter). For fish, a Critical Group of 2 individuals was identified with a maximum consumption rate of 200 ± 10 kg y^{-1} and an average consumption rate of 130 ± 6.5 kg y^{-1}. Table 3.1a contains information on the Critical Group fish consumption rate. Critical Group internal exposure due to the consumption of fish was calculated in accordance with the methodology addressed in Sub-section 2.11.1 and the Critical Group dose due to the consumption of fish was 3.55 x 10^{-7} Sv y^{-1} as per the dose assessment presented in Table 3.1b.

3.2.1.2 Crayfish consumption

Many of the adults interviewed, 125 out of 352, consume crayfish harvested or purchased from hobby fishermen in the radiological habit survey area. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual consumption rate was 20 ± 1 kg y^{-1}. Threshold value calculated in accordance with [IC85] for determining the Critical

Group was 6.67 ± 0.33 kg y^{-1} and the calculated 97.5 percentile rate based on 125 observations was 10 ± 0.5 kg y^{-1}. Figure 3.2 depicts the individual crayfish consumption rates. For crayfish, a Critical Group of 7 individuals were identified with a maximum consumption rate of 20 ± 1 kg y^{-1} and an average consumption rate of 13.29 ± 0.7 kg y^{-1}. Table 3.2a contains information on the Critical Group crayfish consumption rate. Critical Group internal exposure due to the consumption of crayfish was calculated in accordance with the methodology addressed in Sub-section 2.11.1 and the Critical Group dose due to the consumption of crayfish was 2.7 x 10^{-8} (Sv y^{-1}) as per the dose assessment presented in Table 3.2b.

3.2.1.3 Mussel consumption

Many of the adults interviewed, 107 out of 352, consume white and black mussels harvested or purchased from mussel diggers in the radiological habit survey area. Some people consume large quantities of white mussels as a substitute for abalone which is illegal to harvest. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual consumption rate was 50 ± 2.5 kg y^{-1}. Threshold value calculated in accordance with [IC85] for determining the Critical Group was 16.7 ± 0.8 kg y^{-1} and the calculated 97.5 percentile rate based on 107 observations was 20 ± 1 kg y^{-1}. Figure 3.3 depicts the individual mussel consumption rates. For mussels, a Critical Group of 4 individuals was identified with a maximum consumption rate of 50 ± 2.5 kg y^{-1} and an average consumption rate of 32.5 ± 1.6 kg y^{-1}. Table 3.3a contains information on the Critical Group mussel consumption rate. Critical Group internal exposure due to the consumption of mussels was calculated in accordance with the methodology addressed in Sub-section 2.11.1 and the Critical Group dose due to the consumption of mussels was 1.32 x 10^{-6} Sv y^{-1} as per the dose assessment presented in Table 3.3b.

3.2.1.4 Abalone consumption

Seven adults consume small quantities of abalone that are harvested in the radiological habit survey area. The harvesting of abalone is not permitted as it is a

protected species, therefore it is possible that more people may be consuming abalone but did not disclose it during the radiological habit survey. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual consumption rate was 4 ± 0.2 kg y^{-1}. Threshold value calculated in accordance with [IC85] for determining the Critical Group was 1.33 ± 0.07 kg y^{-1} and the calculated 97.5 percentile rate based on 7 observations was 3.55 ± 0.18 kg y^{-1}. Figure 3.4 depicts the individual abalone consumption rates. For abalone, a Critical Group of 1 individual was identified with a maximum consumption rate of 4 ± 0.2 kg y^{-1} and an average consumption rate of 4 ± 0.2 kg y^{-1}. Table 3.4a contains information on the Critical Group abalone consumption rate.

The Critical Group internal exposure due to the consumption of abalone was calculated in accordance with the methodology addressed in Sub-section 2.11.1 and the Critical Group dose due to the consumption of abalone was 9.46 x 10^{-9} Sv y^{-1} as per the dose assessment presented in Table 3.4b.

3.2.1.5 Seawater occupancy

Many of the adults interviewed, 112 out of 352, spend time in the seawater as the wind and waves in the aquatic survey area are ideal for board and kite surfing. Some adults own surfing academies and are providing training to young surfers on a daily basis. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual occupancy in seawater near the Koeberg Power Station was 800 ± 80 h y^{-1}. Threshold value in accordance with [IC85] for determining the Critical Group was 266.7 ± 27 h y^{-1} and the calculated 97.5 percentile rate based on 112 observations was 242.2 ± 24 h y^{-1}. Figure 3.5 depicts the individual occupancy rates in seawater.

For in-water activities, a Critical Group of 3 individuals were identified with a maximum occupancy in seawater of 800 ± 80 h y^{-1} and an average occupancy in seawater of 520 ± 50 h y^{-1}. Table 3.5a contains information on the Critical Group seawater occupancy. Critical Group internal exposure due to the consumption of

seawater was calculated in accordance with the methodology addressed in Sub-section 2.11.3 and the Critical Group dose due to the consumption of seawater was 1.28 x 10^{-8} Sv y^{-1} as per the dose assessment presented in Table 3.5b.

3.2.2 Aquatic pathway external exposure

Figure 3.5 and Table 3.5a shows the individual and Critical Group occupancy data recorded during the radiological habit survey for swimmers and surfers. During 2006 trace amounts of activity was detected in seawater. Effective dose due to immersion in seawater was calculated for the Critical Group in accordance with the methodology addressed in Sub-section 2.11.5. Critical Group dose due to immersion in seawater was 2.87 x 10^{-8} Sv y^{-1} as per the dose assessment presented in Table 3.5c. Skin dose and effective dose due to beach sand in the aquatic survey area was not considered in this report as no contaminated sand was detected in intertidal areas. Doses calculated for the Critical Group due to the aquatic pathway are summarised in Fig. 3.6. The total dose to the Critical Group due to the aquatic pathway was 1.75 x 10^{-6} Sv y^{-1} and the dose assessment is presented in Table 3.6.

3.3 Terrestrial pathways

The terrestrial survey area covered all land and watercourses within a 16 km radius from the Koeberg Nuclear Power Station as depicted in Fig. 2.14, which may potentially be affected by gaseous effluent discharges. Various farms, small-holdings and private residences in the terrestrial survey area grow and harvest small quantities of terrestrial foods from their gardens for personal consumption. Consumption of locally produced foods was identified in the following food groups: broad leaf vegetables, other vegetables, root vegetables, potato, domestic fruit, beef, milk and wine.

3.3.1 Terrestrial pathway internal exposure

The local sewage treatment works processes liquid and solid waste from the terrestrial survey area and some of the sewage sludge is collected and used by local residents in the radiological survey area as fertiliser for vegetable gardens

and growing roll-on lawn. Activity was detected in processed sewage samples collected from the local sewage treatment works during 2006. All of the local users of sewage fertiliser could not be identified during the radiological habit survey, thus for dose assessment purposes, it was conservatively assumed that all locally harvested foods contain the same activity per radionuclide as measured in the sewage sludge during 2006.

3.3.1.1 Worker occupancy

Workers at the sewage treatment works process liquid and solid waste which contains trace amounts of radioactivity. Activity may become airborne during processing due to re-suspension of activity in the sewage. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual outdoor occupancy at the sewage treatment works was 2000 ± 100 h y^{-1}. Threshold value in accordance with [IC85] for determining the Critical Group was 666.67 ± 33 h y^{-1} and the calculated 97.5 percentile rate based on 6 observations was 1988.75 ± 99 h y^{-1}. Figure 3.7 depicts the waste water treatment plant worker outdoor occupancy rates.

For handling of dried sewage, a Critical Group of 6 individuals were identified with a maximum outdoor occupancy of 2000 ± 100 h y^{-1} and an average outdoor occupancy of 1850 ± 92 h y^{-1}. Table 3.7a contains information on the Critical Group occupancy rates. Critical Group internal exposure due to potential inhalation of dust was calculated in accordance with the methodology addressed in Sub-section 2.11.4 and the Critical Group dose due to the inhalation of dust was 7.46 x 10^{-6} Sv y^{-1} as per the dose assessment presented in Table 3.7b.

3.3.1.2 Broad leaf vegetable consumption

Some of the adults interviewed, 5 out of 352, consume broad leaf vegetables i.e. cabbage, lettuce and spinach which were home grown in the terrestrial survey area. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual consumption rate was 25 ± 1.25 kg y^{-1}. Threshold value in accordance with [IC85] for determining the

Critical Group was 6.3 ± 0.3 kg y^{-1} and the calculated 97.5 percentile rate based on 15 observations was 20.45 ± 1 kg y^{-1}. Figure 3.8 depicts the individual broad leaf vegetable consumption rates.

For broad leaf vegetables, a Critical Group of 4 individuals were identified with a maximum consumption rate of 25 ± 1.25 kg y^{-1} and an average consumption rate of 13.5 ± 0.67 kg y^{-1}. Table 3.8a contains information on the Critical Group consumption of broad leaf vegetables. Critical Group internal exposure due to the consumption of broad leaf vegetables was calculated in accordance with the methodology addressed in Sub-section 2.11.2 and the Critical Group dose due to the consumption of broad leaf vegetables was 3.40 x 10^{-7} Sv y^{-1} as per the dose assessment presented in Table 3.8b.

3.3.1.3 Root vegetable consumption

Some of the adults interviewed, 5 out of 352, consume root vegetables i.e. beetroot, parsley, herbs, celery, onions, carrots which were home grown in the terrestrial survey area. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual consumption rate was 1 ± 0.05 kg y^{-1}. Threshold value in accordance with [IC85] for determining the Critical Group was 0.33 ± 0.02 kg y^{-1} and the calculated 97.5 percentile rate based on 5 observations was 1 ± 0.05 kg y^{-1}. Figure 3.9 depicts the individual root vegetable consumption rates.

For root vegetables, a Critical Group of 5 individuals were identified with a maximum consumption rate of 1 kg y^{-1} and an average consumption rate of 0.9 ± 0.04 kg y^{-1}. Table 3.9a contains information on the Critical Group consumption of root vegetables. Critical Group internal exposure due to the consumption of root vegetables was calculated in accordance with the methodology addressed in Sub-section 2.11.2 and the Critical Group dose due to the consumption of root vegetables was 2.26 x 10^{-8} Sv y^{-1} as per the dose assessment presented in Table 3.9b.

3.3.1.4 Other vegetable consumption

Some of the adults interviewed, 15 out of 352, consume other vegetables, i.e. tomatoes, beans, peas and mushrooms which were home grown in the terrestrial survey area. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual consumption rate was 20 ± 1 kg y^{-1}. Threshold value in accordance with [IC85] for determining the Critical Group was 6.67 ± 0.33 kg $y^{-1}$and the calculated 97.5 percentile rate based on 15 observations was 17.2 ± 0.86 kg y^{-1}. Figure 3.10 depicts the individual other vegetable consumption rates. For other vegetables, a Critical Group of 3 individuals were identified with a maximum consumption rate of 20 ± 1 kg $y^{-1}$and an average consumption rate of 14.7 ± 0.73 kg y^{-1}. Table 3.10a contains information on the Critical Group consumption of other vegetables. Critical Group internal exposure due to the consumption of other vegetables was calculated in accordance with the methodology addressed in Sub-section 2.11.2 and the Critical Group dose due to the consumption of other vegetables was 3.71 x 10^{-7} Sv y^{-1} as per the dose assessment presented in Table 3.10b.

3.3.1.5 Potato consumption

Some of the adults interviewed, 8 out of 352, consume potatoes which are home grown in the terrestrial survey area. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual consumption rate was 10 ± 0.5 kg y^{-1}. Threshold value in accordance with [IC85] for determining the Critical Group was 4 ± 0.2 kg y^{-1} and the calculated 97.5 percentile rate based on 8 observations was 9.12 ± 0.46 kg y^{-1}. Figure 3.11 depicts the individual potato consumption rates. For potatoes, a Critical Group of 5 individuals were identified with a maximum consumption rate of 10 ± 0.5 kg y^{-1} and an average consumption rate of 5.8 ± 0.3 kg y^{-1}. Table 3.11a contains information on the Critical Group consumption of potatoes. Critical Group internal exposure due to the consumption of potatoes was calculated in accordance with the methodology addressed in Sub-section 2.11.2 and the Critical Group dose due to the consumption of potatoes was 1.47 x 10^{-7} Sv y^{-1} as per the dose assessment presented in Table 3.11b.

