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|---|---|---|

Title: **A Revised Methodology to Assess the Ionising Radiation Dose for Members of the Public from Normal Operation at the Duynefontyn Site**

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# 1 Introduction

It is a regulatory requirement of the National Nuclear Regulator (NNR) to assess the dose to the public, taking into consideration all the exposure pathways as a result of radioactive discharges and direct radiation from facilities on the Duynefontyn site. Environmental models and habit data of members of the public are used to assess the dose in order to demonstrate compliance with regulatory dose limits and dose constraints as prescribed in the regulations on Safety Standards and Regulatory Practices (SSRP) [1].

The SSRP contains principal radiation protection and nuclear safety requirements further supported by the requirements on risk assessment and compliance with principal safety criteria for nuclear installations [44] and the dose limitation at Koeberg Nuclear Power Station [45].

Before the start of operation of any nuclear facility, when actual radioactive discharge data is not yet known, it is a requirement to conduct a prospective assessment of the radiological impact of a nuclear facility. After a few years of operation, once an operational baseline has been established, it is appropriate and advisable to update the original prospective dose assessment. Periodic retrospective dose assessments can then be done to confirm regulatory requirements, using operational information and experience, measured radioactive discharge data and a more realistic dose assessment methodology than the initial prospective assessment that had to rely on conservative design basis assumptions.

A prospective dose assessment that may be required because of facility design changes or addition of nuclear facilities to the site will also benefit from environmental and habit data of people collected since the commencement of operations on the site, as well as developments in dose assessment methodologies.

# 2 Supporting Clauses

## 2.1 Scope

A public dose assessment methodology for normal operational discharges is described of which an earlier framework document was submitted to the NNR [2]. This document and three other documents form a technical unit that should be read together in the following recommended order:

- Framework on Public Dose Assessment Methodology Normal Operational Discharges at Koeberg Nuclear Power Station [2].
- A Revised Methodology to Assess the Ionising Radiation Dose for Members of the Public from Normal Operation at the Duynefontyn Site (this document).

- Interim Habit Data for the Duynefontyn Site Safety Report Update [3]
- Meteorological Data File Preparation for the PLUME Atmospheric Dispersion Code [4]

### 2.1.1 Purpose

The purpose of this document is threefold:

- to update the methodology for Koeberg Nuclear Power Station (KNPS) retrospective dose assessments;
- to present the methodology for assessing prospective dose
- to propose revised dose conversion factors (DCF) for KNPS.

### 2.1.2 Applicability

This document shall apply to the calculation of radiation dose of members of the public from normal operation of nuclear installations at the Eskom Duynefontyn site.

### 2.1.3 Effective date

This document is effective from the date of authorisation.

## 2.2 Normative/Informative References

### 2.2.1 Normative

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### 2.2.2 Informative

N/A

### 2.3 Definitions

1.1.1 **Atmospheric Dispersion Factor, X/Q:** X/Q, also referred to in the literature as the relative atmospheric concentration, has the unit of s/m$^3$ as derived from radioactivity concentration represented by X, the Greek capital letter Chi, in units of Bq/m$^3$ at a specific location, divided by the radioactivity release rate from a source and represented by Q in units of Bq/s.

1.1.2 **Atmospheric Stability:** Atmospheric stability is a relative indicator of the potential diffusion of pollutants released into the ambient air. In this study, atmospheric stability is based on the delta temperature (ΔT). The method classifies stability based on the temperature change with height (i.e., the difference in °C per 100 metres), also referred to as the vertical temperature difference. It is the measured difference in an ambient temperature between two elevations at the Koeberg weather station. It is defined as the upper-level temperature measurement minus the lower temperature measurement.

1.1.3 **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.

1.1.4 **Dose Assessment – Prospective:** Assessment of expected dose to a representative person hypothetically located at the public exclusion boundary/site boundary and considering all exposure pathways using realistic assumptions.

1.1.5 **Discharge:** A ‘discharge’ is a planned and controlled release of gaseous, aerosol, or liquid radioactive substances to the environment and, as such, the term does not include releases to the environment in an accident.

1.1.6 **Dose Assessment – Retrospective:** Dose assessment for the representative person based on actual measured discharge data and habit data for a representative person, with limited assumptions for exposure pathways.

1.1.7 **Gaussian Plume Model:** A basic atmospheric dispersion model that assumes that the plume spread has a Gaussian distribution in both the horizontal and vertical directions and therefore uses the standard deviations of plume concentration distribution in the horizontal ($\sigma y$) and vertical ($\sigma z$) planes.

1.1.8 **Nuclides:** Abbreviation for radionuclides as is used in this document.

1.1.9 **Potential Impact Area:** It is the surrounding area of the Duynefontyn site where dose to the public and non-human biota is expected to be non-trivial, e.g., public annual dose greater than 1 µSv/yr and non-human dose above the screening dose rate of 10 µGy/h.

**1.1.10 Principal nuclide:** A principal nuclide is any radionuclide whose concentration exceeds 1% of the total discharge (airborne or liquid) or annual does to the representative person. Revision 2 of RG 1.21 defines a principal radionuclide as one that: contributes either (i) greater than 1 per cent of design objective dose for all radionuclides in the type of discharge being considered, or (ii) greater than 1 per cent of the activity of all radionuclides in the type of discharge being considered [6].

**1.1.11 Representative Person:** An individual receiving a dose that is representative of the more highly exposed individuals in the population. This term is the equivalent of, and replaces the term, “average member of the critical group”. The representative person is defined for radiation protection purposes. The representative person will generally be a hypothetical construct and not an actual member of the population. Similar methods can be used for assessing doses to the representative person as have been used previously for assessing doses to the critical group [5].

**1.1.12 Source Term:** The amount and isotopic composition of radioactive material discharged from Duynefontyn during normal operations and used in modelling dispersion in the environment and estimating public dose.

**1.1.13 Validation:** The evidence that demonstrates that the calculation method is fit for its purpose. When calculating physical processes, it may mean showing that the calculation is bounding with a suitable degree of confidence rather than the best estimate.

**1.1.14 Verification:** The process of ensuring that the controlling physical equations have been correctly translated into software coding, or in the case of hand calculations, correctly incorporated into the calculation procedure.

**1.1.15 Wind Direction:** The direction from which the wind is blowing. Wind direction is reported in degrees azimuth, measured clockwise from true north, and ranging from 0 degrees to 360 degrees (e.g., north is 0 degrees or 360 degrees, east is 90 degrees, etc.).

**1.1.16 Wind Direction Sector:** There are 16 wind direction sectors centered at the KNPS, each 22.5 degrees into which the wind directions are classified.

**1.1.17 X/Q:** See Atmospheric Dispersion Factor.

## 2.4 Abbreviations

| Abbreviation | Explanation |
|---|---|
| AADQ | Annual Authorised Discharge Quantity |
| AMM | Activity Migration Model |
| DCF | Dose Conversion Factor |
| Eskom | Eskom Holdings SOC Ltd, its divisions and wholly owned subsidiaries. |
| ESL | Environmental Survey Laboratory |
| GWe-yr | Giga-Watt electric – year |

| Abbreviation | Explanation |
|---|---|
| HTM | Hard-to-measure |
| IAEA | International Atomic Energy Agency |
| ICRP | International Commission Radiological Protection |
| IRP | Interim Representative Person |
| KNPS | Koeberg Nuclear Power Station |
| LTO | Long-Term Operation |
| MDA | Minimum Detectable Activity |
| MWth. | Megawatt thermal |
| NNR | National Nuclear Regulator |
| NPP | Nuclear Power Plant |
| OBT | Organically Bound Tritium |
| OCB | Owner Control Boundary |
| PIA | Potential Impact Area (in respect of radioactive discharges) |
| TISF | Transient Interim Storage Facility |
| TEG | Gaseous Waste Treatment System (KNPS) |
| VER | Volume Exchange Rate (DORIS) |
| V&V | Verification and Validation |

# 3 Overview of the Dose Assessment Methodology and Structure of the Document

The PC-CREAM 08 radiological impact assessment software is the primary tool used to model the environmental transfer and calculate dose to the representative person [7]. It is a Windows-based software application that utilises the “Consequences of Releases to the Environment Assessment Methodology” (CREAM). Appendix 1 provides an overview of PC-CREAM 08 and its interlinked support models. A deterministic dose assessment approach is followed that involves the direct multiplication of selected point values of parameters and environmental concentrations. Input data are mainly conservative values to allow for inherent uncertainties of important input parameters.

The retrospective dose calculated for the representative person at Duynefontyn during quarterly and annual reporting periods for KNPS is based on actual nuclide discharges measured during the reporting period. Habit data representative of the Duynefontyn site is considered, as well as the KNPS power generating history and the Duynefontyn environmental dispersion conditions that existed during the reporting period.

The revised methodology is based on the ICRP Publications 101 and 103 ([7] and [9]). It includes important changes since the dose assessment methodology that is part of the current KNPS Activity Migration Model (AMM) was developed, e.g., an update of the source term, environmental transfer parameters, bio-concentration factors, environmental build-up of radioactivity, and public habit data.

The dose calculation methodology consists of the following supporting information and methodologies:

- radionuclide selection and source terms based on:
  - KNPS normal operational discharges that are measured and reported to the NNR;
  - derived source terms for those nuclides not measured and hard-to-detect but potentially important contributors to public dose; and
  - nuclides that have not been included in dose assessments to date.
- atmospheric dispersion and meteorological data preparation for the PC CREAM_PLUME Model [4];
- an evaluation of soil characteristics in the Duynefontyn regional environment and selection of the appropriate input for use in PC CREAM_GRANIS and terrestrial transfer factors;
- dispersion of liquid discharges to the sea and bioconcentration and sediment distribution factors for use in PC CREAM_DORIS;
- consideration of short-term or batch discharges;
- build-up of radionuclides in the environment;
- exposure pathways; and
- habit data and defining a representative person [3].

# 4 Radionuclide Selection and Source Terms

## 4.1 Koeberg Nuclear Power Station Source Terms for Assessing Normal Operational Discharges

The following characteristics of nuclides were considered to identify those that could be important in respect of public dose:

- half-life and inclusion of progeny;
- environmental transfer and biota concentration factors; and
- environmental accumulation (build-up) over the lifetime of KNPS that includes a long-term operation (LTO) to 60 years.

Each nuclide's contribution to public dose per unit activity, should it be present in the discharges to the environment, can be expressed as its dose conversion factor (DCF). The calculation of the DCFs is discussed in § 12A total eighty-eight (88) nuclides have been selected. The nuclides and their DCFs are included in Appendix 2. The selection includes the sixty-eight (68) nuclides that form the basis for the current Annual Authorised Discharge Quantities (AADQ) of KNPS and which are included in the Eskom Standard 238-49 [10].

The nuclide selection includes C-14 that has previously not been part of dose assessments. C-14 is defined as a principal nuclide, and its source term is discussed in § 4.1.1 . The nuclide selection includes nuclides that are referred to as hard-to-measure (HTM) in the nuclear industry [11]. Two specific HTM nuclides, Ni-63 and Fe-55 are potential principal nuclides and are discussed in § 4.1.2 .

### 4.1.1 Carbon-14

The C-14 present in the earth's atmosphere has two main sources: one of natural origin and one anthropogenic. C-14 has been part of the earth's atmosphere long before humans arrived on the scene. It is produced in the upper atmosphere by the irradiation of N-14 by neutrons of cosmic ray origin. The second C-14 source is from nuclear power plants (NPP). It enters the natural environmental cycle and is added to the naturally occurring C-14, and mixes with the stable carbon to become part of the food chain resulting in additional dose to biota and humans alike [12].