3.3.1.6 Domestic fruit consumption

Some of the adults interviewed, 15 out of 352, consume domestic fruit, i.e. grapes, apples, wild bananas and lemons, which are home grown in the terrestrial survey area. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2. The highest individual consumption rate was 20 ± 1 kg y^{-1}. A Threshold value in accordance with [IC85] for determining the Critical Group was 6.67 ± 0.33 kg y^{-1}. The calculated 97.5 percentile rate based on 8 observations was 16.5 ± 0.82 kg y^{-1}. Figure 3.12 depicts the individual domestic fruit consumption rates. For domestic fruit, a Critical Group of 7 individuals were identified with a maximum consumption rate of 20 ± 1 kg y^{-1} and an average consumption rate of 11 ± 0.55 kg y^{-1}. Table 3.12a contains information on the Critical Group consumption of domestic fruit. Critical Group internal exposure due to the consumption of domestic fruit was calculated in accordance with the methodology addressed in Sub-section 2.11.2 and the Critical Group dose due to the consumption of domestic fruit was 2.77×10^{-7} Sv y^{-1} as per the dose assessment presented in Table 3.12b.

3.3.1.7 Beef consumption

One individual interviewed consumes beef which was obtained from a local farm in the terrestrial survey area. Figure 3.13 is a photograph taken in the local area of cows grazing. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the individual consumption rate for beef was 100 ± 5 kg y^{-1}. Threshold value in accordance with [IC85] for determining the Critical Group was 33.33 ± 1.65 kg y^{-1} and the calculated 97.5 percentile rate could not be calculated for 1 individual. For beef, a Critical Group of 1 individual was identified with a maximum consumption rate of 100 ± 5 kg y^{-1} and an average consumption rate of 100 ± 5 kg y^{-1}. Table 3.13a contains information on the Critical Group consumption of beef. Critical Group internal exposure due to the consumption of beef was calculated in accordance with the methodology addressed in Sub-section 2.11.2 and the Critical Group dose due to the consumption of beef was 2.56×10^{-6} Sv y^{-1} as per the dose assessment presented in Table 3.13b.

3.3.1.8 Milk consumption

Some of the adults interviewed, 7 out of 352, consume milk produced at local dairy farms in the terrestrial survey area. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual consumption rate was 150 ± 7.5 l y^{-1}. Threshold value in accordance with [IC85] for determining the Critical Group was 50 ± 2.5 l y^{-1}. The calculated 97.5 percentile rate based on 7 observations was 97.5 ± 4.8 l y^{-1}. Figure 3.14 depicts the individual milk consumption rates. For consumption of milk, a Critical Group of 5 individuals were identified with a maximum consumption rate of 200 ± 10 l y^{-1} and an average consumption rate of 88 ± 4.4 l y^{-1}. Table 3.14a contains information on the Critical Group consumption of milk. Critical Group internal exposure due to the consumption of milk was calculated in accordance with the methodology addressed in Sub-section 2.11.3 and the Critical Group dose due to the consumption of milk was 2.22 x 10^{-6} Sv y^{-1} as per the dose assessment presented in Table 3.14b.

3.3.1.9 Red wine consumption

Some of the adults interviewed, 2 out of 352, consume red wine produced from locally harvested grapes in the terrestrial survey area. Data were analysed in accordance with the principles and methodologies addressed in Chapter 2 and the highest individual consumption rate was 300 ± 15 l y^{-1}. Threshold value in accordance with [IC85] for determining the Critical Group was 100 ± 5 l y^{-1} and the calculated 97.5 percentile rate based on 2 observations was 297 ± 14.9 l y^{-1}. Figure 3.15 depicts the individual wine consumption rates.

For consumption of wine, a Critical Group of 2 individuals were identified with a maximum consumption rate of 300 ± 15 l y^{-1} and an average consumption rate of 250 ± 12.5 l y^{-1}. Table 3.15a contains information on the Critical Group consumption of wine. Critical Group internal exposure due to the consumption of wine was calculated in accordance with the methodology addressed in Sub-section 2.11.3 and the Critical Group dose due to the consumption of wine was 6.37 x 10^{-6} Sv y^{-1} as per the dose assessment presented in Table 3.15b.

3.3.2 Terrestrial pathway external exposure

As discussed in Sub-section 3.3.1.1, some workers, 6 out of 352, are potentially exposed to radiation from processed sewage at the local sewage treatment works. The Critical Group outdoor occupancy rate was 1850 ± 92.5 h y^{-1}. Critical Group external exposure due to standing on sludge was calculated in accordance with the methodology addressed in Sub-section 2.11.6 and the dose to the Critical Group was 6.13 x 10^{-7} Sv y^{-1} as per the dose assessment presented in Table 3.16. The total dose to the Critical Group due to the terrestrial pathway was 2.06 x 10^{-5} Sv y^{-1} and the dose assessment is presented in Table 3.17.

Outdoor occupancy of members of the public (non-radiation workers) who are working on the Koeberg Nuclear Power Station site was analysed in accordance with the methodologies addressed in Chapter 2 and the highest outdoor annual occupancy was 600 ± 30 h y^{-1}. Threshold value in accordance with [IC85] for determining the Critical Group outdoor occupancy was 200 ± 10 h y^{-1} and the calculated 97.5 percentile rate based on 273 observations was 310 ± 15.5 h y^{-1}. Figure 3.16 depicts the individual outdoor occupancy rates. The Critical Group outdoor occupancy rate based on 273 observations was 248 ± 12.4 h y^{-1}.

Indoor occupancy of members of the public (non-radiation workers) who work on the Koeberg Nuclear Power Station site was analysed in accordance with the methodologies addressed in Chapter 2 and the highest indoor annual occupancy was 1900 h y^{-1}. Threshold value in accordance with [IC85] for determining the Critical Group indoor occupancy was 633 ± 31.6 h $y^{-1}$and the calculated 97.5 percentile rate based on 337 observations was 1822 ± 91.1 h y^{-1}. Figure 3.17 depicts the Koeberg Nuclear Power Station non-radiation worker indoor occupancy rates. The Critical Group indoor occupancy rate based on 337 observations was 1573 ± 78.6 h y^{-1}.

3.4 Direct radiation pathways

No direct radiation was measured beyond the boundaries of the Koeberg Nuclear Power Station. However, low-energy gamma radiation in the order of 10^{-6} Sv h^{-1}

was detected on the Koeberg Nuclear Power Station site. Gamma radiation, attenuated via Compton scatter interactions, was detected in localised areas in the vicinity of the low-level waste storage facility. Figure 3.18 is a photograph showing the location where the dose rates were measured.

Ambient radiation levels were measured on the Koeberg site using portable radiation dose meters in accordance with the principles and methodologies addressed in Chapter 2. The highest outdoor ambient dose rate detected in occupied areas was 4.46 x 10^{-8} Sv h^{-1} and the highest indoor ambient dose rate detected in occupied areas was 2 x 10^{-8} Sv h^{-1}.

The total dose to the Critical Group due to the direct radiation pathway was 4.47 x10^{-5} Sv y^{-1} and the dose assessment is presented in Table 3.18.

3.5 Combined pathways

The combined pathway data collected during the radiological habit surveys are listed in Appendix C. An integrated effective dose was calculated for all 352 individuals taking all sources and pathways into account in accordance with the methodologies addressed in Chapter 2. The highest individual dose was 2.12 x 10^{-4} Sv y^{-1} and the Threshold value in accordance with [IC85] for determining the Critical Group dose was 7.06 x 10^{-5} Sv y^{-1} and the calculated 97.5 percentile dose rate based on 12 observations was 1.94 x 10^{-4} Sv y^{-1}. The Critical Group effective doses for the direct radiation pathway are lower than that calculated for the combined pathway as the Critical Group indoor and outdoor occupancy factors are statistically lower. Figure 3.19 depicts the individual effective dose from combined pathways for members of the Critical Group for the Koeberg Nuclear Power Station.

For combined pathways, a Critical Group of 12 individuals were identified with an average effective dose of 2 x 10^{-4} Sv y^{-1}. Table 3.19 contains information on the individual effective dose for members of the Critical Group due to combined pathways. The Critical Group for the combined pathways are comprised of

individuals whom are all working in temporary accommodation situated in a direct radiation pathway on the Koeberg Nuclear Power Station site. The main pathway of exposure to the Critical Group is low-energy gamma radiation due to Compton scatter interactions from a nearby equipment storage facility.

3.6 Critical Group dose

The combined pathway resulted in the highest dose of 2 x 10^{-4} Sv y^{-1} to the Critical Group during 2006. The Critical Group effective dose calculated for all pathways are listed in Table 3.20. The pathway which gave rise to the highest Critical Group dose, the combined pathway was used to identify the Critical Group for the Koeberg Nuclear Power Station and the set of habits which gave rise to the highest Critical Group dose were analysed to determine the homogeneity of the Critical Group as discussed by [HU04]. The maximum exposure to members of the Critical Group is below the legal public dose limit of 10^{-3} Sv y^{-1}. However, the dose is close to the dose constraint of 2.5 x 10^{-4} Sv y^{-1} prescribed by the regulatory authority. The Critical Group is homogeneous as the individual dose is within a factor of 3 and the group is comprised of adults, working in the same environment and are subjected to the same sources and pathway of exposure.

3.7 Discussion

This study is based on methods applied for similar Retrospective Public Dose Assessments by CEFAS for nuclear power plants in the UK. The study is aligned with reports issued for Wylfa, Aldermaston/Burgfield, Winfrith, Dungeness and Cardiff nuclear power plants [CL04, TI03, SM89, MC06].

The Critical Group of members of the public legitimately working on-site and potentially exposed to radiation from the Koeberg Nuclear Power Station was successfully identified via a radiological habit survey and integrated Retrospective Public Dose Assessments. The following refinements are incorporated in the public dose assessment methodology:

- non-radiation workers working on the Koeberg Nuclear Power Station site who may have been exposed to potential direct radiation from the facility were included in the assessment. Non-Radiation workers at nuclear power stations in the UK are not included in public dose assessments; and
- radiological surveys were performed on the Koeberg Nuclear Power Station site to verify potential direct radiation pathways. On-site radiological survey data are not included in the UK public dose assessments.

The combined pathway resulted in the highest dose of 2×10^{-4} Sv y^{-1} to the Critical Group during 2006. The combined pathway effective dose is not a summation of effective doses calculated for the aquatic, terrestrial and direct radiation pathways. The effective dose calculated for the combined pathway is three times higher than the sum of the aquatic, terrestrial, and direct radiation pathways as the combined pathway method evaluates the integrated effective dose for the individual based on individual habits versus effective doses based on Critical Group rates as determined for the aquatic, terrestrial, and direct radiation pathways. The combined pathway assessment method is rated as the best method [CA05] for identification of the Critical Group.

Two new exposure pathways, i.e. the terrestrial pathway due to sewage sludge and direct radiation pathway were discovered during the study. The methodology developed for this study verified that the radiological habit survey designed by [LE82] may successfully be applied for South African conditions to identify critical groups.

The habit study methodology was applied during 2007 in a formal Eskom Study for the PBMR and is being used for similar studies at new nuclear sites, i.e. Thyspunt, Bantamsklip and Port Nolloth during 2008. The framework document and questionnaire developed for the Research Report were also successfully applied during July 2007 in a training programme at the University of the Western Cape for training of 40 post-graduate students. The training was presented in

preparation for a baseline radiological habit survey required by Eskom and the PBMR Company for application in prospective public dose assessments. The University of the Western Cape has successfully collected radiological habit survey data from more than 3000 households in the Western Cape using the framework document and questionnaire.

The study was used in improve the Eskom environmental-surveillance programme and Retrospective Public Dose Assessment methods. The terrestrial exposure pathway due to contaminated sewage fertiliser is now monitored via the Koeberg Environmental Surveillance Programme. Public Dose assessment Methodologies developed were applied in the 2007/8 Annual Report to the NNR.

A graphical presentation of this Research Report was presented at the 2007 Conference of the South African Institute of Physics, held at the University of the Witwatersrand, Johannesburg during July 2007. The Conference Committee awarded the Nuclear and Particles Group's MSc prize for the presentation.