C-14 is present in virtually all parts of the nuclear reactor primary system and has a high production rate during nuclear reactor operation. It is released to the environment through gaseous and liquid discharges as well as through the disposal of solid radioactive waste. The production of C-14 in the reactor coolant through the neutron-alpha reaction of the O-17 isotope, O-17 (n, 4He) C-14, is almost entirely responsible for the C-14 discharges to the environment. C-14 is mainly released as a gaseous discharge through the stack. This is supported by comprehensive studies in the nuclear industry and includes a study to characterise C-14 in Swedish light water reactors [13].

KNPS intends to measure C-14 discharges to the environment, but at the time of compiling this document, the system was not yet fully operational. However, C-14 discharges can be estimated using the power history of an NPP and derived scaling factors based on an Electric Power Research Institute (EPRI) study [14]. A summary of the methodology for estimating the C-14 discharges is illustrated in Figure 4-1.

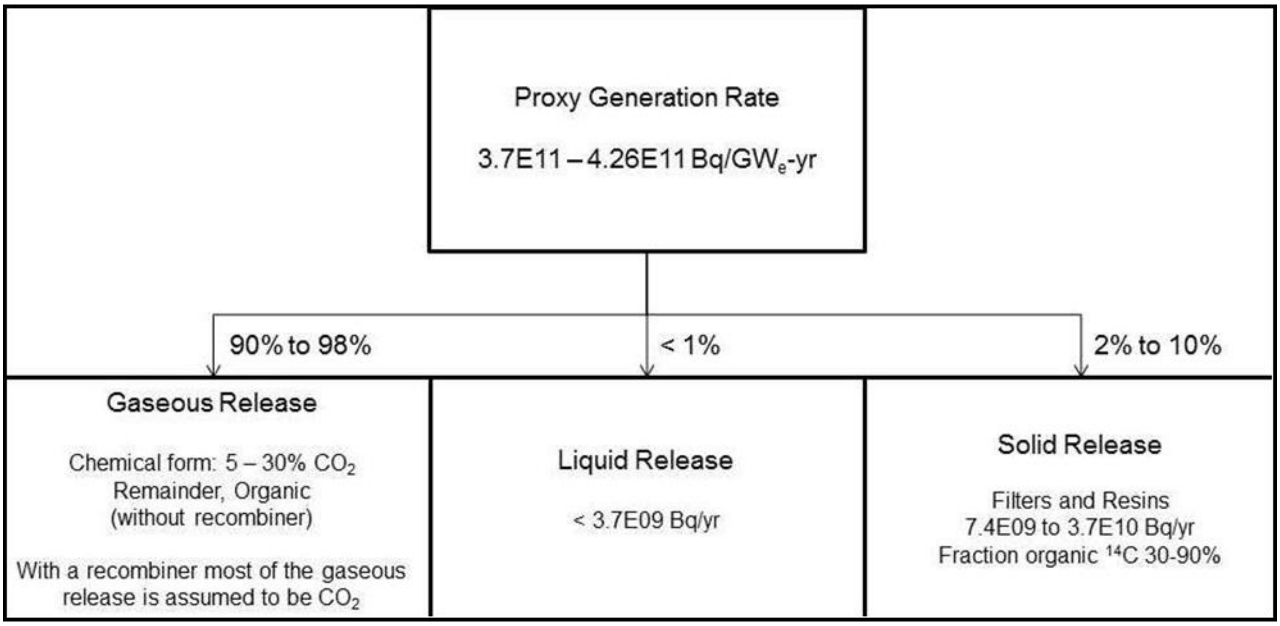


**Figure 4-1:** C-14 Source Terms as a Function of Power Generation [14]

The two proxy generation rates of 3.7E11 Bq/GWe-y and 4.26E11 Bq/GWe-y are for Westinghouse and Combustion Engineering type PWR reactors respectively.

A KNPS-specific calculation for C-14 can be conducted according to the guidance provided in [13]. The uncertainty in a proxy value based on values in Figure 4-1 is reported as ±15%. Figure 4-1 includes reference to 'recombiners'. In the KNPS SAR, it is noted that the TEG charcoal filter beds and the associated recombiners have never been used and cannot be assumed to be available immediately [15]. The gross electrical power generation history for KNPS for the period 2015 to 2019 is shown in Table 4-1 [16].

**Table 4-1:** KNPS electrical power history 2015 to 2019

| Month | 2015 GWe.hr | | 2016 GWe.hr | | 2017 GWe.hr | | 2018 GWe.hr | | 2019 GWe.hr | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Unit 1 | Unit 2 | Unit 1 | Unit 2 | Unit 1 | Unit 2 | Unit 1 | Unit 2 | Unit 1 | Unit 2 |
| JAN | 7.21E+02 | 7.21E+02 | 7.21E+02 | 7.21E+02 | 7.16E+02 | 7.22E+02 | 4.36E+02 | 7.22E+02 | 7.14E+02 | 7.17E+02 |
| FEB | 8.60E+00 | 6.48E+02 | 6.74E+02 | 6.75E+02 | 6.48E+02 | 6.34E+02 | 5.62E+02 | 6.52E+02 | 6.45E+02 | 6.48E+02 |
| MAR | 0.00E+00 | 7.22E+02 | 7.22E+02 | 7.22E+02 | 7.21E+02 | 5.86E+02 | 0.00E+00 | 7.22E+02 | 7.14E+02 | 7.17E+02 |
| APR | 0.00E+00 | 6.83E+02 | 6.95E+02 | 6.98E+02 | 6.96E+02 | 2.59E+02 | 0.00E+00 | 6.98E+02 | 6.91E+02 | 6.97E+02 |
| MAY | 0.00E+00 | 7.22E+02 | 7.22E+02 | 7.22E+02 | 7.16E+02 | 1.15E+02 | 0.00E+00 | 6.40E+02 | 4.53E+02 | 7.18E+02 |
| JUN | 5.63E+02 | 6.98E+02 | 6.98E+02 | 6.98E+02 | 6.94E+02 | 6.92E+02 | 1.59E+02 | 6.98E+02 | 6.91E+02 | 6.95E+02 |
| JUL | 7.22E+02 | 7.07E+02 | 7.22E+02 | 7.22E+02 | 7.17E+02 | 7.22E+02 | 6.85E+02 | 6.80E+02 | 7.14E+02 | 6.91E+02 |
| AUG | 7.22E+02 | 5.77E+02 | 7.18E+02 | 7.22E+02 | 7.18E+02 | 7.22E+02 | 6.98E+02 | 5.86E+02 | 7.14E+02 | 7.18E+02 |
| SEP | 6.98E+02 | 0.00E+00 | 3.90E+02 | 6.98E+02 | 6.96E+02 | 6.98E+02 | 6.77E+02 | 2.80E+02 | 4.38E+02 | 6.98E+02 |