The Research Report may be improved by:

- collecting more data in general and confirm consumption rates for some local terrestrial foods, i.e. beef and wine. Methods applied in the UK for analysis of single data points in similar studies were applied to draw conclusions. However, verification of data may confirm results.

- application of local uncertainty and variability data for habit study results. However, in the absence of local quality assurance programmes to verify habit study data, uncertainty and variability figures obtained from UK Retrospective Public Dose Assessments were applied.

- terrestrial pathway Retrospective Public Dose Assessment methodologies are conservative as it is assumed that 100% of the activity is transferred from sewage fertiliser into the food-chain. However, the conservative assessment results are below the public dose limit and dose constraint.

Conservative assumptions applied in Retrospective Public Dose Assessments are acceptable in the absence of best estimate data.

Table 3.21 contains comparisons of seafood consumption rates derived by [BA89]. In 1987 the occupancy rate in the seawater was less than the occupancy rate in 2007 as in-water activities such as board-surfing and kite surfing have increased locally. Larger volumes of crayfish were consumed during 1987 compared to 2007 due to government restrictions on harvesting of crayfish. Larger volumes of mussels are consumed during 2007 as some people process mussel meat as a substitute for crayfish.

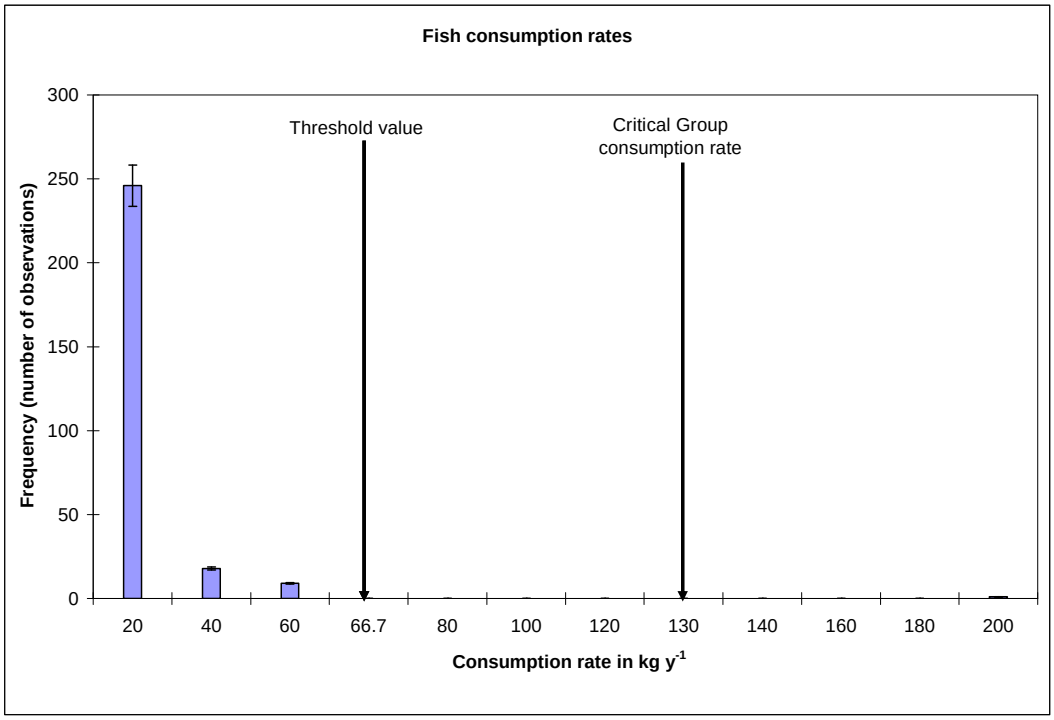

Figure 3.1: Individual consumption rates of fish.

Table 3.1a: Critical Group fish consumption rate.

Members of the Critical Group Unique identifier number	Fish consumption rates kg y^{-1}
86	60 ± 3
112	200 ± 10
Critical Group rate	130 ± 6.5

Table 3.1b: Critical Group dose due to fish consumption.

Radionuclide	Specific activity (Bq kg^{-1})	[IC96] DCF (Sv Bq^{-1})	Critical Group rate in (kg y^{-1})	Maximum dose (Sv y^{-1})
^{137}Cs	0.18 ± 0.02	1.30 x 10^{-8}	130 ± 6.5	3.55 x 10^{-7}
Total dose to the Critical Group (Sv y^{-1})				**3.55 x 10^{-7}**

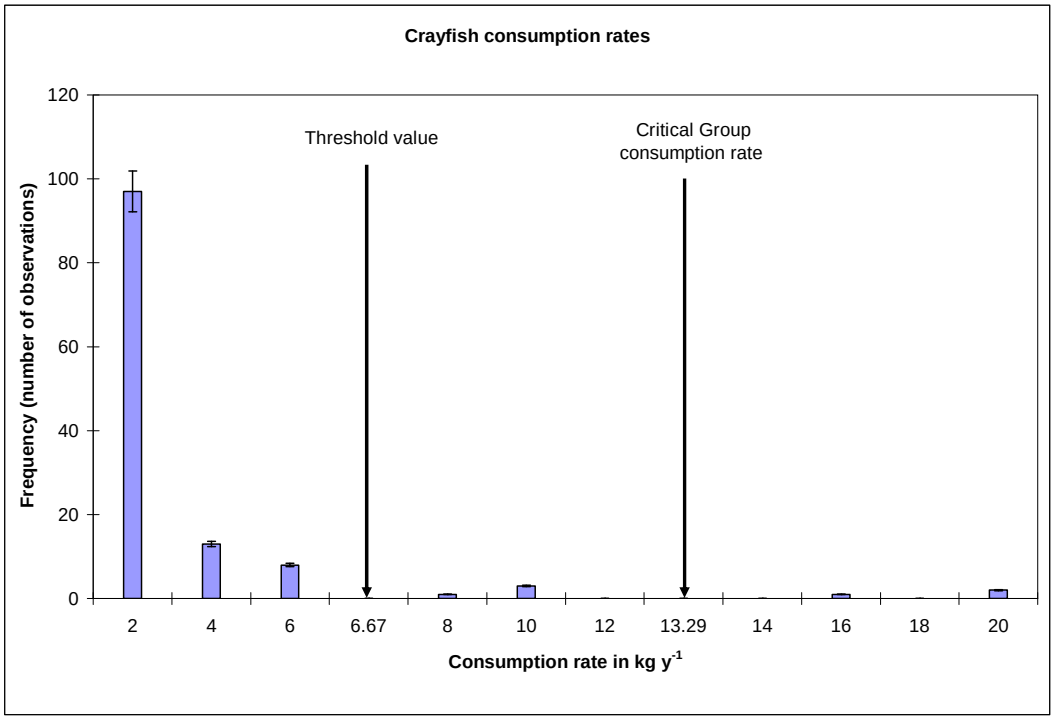

Figure 3.2: Individual crayfish consumption rates.

Table 3.2a: Critical Group crayfish consumption rate.

Members of the Critical Group Unique identifier number	Crayfish consumption rates (kg y^{-1})
201	8 ± 0.4
127	10 ± 0.5
164	10 ± 0.5
112	10 ± 0.5
28	15 ± 0.75
21	20 ± 1
132	20 ± 1
Critical Group rate	13.29 ± 0.7

Table 3.2b: Critical Group dose due to crayfish consumption.

Radionuclide	Specific activity (Bq kg^{-1})	[IC96] DCF (Sv Bq^{-1})	Critical Group rate in (kg y^{-1})	Maximum dose (Sv y^{-1})
^{110m}Ag	0.63 ± 0.06	2.80 x 10^{-9}	13.29 ± 0.7	2.70 x 10^{-8}
Total dose to the Critical Group (Sv y^{-1})				**2.70 x 10^{-8}**

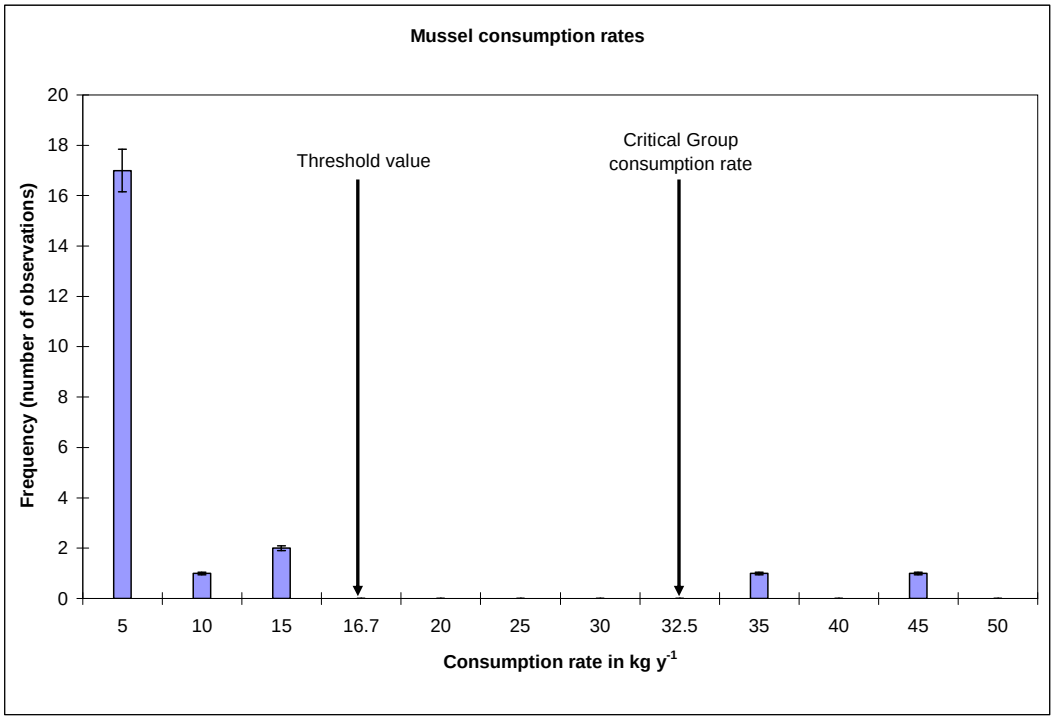

Figure 3.3: Individual mussel consumption rates.

Table 3.3a: Critical Group mussel consumption rate.

Members of the Critical Group Unique identifier number	Mussel consumption rates $kg\,y^{-1}$
302	20 ± 1
300	20 ± 1
200	40 ± 2
301	50 ± 2.5
Critical Group rate	32.5 ± 1.6

Table 3.3b: Critical Group dose due to mussel consumption.

Radionuclide	Specific activity ($Bq\,kg^{-1}$)	[IC96] DCF ($Sv\,Bq^{-1}$)	Critical Group rate in ($kg\,y^{-1}$)	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	1.12 ± 0.12	7.40×10^{-10}	32.5 ± 1.6	3.13×10^{-8}
^{60}Co	0.22 ± 0.02	3.40×10^{-9}		2.78×10^{-8}
^{110m}Ag	12 ± 1.20	2.80×10^{-9}		1.26×10^{-6}
Total dose to the Critical Group ($Sv\,y^{-1}$)				**1.32×10^{-6}**

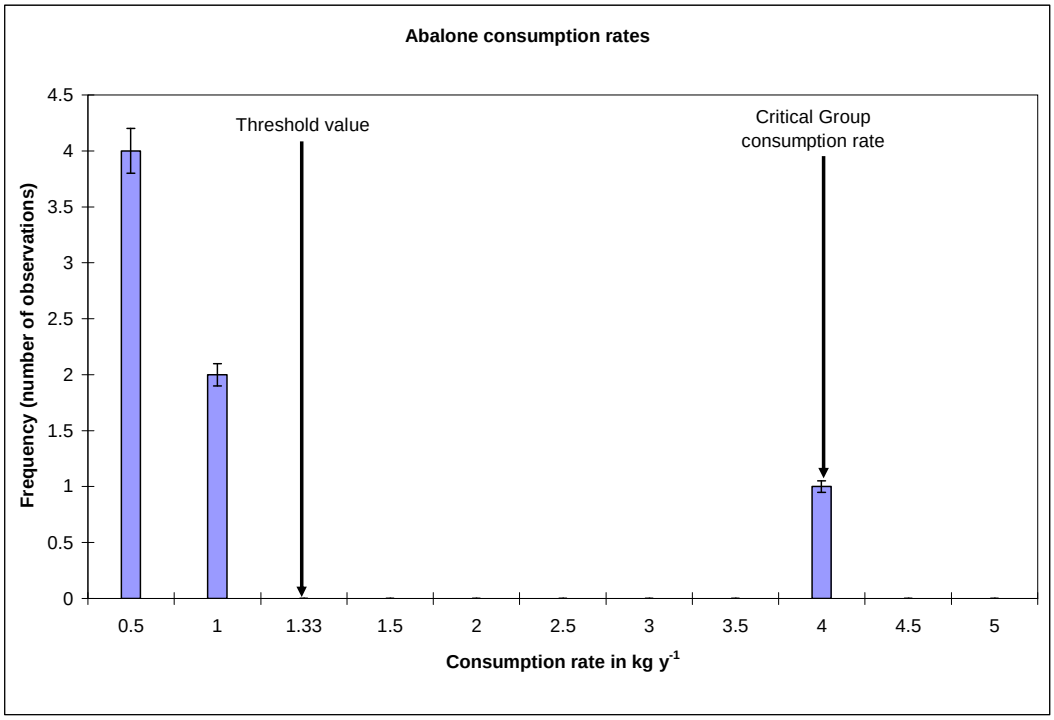

Figure 3.4: Individual abalone consumption rates.

Table 3.4a: Critical Group abalone consumption rate.

Members of the Critical Group Unique identifier number	Abalone consumption rates kg y^{-1}
221	4 ± 0.2
Critical Group rate	4 ± 0.2

Table 3.4b: Critical Group dose due to abalone consumption.

Radionuclide	Specific activity (Bq kg^{-1})	[IC96] DCF (Sv Bq^{-1})	Critical Group rate in (kg y^{-1})	Maximum dose (Sv y^{-1})
^{58}Co	0.12 ± 0.01	7.4 x 10^{-10}	4 ± 0.2	4.04 x 10^{-10}
^{110m}Ag	0.7 ± 0.07	2.8 x 10^{-9}		9.06 x 10^{-9}
Total dose to the Critical Group (Sv y^{-1})				**9.46 x 10^{-9}**

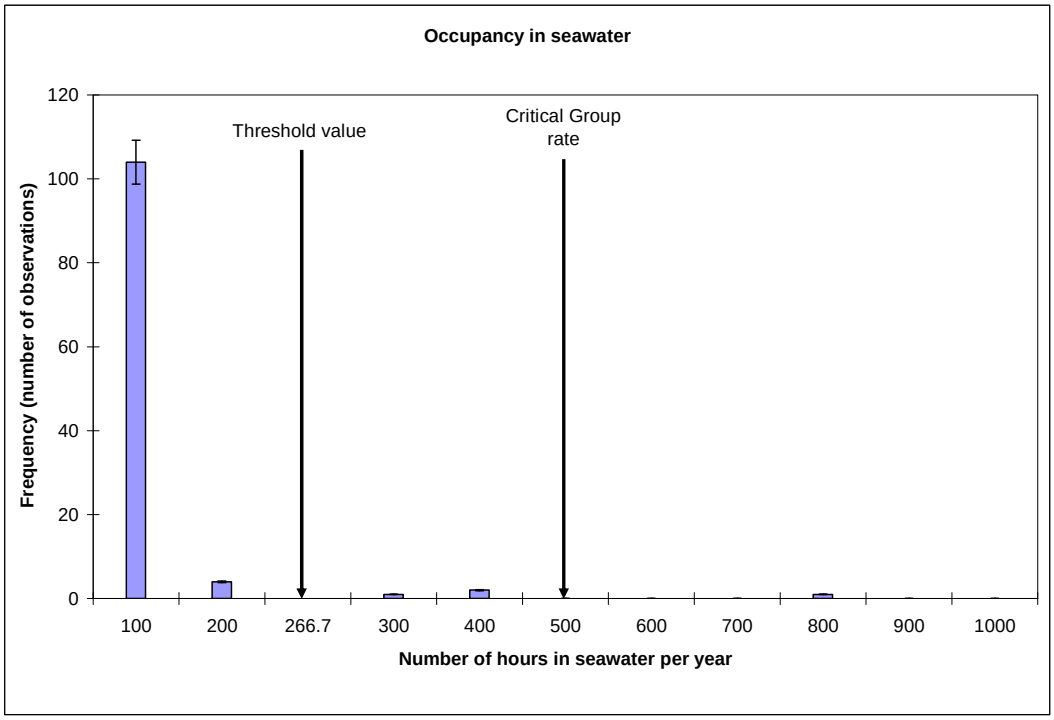

Figure 3.5: Individual occupancy rates in seawater.

Table 3.5a: Critical Group occupancy rates in seawater.

Members of the Critical Group Unique identifier number	Occupancy rates in seawater ($h\ y^{-1}$)
157	360 ± 36
112	400 ± 40
320	800 ± 80
Critical Group rate	520 ± 50

Table 3.5b: Critical Group dose due to ingestion of seawater.

Radionuclide	Specific activity ($Bq\ l^{-1}$)	[IC96] DCF ($Sv\ Bq^{-1}$)	Critical Group rate in ($lh\ y^{-1}$)	Maximum dose ($Sv\ y^{-1}$)
^{58}Co	0.03 ± 0.01	4.4×10^{-9}	52 ± 0.5	9.00×10^{-9}
^{60}Co	0.026 ± 0.01	2.7×10^{-9}		3.82×10^{-9}
Total dose to the Critical Group ($Sv\ y^{-1}$)				**1.28×10^{-8}**

Table 3.5c: Critical Group dose due to immersion in seawater.

Radionuclide	Specific activity ($Bq\,l^{-1}$)	DCF $Sv\,h^{-1}$ / $Bq\,l^{-1}$	Critical Group rate in ($h\,y^{-1}$)	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	0.03 ± 0.01	3.71×10^{-10}	520 ± 50	8.46×10^{-9}
^{60}Co	0.026 ± 0.01	9.85×10^{-10}		2.02×10^{-8}
Total dose to the Critical Group ($Sv\,y^{-1}$)				**2.87×10^{-8}**

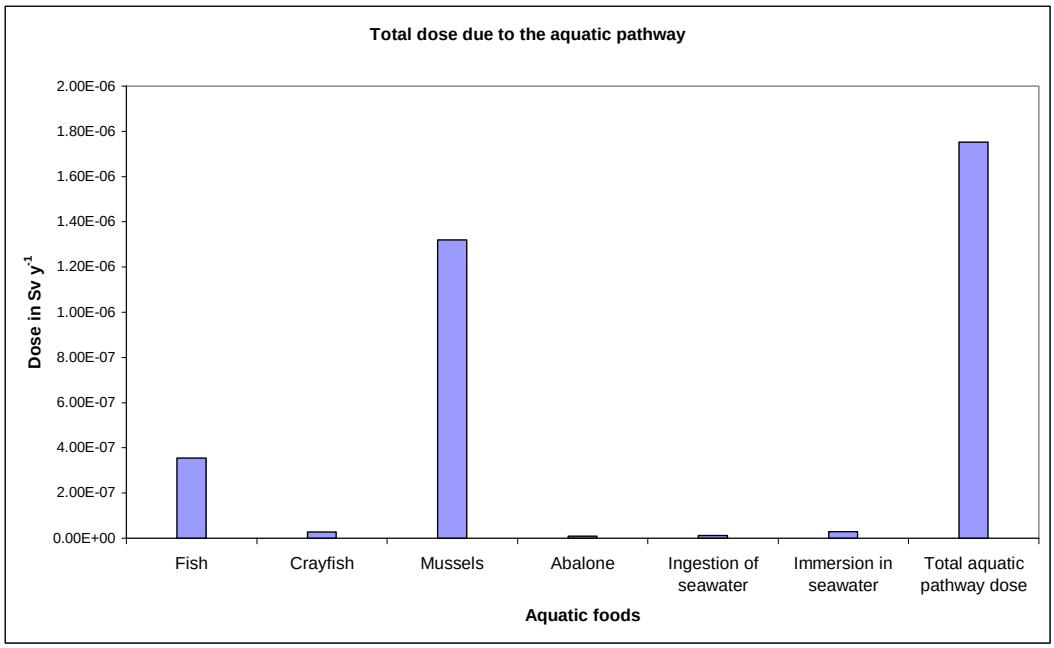

Figure 3.6: Total dose to the Critical Group due to the aquatic pathway.

Table 3.6: Total dose to the Critical Group due to the aquatic pathway.

Aquatic pathway	Dose in ($Sv\,y^{-1}$)
Critical Group dose due to fish consumption	3.55×10^{-7}
Critical Group dose due to crayfish consumption	2.70×10^{-8}
Critical Group dose due to mussel consumption	1.32×10^{-6}
Critical Group dose due to abalone consumption	9.46×10^{-9}
Critical Group dose due to ingestion of seawater	1.28×10^{-8}
Critical Group dose due to immersion in seawater	2.87×10^{-8}
Total Critical Group dose due to the aquatic pathway	**1.75×10^{-6}**

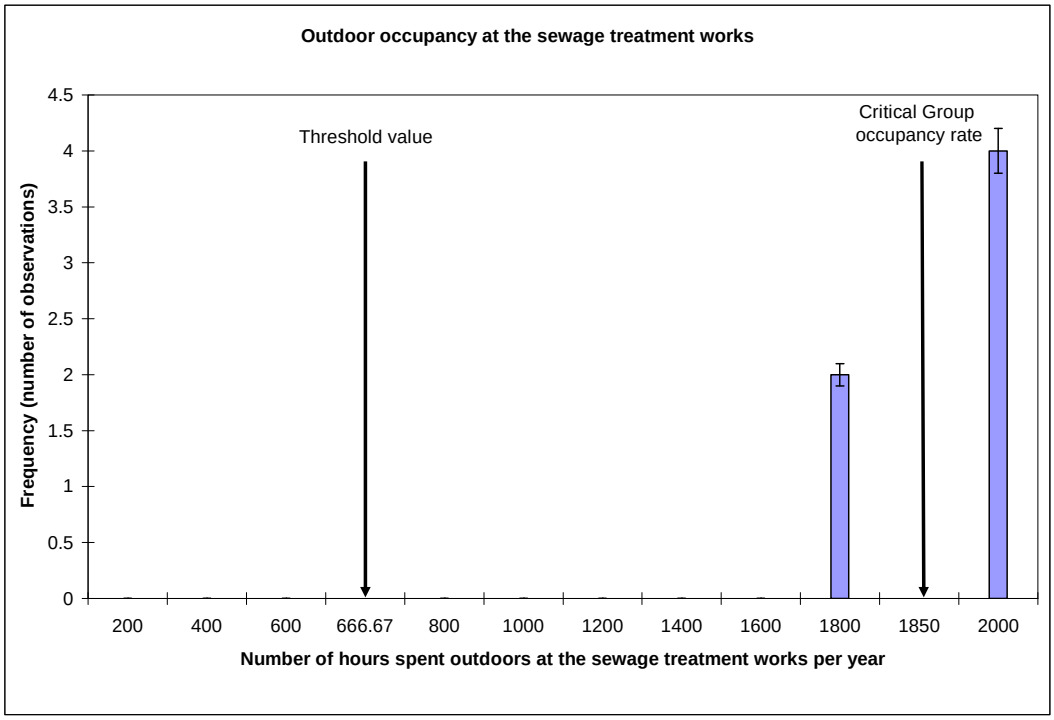

Figure 3.7: Individual outdoor occupancy rates at the sewage treatment works.

Table 3.7a: Critical Group dose due to inhalation of dust.

Members of the Critical Group Unique identifier number	Outdoor occupancy rates ($h\,y^{-1}$)
50	2000 ± 100
51	1890 ± 94
53	1690 ± 84.5
286	1720 ± 86
338	1910 ± 96
344	1860 ± 93
Critical Group rate	1850 ± 92

Table 3.7b: Critical Group dose due to inhalation of dust.