An example to derive the KNPS C-14 annual source term is illustrated in Table 4-2

**Table 4-2:** An estimate of KNPS C-14 discharges

| KNPS $GW_e$-yr in 2015 | Reference Reactor Type | $Bq/GW_e.yr$ | KNPS Total C-14 Bq for 2015 | Airborne Discharge: KNPS Total Bq for 2015 ($^{14}CO_2$ at 30%) | Liquid Discharge: KNPS Total Bq for 2015 ($^{14}CO_2$ at <1% or <0.1Ci/yr (3.7E9 Bq/yr) | |
|---|---|---|---|---|---|---|
| 1.31E+00 | Westinghouse PWR | 3.70E+11 | 4.84E+11 | 1.42E+11 | 1.42E+09 | < 3.70E+09 |
| | CE PWR | 4.26E+11 | 5.57E+11 | 1.64E+11 | 1.64E+09 | |

The C-14 source term can also be estimated based on operational experience reported by EDF for NPPs similar to KNPS [17]. KNPS has opted to use the EDF formulae of [18]:

- 15 GBq/GWe.y for liquid; and
- 200 GBq/GWe.y for gases

**Table 4-3:** KNPS C-14 discharges derived from EDF operational experience

| KNPS Annual Power | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|
| $GW_e$.yr | 1.31 | 1.82 | 1.80 | 1.27 | 1.62 |
| C-14 liquid discharge, Bq/yr | 1.97E+10 | 2.73E+10 | 2.70E+10 | 1.90E+10 | 2.43E+10 |
| C-14 airborne discharge, Bq/yr | 2.62E+11 | 3.63E+11 | 3.59E+11 | 2.53E+11 | 3.24E+11 |

### 4.1.2 Hard-to-Measure Nuclides

Research conducted by EPRI on HTM nuclides indicated that they might be important for off-site dose calculations [19]. The EPRI research concluded that the nuclides typically analysed for inclusion in the United States (U.S.) nuclear power plant discharge reports by a majority of the pressurised water reactors (PWRs), could account for about 70% of the offsite dose from any pathway, not including H-3, C-14, and noble gases. Some of the main conclusions reached are the following:

a. Based on the research conducted to date, it is seen that the nuclides typically analysed for inclusion in the U.S. nuclear power plant discharge reports can account for at least 66% of the offsite dose. This is applicable for at least 25% of the PWRs and from any pathway from mixed fission and activation products analysed as part of the research. This percentage includes the contribution of the following HTMs typically analysed for:

- Fe-55;
- Ni-63;
- Sr-89; and
- Sr-90.

This percentage does not include the dose contributions from C-14, H-3, and noble gases. It should be noted that C-14, H-3, and noble gases constitute most doses to the public due to nuclear power plants' discharges.

b. The research found six more 'not-typically' HTMs that individually contribute more than 0.1% of the dose from mixed fission and activation radionuclides analysed for (HTM and non-HTM, but not including carbon-14, tritium, or nobles gases), namely:

- P-32, Y-90, Y-91, Sn-123, Te-127m, and Pr-143.

The total mixed fission and activation product dose contribution by these six radionuclides ranges between 0.7% for the submersion/inhalation pathway to 5.5% for the ingestion pathway at a saltwater site that was included in this analysis. The dose contribution by the remaining non-analysed HTMs is minimal, amounting to no more than 0.24% of the mixed activation product doses that were included in this analysis.

c. These nuclides are included in the selected list of nuclides for KNPS in Appendix 2. The two nuclides considered the most important in terms of KNPS discharges are Ni-63 and Fe-55. Scaling factors to determine their discharge quantities in relation to Co-60 measured in discharges were used, as follows [18]:

- Ni-63 = 3.6 × Co-60
- Fe-55 = 2.9 × Co-60

### 4.1.3 Source Terms used in KNPS Dose Assessments

The annual retrospective dose assessment is based on radionuclides measured in discharges (airborne and liquid), and in future will include discharge activities for C-14, Fe-55, and Ni-63 when measured data are not available.

Improved management of KNPS discharges has resulted in a significant decrease in measured discharges in recent years. This can be seen when comparing discharges during the early operational period of 1984 to 2003, which included leaking nuclear fuel elements, with those during 2015 to 2019 shown in Table 4-4 and Table 4-5 [20].