Radionuclide	Specific activity ($Bq\,kg^{-1}$)	[IC96] DCF ($Sv\,Bq^{-1}$)	Critical Group rate ($kg.y^{-1}$)	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	3.11 ± 0.31	5.30×10^{-10}	373	6.76×10^{-7}
^{60}Co	2.41 ± 0.24	5.20×10^{-9}		5.14×10^{-6}
^{137}Cs	0.87 ± 0.09	4.60×10^{-9}		1.65×10^{-6}
Total dose to the Critical Group ($Sv\,y^{-1}$)				**7.46×10^{-6}**

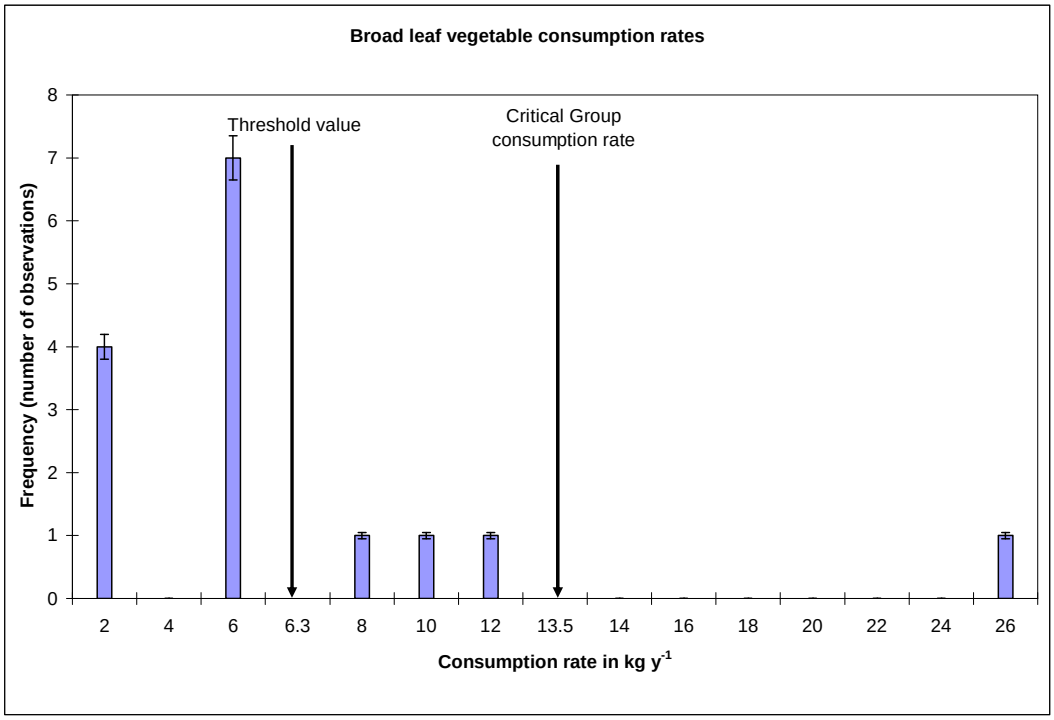

Figure 3.8: Individual broad leaf vegetable consumption rates.

Table 3.8a: Critical Group consumption of broad leaf vegetables.

Members of the Critical Group Unique identifier number	Broad leaf vegetable consumption rates ($kg\,y^{-1}$)
78	7 ± 0.35
301	10 ± 0.5
72	12 ± 0.6
345	25 ± 1.25
Critical Group rate	13.5 ± 0.67

Table 3.8b: Critical Group dose due to broad leaf vegetable consumption.

Radionuclide	Specific activity ($Bq\,kg^{-1}$)	[IC96] DCF ($Sv\,Bq^{-1}$)	Critical Group rate in ($kg\,y^{-1}$)	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	3.11 ± 0.31	7.40×10^{-10}	13.5 ± 0.67	3.59×10^{-8}
^{60}Co	2.41 ± 0.24	3.40×10^{-9}		1.28×10^{-7}
^{137}Cs	0.87 ± 0.09	1.30×10^{-8}		1.53×10^{-7}
Total dose to the Critical Group ($Sv\,y^{-1}$)				**3.40×10^{-7}**

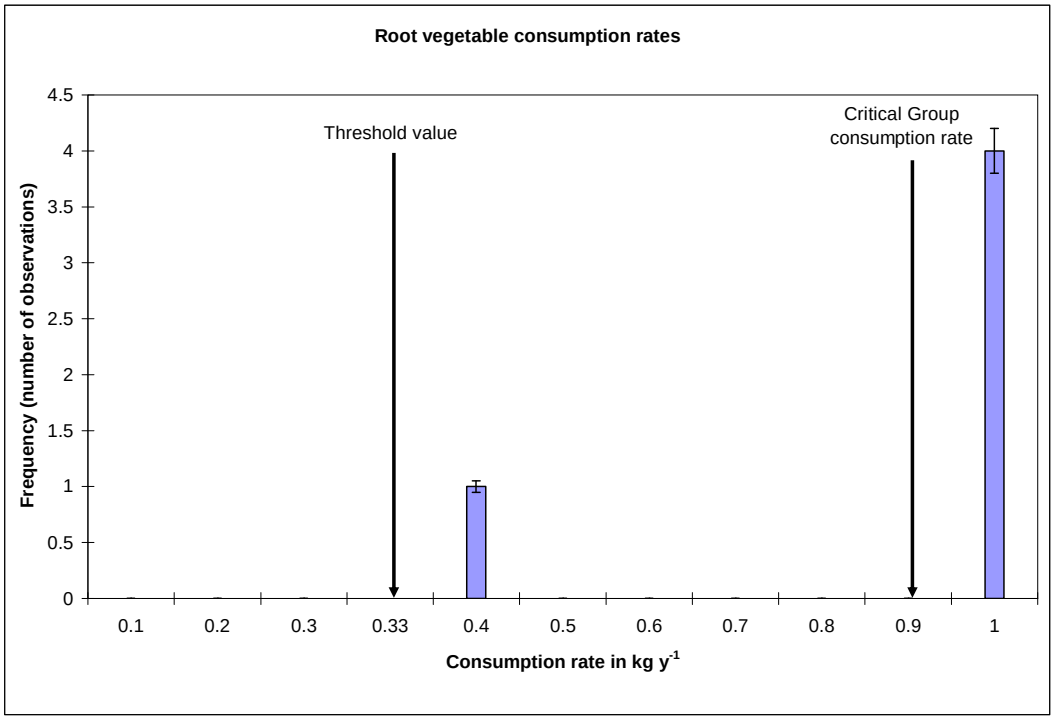

Figure 3.9: Individual root vegetable consumption rates.

Table 3.9a: Critical Group consumption of root vegetables.

Members of the Critical Group Unique identifier number	Root vegetable consumption rates ($kg\,y^{-1}$)
312	0.5 ± 0.02
13	1 ± 0.05
46	1 ± 0.05
296	1 ± 0.05
247	1 ± 0.05
Critical Group rate	0.9 ± 0.04

Table 3.9b: Critical Group dose due to root vegetable consumption.

Radionuclide	Specific activity ($Bq\,kg^{-1}$)	[IC96] DCF ($Sv\,Bq^{-1}$)	Critical Group rate in ($kg\,y^{-1}$)	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	3.11 ± 0.31	7.40×10^{-10}	0.9 ± 0.04	2.38×10^{-9}
^{60}Co	2.41 ± 0.24	3.40×10^{-9}		8.47×10^{-9}
^{137}Cs	0.87 ± 0.09	1.30×10^{-8}		1.17×10^{-8}
Total dose to the Critical Group ($Sv\,y^{-1}$)				**2.26×10^{-8}**

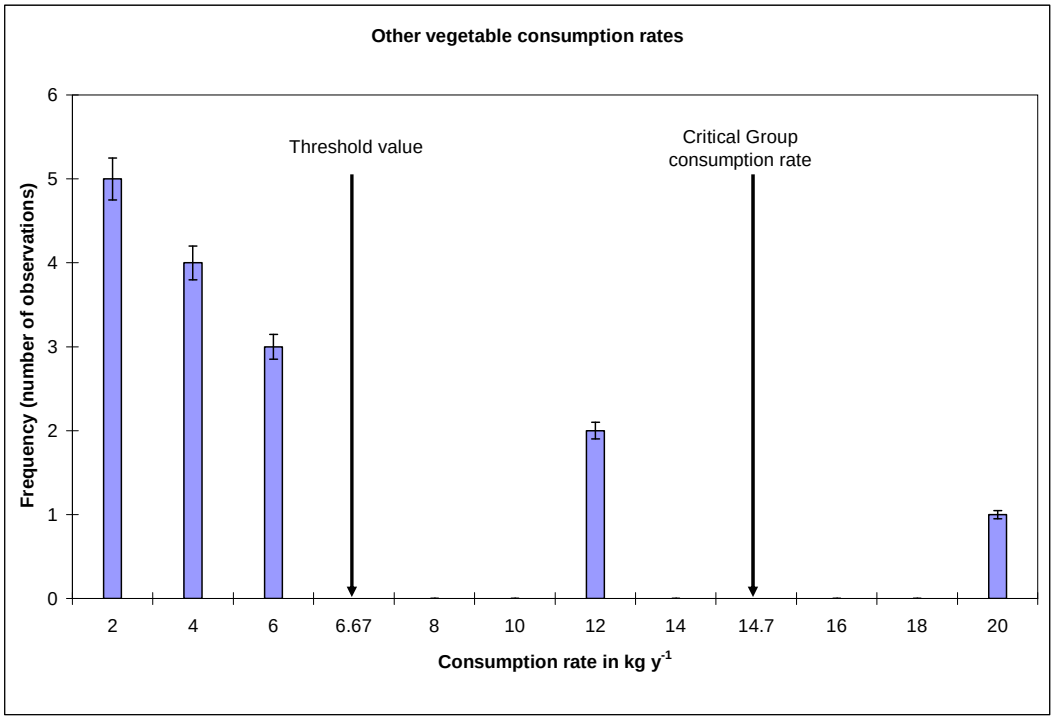

Figure 3.10: Individual other vegetable consumption rates.

Table 3.10a: Critical Group consumption of other vegetables.

Members of the Critical Group Unique identifier number	Other vegetable consumption rates ($kg\,y^{-1}$)
344	20 ± 1
73	12 ± 0.6
301	12 ± 0.6
Critical Group rate	14.7 ± 0.73

Table 3.10b: Critical Group dose due to consumption of other vegetables.

Radionuclide	Specific activity ($Bq\,kg^{-1}$)	[IC96] DCF ($Sv\,Bq^{-1}$)	Critical Group rate in ($kg\,y^{-1}$)	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	3.11 ± 0.31	7.40×10^{-10}	14.7 ± 0.73	3.91×10^{-8}
^{60}Co	2.41 ± 0.24	3.40×10^{-9}		1.39×10^{-7}
^{137}Cs	0.87 ± 0.09	1.30×10^{-8}		1.93×10^{-7}
Total dose to the Critical Group ($Sv\,y^{-1}$)				**3.71×10^{-7}**

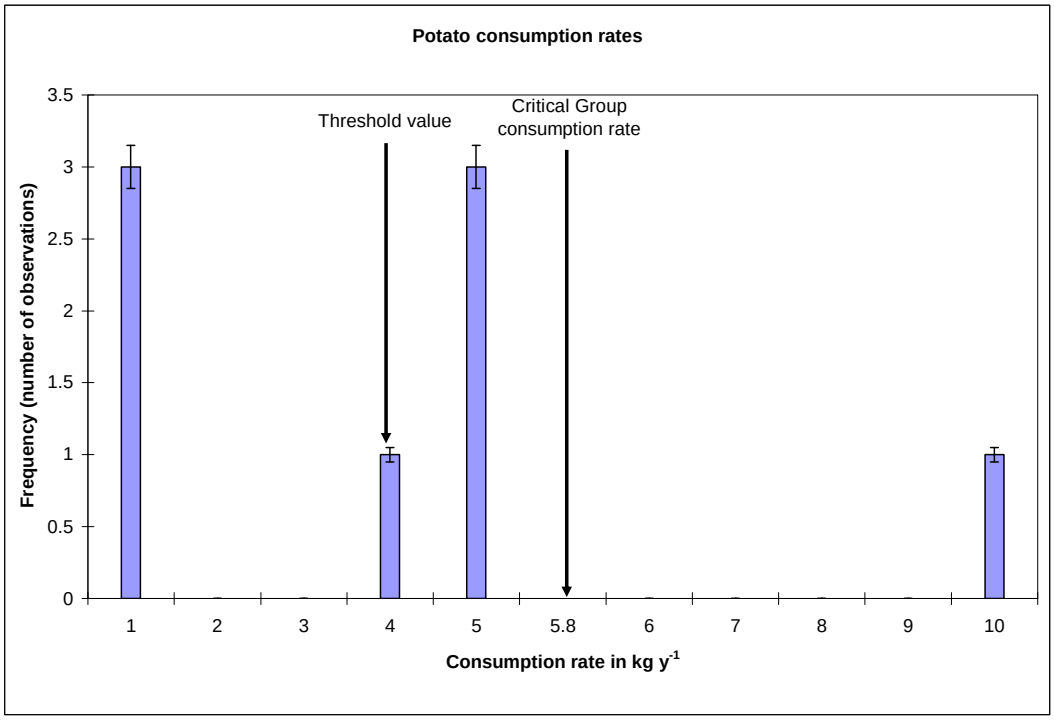

Figure 3.11: Individual potato consumption rates.

Table 3.11a: Critical Group consumption of potatoes.

Members of the Critical Group Unique identifier number	Potato consumption rates ($kg\,y^{-1}$)
303	4 ± 0.2
78	5 ± 0.25
343	5 ± 0.25
344	5 ± 0.25
301	10 ± 0.5
Critical Group rate	5.8 ± 0.3

Table 3.11b: Critical Group dose due to consumption of potatoes.

Radionuclide	Specific activity ($Bq\,kg^{-1}$)	[IC96] DCF ($Sv\,Bq^{-1}$)	Critical Group rate in ($kg\,y^{-1}$)	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	3.11 ± 0.31	7.40×10^{-10}	5.8 ± 0.3	1.54×10^{-8}
^{60}Co	2.41 ± 0.24	3.40×10^{-9}		5.50×10^{-8}
^{137}Cs	0.87 ± 0.09	1.30×10^{-8}		7.61×10^{-8}
Total dose to the Critical Group ($Sv\,y^{-1}$)				**1.47×10^{-7}**

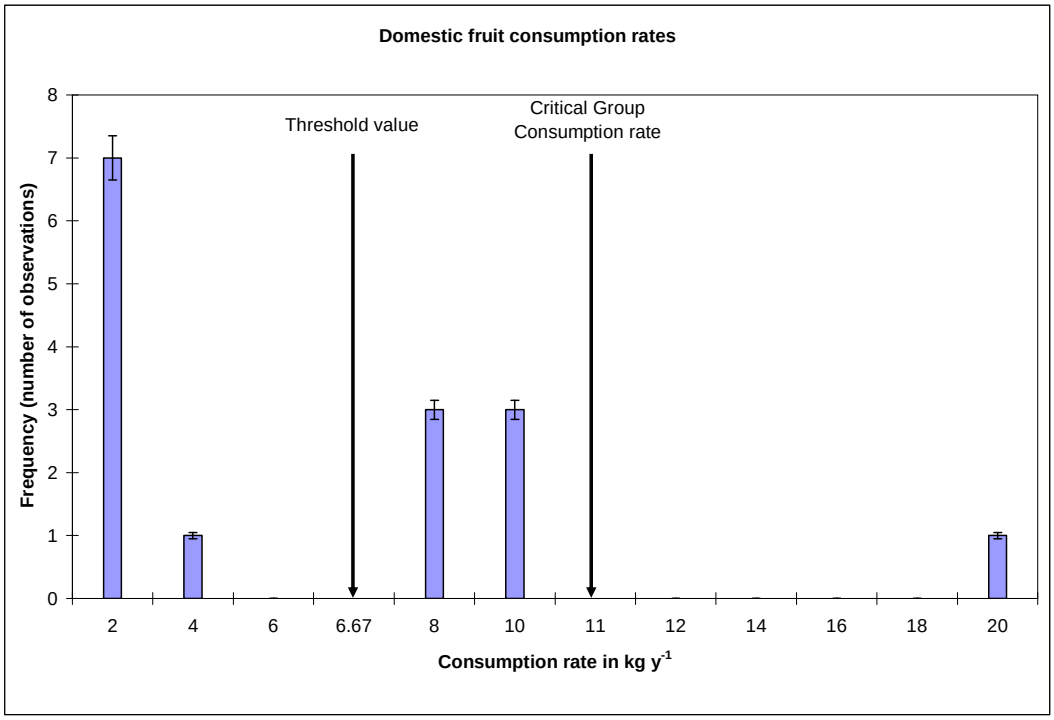

Figure 3.12: Individual domestic fruit consumption rates.

Table 3.12a: Critical Group consumption of domestic fruit.

Members of the Critical Group Unique identifier number	Domestic fruit consumption rates ($kg\,y^{-1}$)
246	7 ± 0.35
247	7 ± 0.35
248	7 ± 0.35
55	10 ± 0.5
56	10 ± 0.5
58	10 ± 0.5
57	20 ± 1
Critical Group rate	11 ± 0.55

Table 3.12b: Critical Group dose due to consumption of domestic fruit.

Radionuclide	Specific activity ($Bq\,kg^{-1}$)	[IC96] DCF ($Sv\,Bq^{-1}$)	Critical Group rate in ($kg\,y^{-1}$)	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	3.11 ± 0.31	7.40×10^{-10}	11 ± 0.55	2.92×10^{-8}
^{60}Co	2.41 ± 0.24	3.40×10^{-9}		1.04×10^{-7}
^{137}Cs	0.87 ± 0.09	1.30×10^{-8}		1.44×10^{-7}
Total dose to the Critical Group ($Sv\,y^{-1}$)				**2.77×10^{-7}**



Figure 3.13: Photograph of cows in the radiological habit survey area.

Table 3.13a: Critical Group consumption of beef.

Members of the Critical Group Unique identifier number	Beef consumption rates ($kg\,y^{-1}$)
63	100 ± 5
Critical Group rate	100 ± 5

Table 3.13b: Critical Group dose due to consumption of beef.

Radionuclide	Specific activity ($Bq\,kg^{-1}$)	[IC96] DCF ($Sv\,Bq^{-1}$)	Critical Group rate in ($kg\,y^{-1}$)	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	3.11 ± 0.31	7.40×10^{-10}	100 ± 5	2.66×10^{-7}
^{60}Co	2.41 ± 0.24	3.40×10^{-9}		9.46×10^{-7}
^{137}Cs	0.87 ± 0.09	1.30×10^{-8}		1.31×10^{-6}
Total dose to the Critical Group ($Sv\,y^{-1}$)				**2.56×10^{-6}**

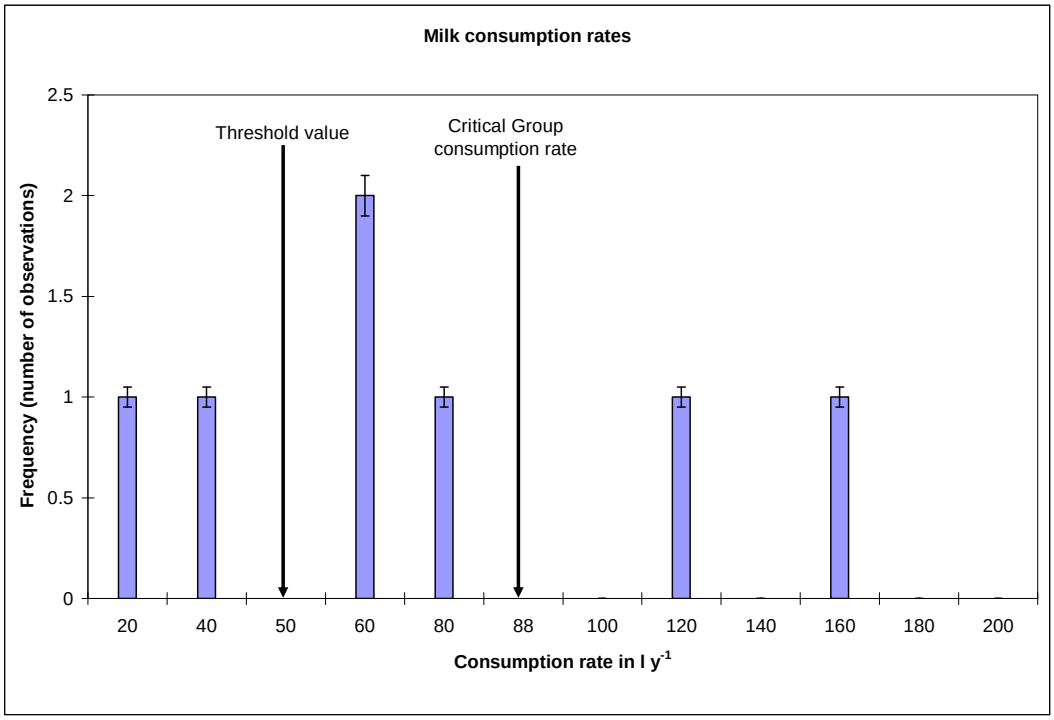

Figure 3.14: Individual milk consumption rates.

Table 3.14a: Critical Group consumption of milk.

Members of the Critical Group Unique identifier number	Milk consumption rates ($l\,y^{-1}$)
50	50 ± 2.5
286	50 ± 2.5
311	70 ± 3.5
39	120 ± 6
352	150 ± 7.5
Critical Group rate	88 ± 4.4

Table 3.14b: Critical Group dose due to consumption of milk.

Radionuclide	Specific activity ($Bq\,kg^{-1}$)	[IC96] DCF ($Sv\,Bq^{-1}$)	Critical Group rate in ($kg\,y^{-1}$)	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	3.11 ± 0.31	7.40×10^{-10}	88 ± 4.4	2.34×10^{-7}
^{60}Co	2.41 ± 0.24	3.40×10^{-9}		8.33×10^{-7}
^{137}Cs	0.87 ± 0.09	1.30×10^{-8}		1.15×10^{-6}
Total dose to the Critical Group ($Sv\,y^{-1}$)				**2.22×10^{-6}**

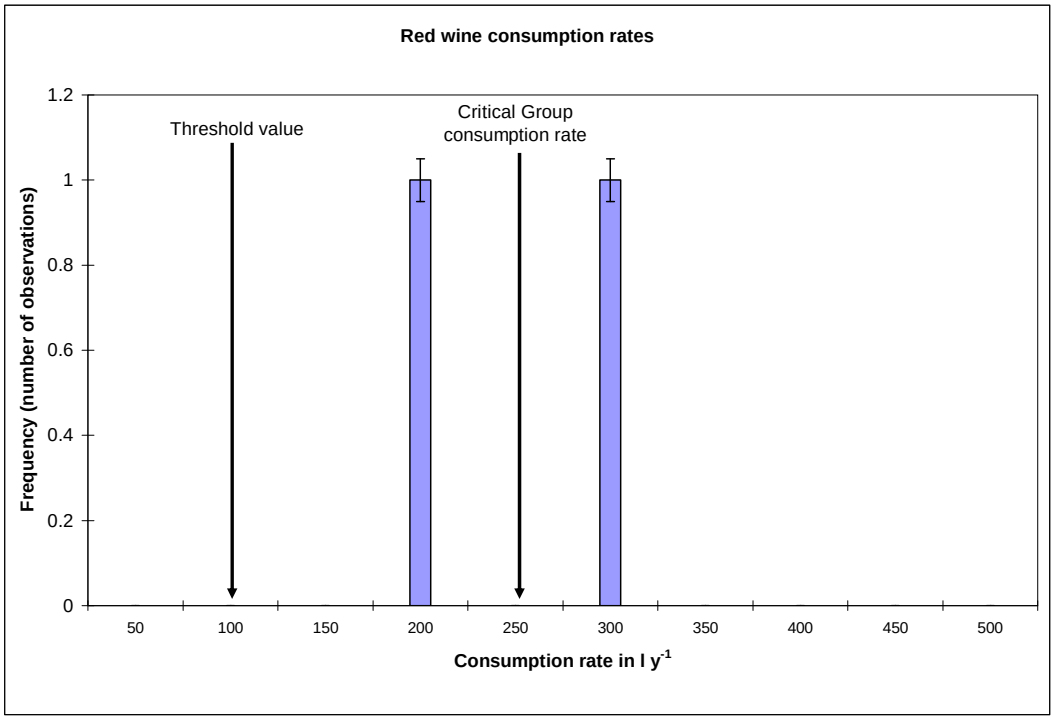

Figure 3.15: Individual wine consumption rates.