**Table 4-4:** Annual liquid discharges for two different operational periods

| Annual Liquid Discharges 1984 – 2003 | | | Annual Liquid Discharges 2015 – 2019 (Derived Values of C-14, Ni-63 and Fe-55 included) | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Nuclide** | **Average activity over the period, Bq/yr** | **Maximum activity over the period, Bq/yr** | **2015 Bq/yr** | **2016 Bq/yr** | **2017 Bq/yr** | **2018 Bq/yr** | **2019 Bq/yr** | **Maximum activity for the period, Bq/yr** |
| Ag-110m | 1.16E+09 | 2.51E+09 | 3.84E+08 | 1.06E+08 | 9.02E+07 | 5.74E+08 | 1.11E+08 | 5.74E+08 |
| Ce-141 | NR(1) | NR | NR | 1.72E+05 | ND | ND | ND | 1.72E+05 |
| Ce-144 | NR | NR | NR | NR | NR | NR | 9.85E+05 | 9.85E+05 |
| Ba-140 | 4.06E+07 | 5.84E+07 | NR | NR | NR | NR | NR | NR |
| Be-7 | 6.38E+07 | 3.15E+08 | NR | NR | NR | NR | NR | NR |
| C-14 | NR | NR | 1.97E+10(2) | 2.73E+10(2) | 2.70E+10(2) | 1.90E+10(2) | 2.43E+10(2) | 2.73E+10 |
| Co-57 | 3.35E+07 | 1.56E+08 | 3.24E+06 | 2.15E+06 | 1.13E+07 | 9.92E+06 | 3.25E+06 | 1.13E+07 |
| Co-58 | 1.06E+10 | 5.33E+10 | 1.70E+09 | 7.30E+08 | 2.88E+09 | 5.68E+09 | 8.60E+08 | 5.68E+09 |
| Co-60 | 3.89E+09 | 1.88E+10 | 5.31E+08 | 1.73E+08 | 3.40E+08 | 8.08E+08 | 3.63E+08 | 8.08E+08 |
| Cr-51 | 2.36E+08 | 1.13E+09 | 8.91E+07 | 4.41E+06 | 3.31E+07 | 2.91+08 | 4.030+06 | 8.91E+07 |

| Annual Liquid Discharges 1984 – 2003 | | | Annual Liquid Discharges 2015 – 2019 (Derived Values of C-14, Ni-63 and Fe-55 included) | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Nuclide** | **Average activity over the period, Bq/yr** | **Maximum activity over the period, Bq/yr** | **2015 Bq/yr** | **2016 Bq/yr** | **2017 Bq/yr** | **2018 Bq/yr** | **2019 Bq/yr** | **Maximum activity for the period, Bq/yr** |
| Ni-63 | NR | NR | 1.91E+09 | 6.23E+08 | 1.22E+09 | 2.91E+09 | 1.31E+09 | 2.91E+09 |
| Cs-134 | 6.35E+09 | 3.00E+10 | NR | NR | NR | 7.71E+04 | N.R. | 7.71E+04 |
| Cs-136 | 2.85E+07 | 1.58E+08 | NR | NR | NR | NR | NR | NR |
| Cs-137 | 1.07E+10 | 4.49E+10 | 2.31E+07 | 1.44E+07 | 2.34E+06 | 2.21E+07 | 1.62E+07 | 2.31E+07 |
| Cs-138 | 2.16E+06 | 2.16E+06 | NR | NR | NR | NR | NR | NR |
| Fe-55 | NR | NR | 1.54E+09 | 5.02E+08 | 9.86E+08 | 2.34E+09 | 1.05E+09 | 2.34E+09 |
| Fe-59 | 1.76E+07 | 5.25E+07 | 1.89E+06 | NR | NR | 7.82E+05 | NR | 1.89E+06 |
| H-3 | 2.86E+13 | 9.10E+13 | 1.82E+13 | 2.99E+13 | 3.33E+13 | 2.51E+13 | 2.72E+13 | 3.33E+13 |
| I-131 | 5.37E+08 | 3.90E+09 | ND | ND | ND | 1.92E+07 | 2.38E+05 | 1.92E+07 |
| I-132 | 4.59E+05 | 4.59E+05 | NR | NR | NR | NR | NR | NR |
| I-133 | 2.24E+08 | 1.86E+09 | NR | NR | NR | NR | NR | NR |
| I-135 | 5.31E+07 | 1.20E+08 | NR | NR | NR | NR | NR | NR |
| La-140 | 1.80E+07 | 1.57E+08 | NR | NR | NR | NR | NR | NR |
| Mn-54 | 4.32E+08 | 1.63E+09 | 2.57E+07 | 1.05E+07 | 1.80E+07 | 5.86E+07 | 1.01E+07 | 5.86E+07 |
| Mn-56 | 2.03E+05 | 3.83E+05 | 7.64E+04 | NR | NR | NR | NR | 7.64E+04 |
| Mo-99 | 2.12E+07 | 1.34E+08 | NR | NR | NR | NR | NR | NR |
| Na-24 | 8.04E+07 | 5.43E+08 | 4.40E+04 | NR | NR | 1.06E+06 | 2.98E+06 | 2.98E+06 |
| Nb-94 | NR | NR | NR | 9.67E+04 | NR | NR | NR | 9.67E+04 |
| Nb-95 | 2.76E+07 | 1.07E+08 | 2.20E+07 | 6.24E+06 | 1.23E+07 | 3.54E+06 | 2.14E+06 | 2.20E+07 |
| Rh-105 | NR | NR | 7.82E+05 | NR | NR | 9.78E+05 | NR | 9.78E+05 |
| Nd-147 | 2.24E+06 | 5.46E+06 | NR | NR | NR | NR | NR | NR |
| Ru-103 | 7.42E+06 | 2.19E+07 | NR | NR | NR | NR | NR | NR |
| Rb-88 | 5.96E+06 | 1.62E+07 | NR | NR | NR | NR | NR | NR |
| Nd-147 | NR | NR | NR | NR | NR | NR | 3.37E+05 | 3.37E+05 |
| Sb-122 | 4.59E+07 | 3.64E+08 | 7.83E+04 | NR | NR | 5.57E+05 | NR | 5.57E+05 |
| Sb-124 | 4.06E+08 | 2.26E+09 | 2,99E+07 | 1.89E+07 | 1.43E+07 | 6.40E+07 | 3.70E+07 | 6.40E+07 |
| Sb-125 | 1.16E+08 | 5.18E+08 | NR | NR | NR | NR | NR | 5.68E+05 |
| Te-123m | NR | NR | 9.01E+06 | 3.42E+06 | 1.78E+06 | 1.74E+06 | 3.93E+06 | 9.01E+06 |
| Sn-113 | 1.24E+06 | 1.24E+06 | NR | NR | NR | NR | NR | NR |
| Sr-89 | 5.50E+06 | 1.07E+07 | NR | NR | NR | NR | NR | NR |
| Sr-90 | 1.15E+07 | 5.34E+07 | NR | NR | NR | NR | NR | NR |
| Tc-99m | 5.86E+07 | 2.81E+08 | NR | NR | NR | NR | NR | NR |
| Zn-65 | 1.50E+07 | 7.19E+07 | 5.84E+05 | 9.54E+04 | 2.45E+06 | 7.63E+06 | 4.05E+05 | 7.63E+06 |