Table 3.15a: Critical Group consumption of wine.

Members of the Critical Group Unique identifier number	Wine consumption rates ($l\,y^{-1}$)
57	300 ± 15
58	200 ± 10
Critical Group rate	250 ± 15

Table 3.15b: Critical Group dose due to consumption of wine.

Radionuclide	Specific activity ($Bq\,kg^{-1}$)	[IC96] DCF ($Sv\,Bq^{-1}$)	Critical Group rate in ($kg\,y^{-1}$)	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	3.11 ± 0.31	7.40×10^{-10}	250 ± 15	6.71×10^{-7}
^{60}Co	2.41 ± 0.24	3.40×10^{-9}		2.39×10^{-6}
^{137}Cs	0.87 ± 0.09	1.30×10^{-8}		3.31×10^{-6}
Total dose to the Critical Group ($Sv\,y^{-1}$)				**6.37×10^{-6}**

Table 3.16: Critical Group dose due to standing on sludge.

Radionuclide	Specific activity ($Bq\,kg^{-1}$)	DCF in ($Sv\,h^{-1}$ per $Bq\,m^{2}$)	Outdoor occupancy rate in ($h\,y^{-1}$)	Specific activity factor $kg.Bq.m^{-2}$	Maximum dose ($Sv\,y^{-1}$)
^{58}Co	3.11 ± 0.31	1.89×10^{-12}	1850 ± 92.5	16	2.01×10^{-7}
^{60}Co	2.41 ± 0.24	4.59×10^{-12}			3.78×10^{-7}
^{137}Cs	0.87 ± 0.09	1.13×10^{-12}			3.37×10^{-8}
Total dose to the Critical Group ($Sv\,y^{-1}$)					**6.13×10^{-7}**

Table 3.17: Total dose to the Critical Group due to the terrestrial pathway.

Terrestrial pathway	Dose ($Sv\,y^{-1}$)
Critical Group dose due to inhalation of dust	7.46×10^{-6}
Critical Group dose due to broad leaf vegetable consumption	3.40×10^{-7}
Critical Group dose due to root vegetable consumption	2.26×10^{-8}
Critical Group dose due to consumption of other vegetables	3.71×10^{-7}
Critical Group dose due to consumption of potatoes	1.47×10^{-7}
Critical Group dose due to consumption of domestic fruit	2.77×10^{-6}
Critical Group dose due to consumption of beef	2.56×10^{-7}
Critical Group dose due to consumption of milk	2.22×10^{-6}
Critical Group dose due to consumption of wine	6.37×10^{-6}
Critical Group dose due to standing on sludge	6.13×10^{-7}
Total Critical Group dose due to the terrestrial pathway	**2.06×10^{-5}**

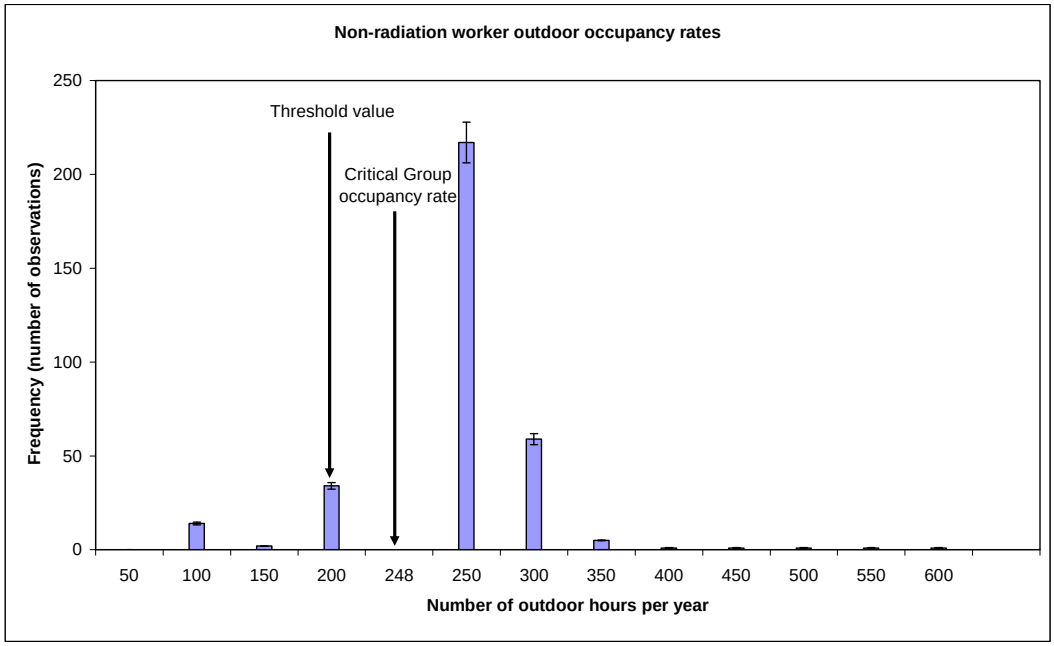

Figure 3.16: Non-radiation worker outdoor occupancy rates.

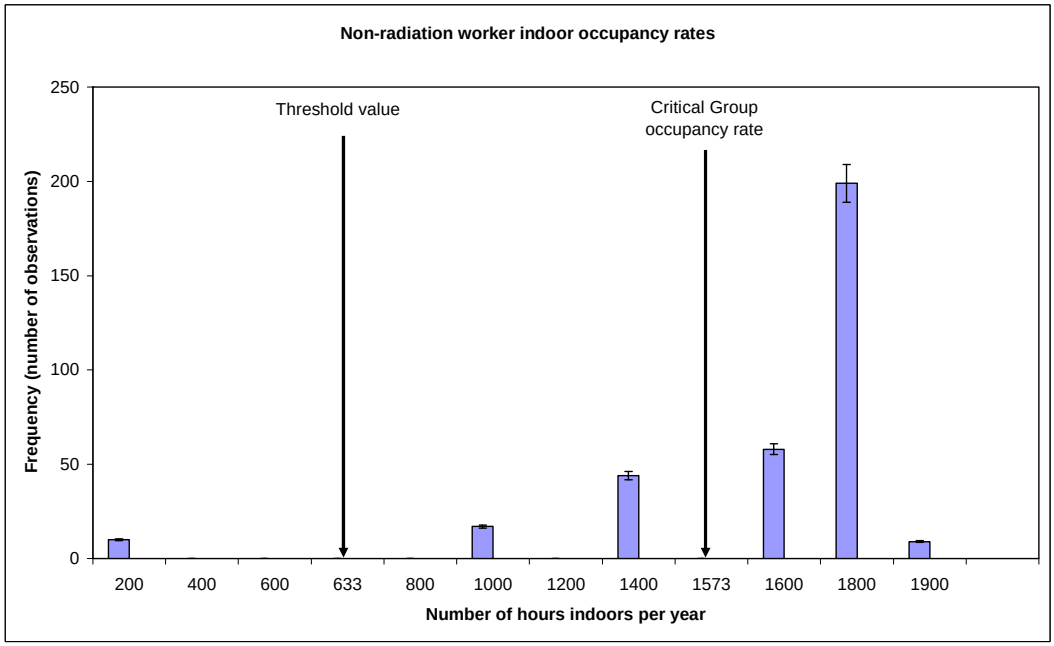

Figure 3.17: Non-radiation worker indoor occupancy rates.



Figure 3.18: Photograph of demarcated area where dose rates were measured.

Table 3.18: Critical Group dose due to direct radiation.

Critical Group outdoor occupancy ($h\,y^{-1}$)	Outdoor dose rate ($Sv\,h^{-1}$)	Critical Group indoor occupancy ($h\,y^{-1}$)	Indoor dose rate ($Sv\,h^{-1}$)	Maximum Critical Group dose ($Sv\,y^{-1}$)
248 ± 12.4	4.46×10^{-8}	1573 ± 78.6	2×10^{-8}	4.47×10^{-5}

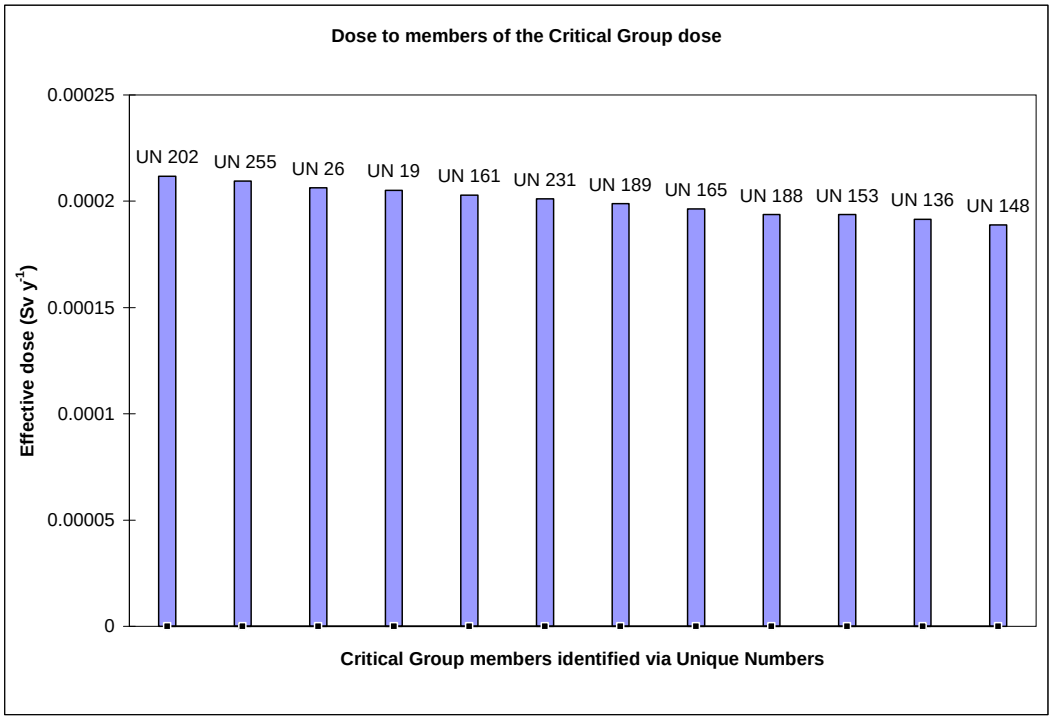

Figure 3.19: Individual effective dose due to combined pathways for members of the Critical Group.

Table 3.19: Individual effective dose for members of the Critical Group due to combined pathways.

Members of the Critical Group Unique identifier number	Effective dose ($Sv\ y^{-1}$)
148	1.89×10^{-4}
136	1.92×10^{-4}
153	1.94×10^{-4}
188	1.94×10^{-4}
165	1.96×10^{-4}
189	1.99×10^{-4}
231	2.01×10^{-4}
161	2.03×10^{-4}
19	2.05×10^{-4}
26	2.06×10^{-4}
255	2.10×10^{-4}
202	2.12×10^{-4}
Critical Group effective dose	**2.00×10^{-4}**

Table 3.20: Critical Group effective dose due to all pathways.

Pathways	Effective dose ($Sv\,y^{-1}$)
Aquatic pathway	1.75×10^{-6}
Terrestrial pathway	2.06×10^{-5}
Direct radiation pathway	4.47×10^{-5}
Combined pathway	2.00×10^{-4}

Table 3.21: Comparison of seafood consumption rates.

Seafood	Average adult consumption rates by Bain derived in 1987. ($kg\,y^{-1}$)	Average adult consumption rates derived via a radiological habit survey during 2007. ($kg\,y^{-1}$)
Fish	50	130 ± 6.5 kg
Crayfish	33	13.29 ± 0.67
Mussels	15.6	32.5 ± 1.6
Abalone	10.4	4 ± 0.2

CHAPTER 4

CONCLUSIONS

The Critical Group of members of the public potentially exposed to radiation from the Koeberg Nuclear Power Station was successfully identified via a radiological habit survey and integrated Retrospective Public Dose Assessments. The Critical Group is comprised of 12 adults who are working in the same environment and they are subjected to the same sources of direct radiation exposure. The Critical Group is homogeneous as the individual doses on members are within a factor of 3 as recommended by the ICRP.