| Annual Liquid Discharges 1984 – 2003 | | | Annual Liquid Discharges 2015 – 2019 (Derived Values of C-14, Ni-63 and Fe-55 included) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Nuclide | Average activity over the period, Bq/yr | Maximum activity over the period, Bq/yr | 2015 Bq/yr | 2016 Bq/yr | 2017 Bq/yr | 2018 Bq/yr | 2019 Bq/yr | Maximum activity for the period, Bq/yr |
| Zr-95 | 1.41E+07 | 4.96E+07 | 1.31E+07 | 1.31E+06 | 4.52E+06 | 1.91E+06 | 4.87E+05 | 1.31E+07 |
| Sb-125 | 1.16E+08 | 5.18E+08 | NR | NR | NR | NR | NR | 5.68E+05 |

(1) : NR = Nuclide activity not detected/reported.
(2) : The activities were not reported and calculated for this report.

**Table 4-5:** Annual airborne discharges for two different operational periods

| Annual Airborne Discharges 1984 – 2003 | | | Annual Airborne Discharges 2015 – 2019 (Derived Values of C-14, Ni-63 and Fe-55 included) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Nuclide | Average activity over the period, Bq/yr | Maximum activity over the period, Bq/yr | 2015 Bq/yr | 2016 Bq/yr | 2017 Bq/yr | 2018 Bq/yr | 2019 Bq/yr | Maximum activity, Bq/yr |
| Ag-110m | 8.06E+05 | 1.05E+06 | NR | NR | NR | NR | 3.42E+05 | 3.42E+05 |
| Ar-41 | 3.20E+12 | 3.87E+13 | 8.83E+10 | 1.18E+11 | 1.05E+11 | 9.93E+10 | 8.20E+10 | 1.18E+11 |
| C-14 | NR | NR | 2.62E+11(2) | 3.63E+11(2) | 3.59E+11(2) | 2.53E+11(2) | 3.24E+11(2) | 3.63E+11(2) |
| Co-58 | 1.80E+06 | 6.43E+06 | 4.80E+05 | 4.50E+05 | NR | 2.88E+06 | 6.59E+06 | 6.59E+06 |
| Co-60 | 1.80E+06 | 4.42E+06 | NR | 4.92E+04 | NR | NR | 1.39E+06 | 1.39E+06 |
| Ni-63 | NR | NR | NR(3) | 1.77E+05 | NR(3) | NR(3) | 5.01E+06 | 5.01E+06 |
| Cs-134 | 6.44E+06 | 1.18E+07 | NR | NR | NR | NR | NR | NR |
| Cs-137 | 3.58E+06 | 1.94E+07 | NR | 2.13E+05 | NR | 8.60E+04 | NR | 2.13E+05 |
| Fe-55 | NR | NR | NR(3) | 1.43E+05 | NR(3) | NR(3) | 4.04E+06 | 4.04E+06 |
| Fe-59 | 1.07E+06 | 1.07E+06 | NR | NR | NR | NR | NR | NR |
| H-3 | 7.69E+12 | 1.74E+13 | 2.23E+12 | 4.56E+12 | 1.58E+13 | 5.26E+12 | 1.01E+13 | 1.58E+13 |
| I-131 | 7.22E+08 | 2.62E+09 | 2.09E+08 | 1.67E+08 | 1.64E+08 | 2.77E+08 | 1.93E+08 | 2.77E+08 |
| I-132 | 1.86E+09 | 1.24E+10 | 2.45E+08 | 2.86E+08 | 1.67E+08 | 2.45E+08 | 3.05E+08 | 3.05E+08 |
| I-133 | 1.54E+09 | 7.86E+09 | 1.82E+08 | 2.30E+08 | 5.13E+08 | 3.57E+08 | 3.40E+08 | 5.13E+08 |
| I-134 | 2.41E+09 | 1.83E+10 | 3.55E+08 | 4.14E+08 | 2.35E+08 | 3.48E+08 | 4.52E+08 | 4.52E+08 |
| I-135 | 1.97E+09 | 1.15E+10 | 2.95E+08 | 3.17E+08 | 2.03E+08 | 2.88E+08 | 3.51E+08 | 3.51E+08 |
| Kr-85 | 2.63E+12 | 1.01E+13 | 6.52E+11 | NR | NR | NR | 5.28E+10 | 6.52E+11 |
| Kr-85m | 9.82E+11 | 5.75E+12 | 2.66E+08 | 8.54E+06 | 4.32E+06 | 1.43E+07 | 3.23E+07 | 2.66E+08 |
| Kr-87 | 9.38E+11 | 5.53E+12 | 2.33E+07 | NR | NR | NR | NR | 2.33E+07 |
| Kr-88 | 1.59E+12 | 9.51E+12 | 2.66E+08 | NR | NR | NR | 1.27E+07 | 2.66E+08 |
| Mn-54 | 6.04E+05 | 6.04E+05 | NR | NR | NR | NR | NR | NR |
| Na-24 | 5.21E+04 | 6.44E+04 | NR | NR | NR | NR | NR | NR |