The pathway which contributed primarily to the highest individual exposures was the combined pathway. The main source of exposure to the Critical Group was direct radiation exposure caused mainly by low-energy gamma radiation from Compton scatter interactions due to low and intermediate waste sources of exposure. Dose for the Critical Group was calculated to be 2×10^{-4} Sv y^{-1}. This Critical Group dose was below the legal public dose limit of 10^{-3} Sv y^{-1} and dose constraint of 2.5×10^{-4} Sv y^{-1}.

The Critical Group was successfully identified via refinements to principles, methodologies and techniques developed by international scientists and experts in the field of Retrospective Public Dose Assessments. The pathways and sources of public radiation exposure from the Koeberg Nuclear Power Station site were identified. A radiological habit survey was implemented in accordance with a framework document and questionnaire approved by the National Nuclear Regulator. Information and habit data were collected from 352 adults, including fishermen, mussel collectors, people partaking in water sports and beach sports, farmers and members of the public spending time on the Koeberg Nuclear Power Station site.

Most adults interviewed were members of the public who may have been subjected to radiation exposure due to their eating and recreational habits and their work environment. All consumption rates recorded relates to locally produced or

caught foods. The predominant aquatic foods consumed by the people interviewed are fish, crayfish, white mussels, black mussels and abalone.

The following improvements are recommended for Retrospective Public Dose Assessments relating to the identification of Critical Groups based on the findings of this report:

- It is recommended that Retrospective Public Dose Assessments include assessments of non-radiation workers or members of the public inside the boundaries of authorised facilities where potential exposure to radiation may occur as the direct radiation pathway may be highest on-site and not all workers reside in the radiological habit survey area. This assessment and similar assessments at Devonport, Hinkley Point and Wylfa [HU04] concluded that the direct radiation pathway at nuclear power plants may be the main source of exposure to non-radiation workers inside the boundaries of such facilities. Non-radiation workers or members of the public inside the boundaries of nuclear power plants are generally not included Retrospective Public Dose Assessments.
- Members of the public who may be potentially exposed to radiation from authorised facilities where potential exposure to radiation may occur should be included in a formal radiological or biological dosimetry programme. Members of the Critical Group should be invited to participate in whole-body monitoring programmes as a quality assurance measure and to provide public confidence that activity released into the environment does not have an adverse impact on locally produced foods and public health. Members of Critical Groups are generally not included in formal radiological or biological dosimetry programmes at nuclear power stations. Some of the Critical Group members working on the Koeberg Nuclear Power Station site and who consumed locally harvested terrestrial and/or seafood were invited for internal contamination assessments. No internal contaminations were detected via the Whole-body monitoring process. This exercise resulted in a new quality assurance process to benchmark the effectiveness of radiological control

programmes at the Koeberg Nuclear Power Station to maintain public dose ALARA.

- All on-site and off-site sources of exposure to members of the public must be assessed including radon at the workplaces. Sources of terrestrial radiation due to building materials used for construction of nuclear power plant buildings and roads are generally excluded from Retrospective Public Dose Assessments. Building materials containing natural activity were used for building roads at the Koeberg Nuclear Power Station. These materials increase ambient dose rates and contribute to public dose. However, doses due to sources of terrestrial radiation were not included in this study due to exemption requirements approved by the NNR. The ALARA principle should be applied to limit all natural and man-made sources of radiation including radon to Critical Groups.
- Potential public exposures due to noble gas airborne discharges must be measured in real time during discharges and be included in Retrospective Public Dose Assessments. Composite environmental dose rate measurements are recorded via thermoluminescence dosimeters (TLD) during this study in order to assess ambient dose rates. However, the public dose due to gaseous effluent discharges could not be identified via TLD measurements since terrestrial sources of radiation in the vicinity of TLD locations significantly influenced TLD readings. On-line remote monitoring systems may be employed to measure and trend ambient dose rates in the vicinity of the Koeberg Nuclear Power Station and variations in dose trends should be used to in Public Dose Assessments.
- The Koeberg Nuclear Power Station environmental-surveillance programme must be expanded to include sampling and monitoring of new sources and pathways of exposure which were identified during the radiological habit survey. Applications of potentially contaminated sewage sludge i.e. fertiliser for vegetable gardens and harvesting of local grapes for wine must be included in the Koeberg Environmental Surveillance Programme.

- A pre-operational radiological habit survey should be performed in areas earmarked for new authorised facilities where potential exposure to radiation may occur. The methodology that was developed for radiological habit surveys is currently being applied by Eskom for collection of local habit data at proposed new nuclear power station sites near Thyspunt and Bantamsklip.
- Radiological habit surveys should be performed routinely in the vicinity of authorised practices whenever significant changes occur in source term, demographics and land-use. This survey has revealed that routine radiological habit surveys are a necessity as potential exposure pathways may develop and not be accounted for in Retrospective Public Dose Assessments.
- Data was verified randomly via telephone, three months after collection of the initial information. Data comparisons were performed and overestimations and underestimations were evaluated. The results showed a discrepancy of approximately 5% which confirms results of a similar benchmarking exercise performed by Leonard [LE82]. Verification of radiological habit survey data may be performed by requesting members of the Critical Group to document their diet for a specified period. Detailed information may be obtained on the amounts of food consumed for application in Retrospective Dose Assessments.

In conclusion, this study contains various recommendations for improvements to current Retrospective Dose Assessment methods. All of the issues and recommendations addressed in this study are currently being implemented via the Koeberg Nuclear Power Station Radiation Protection Programme.

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APPENDIX A:

Definitions and glossary

Activity: The quantity A for an amount of radionuclide in a given energy state at a given time, defined as: where dN is the expectation value of the number of spontaneous nuclear transformations from the given energy state in the time interval dt. The SI unit of activity is the reciprocal second (s^{-1}), termed the becquerel (Bq). Formerly expressed in curie (Ci), which is still sometimes used: 1 Ci = 3.7 x 10^{10} Bq

Annual authorised discharge quantity (AADQ): A limit on a measurable quantity, established or formally accepted by a Regulatory Body. Authorised limit has been commonly used particularly in the context of limits on discharges.

ALARA: Acronym for "As low as reasonably achievable". Optimisation is the process of determining the level of ALARA in protection and safety, taking economic and social factors into account.

Assessment: The process, and the result, of analysing systematically the hazards associated with sources and practices, and associated protection and safety measures, aimed at quantifying performance measures for comparison with criteria. Assessment should be distinguished from analysis. Assessment is aimed at providing information that forms the basis of a decision whether something is satisfactory or not. Various kinds of analyses may be used as tools in doing this. Hence an assessment may include a number of analyses.

Background radiation: The dose, dose rate or an observed measure related to the dose or dose rate, attributable to all sources other than the one(s) specified.

Collective dose: An expression for the total radiation dose incurred by a population, defined as the product of the number of individuals exposed to a

source and their average radiation dose. The collective dose is expressed in man-sievert (man -Sv). (See collective effective dose.)

Contamination: Radioactive substances on surfaces, or within solids, liquids or gases where their presence is unintended or undesirable.

Critical Group: A group of members of the public which is reasonably homogeneous with respect to its exposure for a given radiation source and given exposure pathway and is typical of individuals receiving the highest effective dose or equivalent dose (as applicable) by the given exposure pathway from the given source.

Critical pathway: The dominant environmental route by which members of the Critical Group are exposed to radiation. For example, the Critical pathway for iodine discharged with gaseous effluents is from pasture to cows and then to milk. Consumption of the milk by individuals gives rise to exposure to radiation.

Detection limit: Limit at which it can be certain at a predetermined confidence level that a measurement or an analytical procedure will lead to detection. i.e. the true net signal level which may a priori be expected to lead to the detection of activity. The detection limit is also often referred to as the lower limit of detection (LLD).

Discharges: Planned and controlled release of (usually gaseous or liquid) radioactive material to the environment.

Dose: A measure of the energy deposited by radiation in a target. Absorbed dose, committed equivalent dose, committed effective dose, effective dose, equivalent dose or organ dose, depending on the context. All these quantities have the dimensions of energy divided by mass.

Dose limit: The value of the effective dose or the equivalent dose to individuals from controlled practices that shall not be exceeded.

Effective dose: A summation of the tissue equivalent doses, each multiplied by the appropriate tissue weighting factors. The unit of effective dose is $J\,kg^{-1}$, with the special name sievert (Sv).

Effluent: Gaseous or liquid radioactive materials which are discharged to the environment.

Environmental monitoring: The measurement and evaluation of external dose rates due to sources in the environment or of radionuclide concentrations in the environmental media.

Exposure: The act or condition of being subject to irradiation. Exposure can either be external exposure due to sources outside the body or internal exposure due to sources inside the body.

Exposure pathway: A route by which radiation or radionuclides can reach humans and cause exposure. An exposure pathway may be very simple, for example external exposure from airborne radionuclides, or involve a more complex chain, for example internal exposure from drinking milk from cows that ate grass contaminated with deposited radionuclides.

Licence: A legal document issued by the Regulatory Body granting authorization toperform specified activities related to a facility or activity. The holder of a current licence is termed a licensee. A licence is a product of the authorization process, although the term licensing process is sometimes used.

Member of the public: in a general sense, any individual in the population except, for the purposes of the Standards, when subject to occupational or medical

exposure. For the purpose of verifying compliance with the annual dose limit for public exposure, the representative individual in the relevant Critical Group.

Monitoring: The measurement of dose or contamination for reasons related to the assessment or control of exposure to radiation or radioactive substances, and the interpretation of the results.

Naturally occurring radionuclides: Radionuclides that occur naturally in significant quantities on earth. The term is usually used to refer to the primordial radionuclides potassium-40, uranium-235, uranium-238 and thorium-232 (the decay product of primordial uranium-236), their radioactive decay products, and tritium and carbon-14 generated by natural activation processes.

Off-site: Outside the physical boundary of a site.

On-site: Within the physical boundary of a site.

Operation: All the activities performed to achieve the purpose for which a facility was constructed.

Optimisation: The process of determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, 'as low as reasonably achievable, economic and social factors being taken into account' (see ALARA).

Practice: Any human activity that introduces additional sources of exposure or exposure pathways or extends exposure to additional people or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure of people or the number of people exposed.

Public exposure: Exposure incurred by members of the public from radiation sources, excluding any occupational or medical exposure and the normal local

natural background radiation but including exposure from authorized sources and practices and from intervention situations.

Quality control: The part of quality assurance intended to verify that systems and components correspond to predetermined requirements.

Radiological monitoring: Continuous or periodic measurement of radiological and other parameters or determination of the status of a system.

Radiological survey: An evaluation of the radiological conditions and potential hazards associated with the production, use, transfer, release, disposal, or presence of radioactive material or other sources of radiation.

Regulatory Body: An authority or a system of authorities designated by the government of a State as having legal authority for conducting the regulatory process, including issuing authorizations, and thereby for regulating the siting, design, construction, commissioning, operation, closure, decommissioning and, if required, subsequent institutional control of the nuclear facilities

Requirement: A condition defined as necessary to be met by a product, material or process.

Source: Anything that may cause radiation exposure, such as by emitting ionizing radiation or by releasing radioactive substances or materials.

Specific activity: Of a radionuclide, the activity per unit mass of that nuclide. Of a material, the activity per unit mass or volume of the material in which the radionuclides are essentially uniformly distributed.

Storage: The holding of radioactive waste in a facility that provides for its containment. Storage is by definition an interim measure, and the term interim storage is generally used.

Surveillance: Activities performed to ensure that conditions at a nuclear facility remain within the authorized limits.

Waste: Material in gaseous, liquid or solid form for which no further use is foreseen.

APPENDIX B:

Framework document

Report number: RP5.294

Radiological Habits Survey: Pathways and sources near Koeberg Nuclear Power Station

Revision 2

Marc Maree
Generation Nuclear Safety and Assurance

April 2007

APPENDIX C:

Radiological habit survey results.