| Annual Airborne Discharges 1984 – 2003 | | | Annual Airborne Discharges 2015 – 2019 (Derived Values of C-14, Ni-63 and Fe-55 included) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Nuclide | Average activity over the period, Bq/yr | Maximum activity over the period, Bq/yr | 2015 Bq/yr | 2016 Bq/yr | 2017 Bq/yr | 2018 Bq/yr | 2019 Bq/yr | Maximum activity, Bq/yr |
| Tc-99m | 4.18E+08 | 1.81E+09 | NR | NR | NR | NR | NR | NR |
| Sr-90 | 2.14E+05 | 2.14E+05 | N.R. | 1.98E+04 | NR | NR | NR | 1.98E+04 |
| Xe-131m | 4.99E+11 | 5.14E+12 | 1.07E+08 | NR | NR | 4.31E+07 | 1.29E+10 | 1.29E+10 |
| Xe-133 | 4.08E+13 | 2.30E+14 | 6.18E+10 | 7.21E+09 | 1.17E+10 | 2.66E+10 | 1.29E+12 | 1.29E+12 |
| Xe-133m | 4.89E+11 | 2.83E+12 | 6.02E+08 | 9.61E+07 | 5.68E+07 | 2.91E+08 | 2.62E+09 | 2.62E+09 |
| Xe-135 | 6.09E+12 | 3.91E+13 | 6.62E+09 | 8.54E+08 | 3.84E+08 | 1.64E+09 | 8.98E+08 | 6.62E+09 |
| Xe-135m | 2.16E+12 | 8.78E+12 | NR | NR | NR | NR | NR | NR |
| Xe-138 | 1.04E+12 | 4.48E+12 | NR | NR | NR | NR | NR | NR |

(1) : NR = Nuclide activity not detected/reported.
(2) : The activities were not reported and derived using the EDF method for this report.
(3) Activities could not be derived since Co-60 not reported.

## 4.2 Direct External Radiation from KNPS

Direct radiation from the nuclear installation(s) can potentially contribute to the public dose. The source terms, in this case, are the buildings housing the reactor core and stored irradiated fuel. These source terms of direct radiation make a negligible contribution to annual dose based on monitoring results of the ESL surveillance programme.

Two sets of thermoluminescent dosimeters (TLDs) are employed for direct radiation monitoring [20]. Twenty-nine (29) TLDs are in three roughly concentric rings, which are replaced every month:

- the inner perimeter fence (IPF): 0.6 km to 1 km;
- the public exclusion boundary (PEB): 1.5 km to 2.9 km;
- rural areas: 3.3 km to 10.5 km from Koeberg.

Most of these TLDs are strategically located such that there is at least one in each of the 16 geographical sectors. Nineteen (19) TLDs are located further afield and are replaced every three months at the following localities:

- urban areas such as Mamre, Atlantis, Table View, Milnerton, Durbanville, Epping, Pinelands, Woodstock, Sea Point, and Robben Island; and
- the rest of the TLDs are located on farms.

The direct radiation from the Duynefontyn nuclear installation(s) at the Owner Controlled Boundary (OCB) is not distinguishable from the natural background radiation. Some areas in the public domain and at a greater distance than the OCB show higher values. This is as a result of variations in terrestrial radiation associated with naturally occurring radioactivity in the underlying geological strata.

### 4.3 Future Nuclear Facilities on the Duynefontyn Site

Eskom intends to construct a transient interim storage facility TISF for the temporary storage of up to 160 dry casks. The TISF footprint is also planned to house the Old Steam Generators. The licensing safety case will provide information on public exposure and whether there will be any additional dose from the TISF to members of the public. The TISF will be located north of KNPS, and no additional radiation to areas outside the OCB is expected. The KNPS environmental monitoring programme will include the TISF.

The Duynefontyn Site Safety Report includes a prospective screening assessment of the public dose for proposed new nuclear power plants [21]. Source terms were derived from the data provided for two reference reactor types, AP1000 and EPR. It was shown that the NNR dose limits for the site would be met. The annual dose reports during actual operation for any new plants will follow the same dose assessment methodology as for KNPS. Distinct discharge points will be included in the environmental dispersion models, and the cumulative dose to the representative person from all discharges and sources on the Duynefontyn site will be calculated.

The site-specific input data to calculate DCFs for KNPS should be bounding in respect of any proposed new nuclear facilities until such time that annual ESL land-use surveys indicate a significant change in land use and the habit data. The DCFs calculated for design basis assessment purposes and discussed in §12 are conservative. They can be used to assess the proposed new build of 4500 MWe source terms against NNR dose constraint criteria for the Duynefontyn site except if X/Q dispersion factors are significantly different when assessing airborne discharges from stacks at different locations than the KNPS stack.

## 5 Atmospheric Dispersion Modelling and Meteorological Data Preparation

Nuclides discharged to the atmosphere are dispersed due to normal atmospheric mixing processes. As they travel downwind, they irradiate people externally and internally when inhaled. During their transport downwind, nuclides may be deposited from the atmosphere by impaction with the underlying surface or due to rainfall. This transfer onto land surfaces may lead to further irradiation of people because of external irradiation from deposited activity, internal irradiation from inhalation of resuspended activity, and ingestion of contaminated food. The relative importance of these pathways depends on the specific nuclides and the nature of the surface onto which the deposition occurs.

The atmospheric dispersion model in PC-CREAM 08 is PLUME. It is based on the semi-empirical Gaussian plume model, and its mathematical basis and validation are described in [7]. PLUME is considered suitable for calculating the long-term average or time-integrated concentrations in air. The basic model was developed for dispersion over the land of neutrally buoyant releases from isolated stacks in flat terrain. This involves the application of site-specific parameters such as meteorological conditions and nuclides discharged. Concentrations of activity in the air, deposition rates, and external dose rates from the airborne nuclides are calculated as a function of distance for a unit nuclide discharge rate.

The calculations are done for atmospheric conditions that existed during the year or quarter for which the dose assessment is required. The concentrations of activity in air and external dose rates are combined with the spatial distribution of different impact areas in the sixteen wind direction sectors selected for the Duynefontyn site. These sectors are illustrated in Figure 5-1. The distance over which radionuclides may be transported in the atmosphere depends on many factors such as radioactive half-life, physicochemical form, weather conditions, and deposition processes. These factors are accounted for in PLUME.

| Sector | Wind Direction (Deg.) | |
|---|---|---|
| 1 | NNE | 11.25 ≤ θ < 33.75 |
| 2 | NE | 33.75 ≤ θ < 56.25 |
| 3 | ENE | 56.25 ≤ θ < 78.75 |
| 4 | E | 78.75 ≤ θ < 101.25 |
| 5 | ESE | 101.25 ≤ θ < 123.75 |
| 6 | SE | 123.7 5 ≤ θ < 146.25 |
| 7 | SSE | 146.25 ≤ θ < 168.75 |
| 8 | S | 168.75 ≤ θ < 191.25 |
| 9 | SSW | 191.25 ≤ θ < 213.75 |
| 10 | SW | 213.75 ≤ θ < 236.25 |
| 11 | WSW | 236.25 ≤ θ < 258.75 |
| 12 | W | 258.75 ≤ θ < 281.25 |
| 13 | WNW | 281.25 ≤ θ < 303.75 |
| 14 | NW | 303.75 ≤ θ < 326.25 |
| 15 | NNW | 326.25 ≤ θ < 348.75 |
| 16 | N | 348.75 ≤ θ < 11.25 |

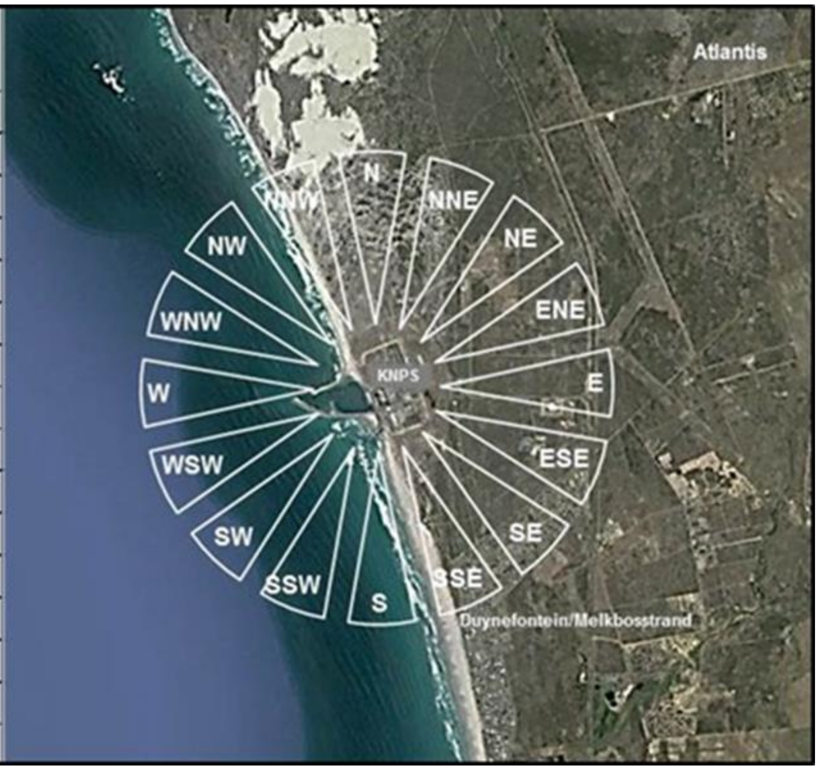


**Figure 5-1:** Sectors used in the PLUME meteorological data file

Weather data for the specific reporting period to be assessed (3-month and annual) are obtained from the KNPS weather station. Hourly data are processed using multiple calculational steps to provide the correct data format for PLUME. The data is prepared for the sixteen wind directional sectors and reflect the atmospheric stability indices and rain frequencies per sector. The methodology to prepare the input data for PLUME is described in a separate supporting document for PRIPE methodology document [4]. Various sensitivities studies were done with PLUME. Table 5-1 shows the results of one such study when calculating dose from airborne discharges based on the maximum nuclide activities reported for the period 2015 to 2019 in Table 4-5.

The study compared derivation of the stability categories using two different sets of data for the year 2018 and two different sets of stack heights (10 m and the KNPS effective stack height of 64 m). The 2018 annual meteorological data was used since it results in the highest nuclide concentrations at the representative person locations when comparing results using the meteorological data for the years 2015 to 2019. Two sets of atmospheric stability categories were calculated using the difference in vertical temperature measured by the KNPS weather station between 10 m and 50 m heights for the first set and between 10 m and 100 m heights for the second set.

**Table 5-1:** Sensitivity of dose results to PLUME parameter values

| Meteorology data – 2018 | ΔT (10m – 50m) (1) | ΔT (10 m – 100 m) | ΔT (10 m – 50 m) | ΔT (10 m – 100 m) |
|---|---|---|---|---|
| **Stack height** | **10 m** | **10 m** | **64 m** | **64 m** |
| IRP(DB), µSv/yr | 10.40 | 5.84 | 0.25 | 0.55 |
| IRP01, µSv/yr | 3.07 | 1.72 | 0.08 | 0.16 |
| IRP02, µSv/yr | 1.35 | 0.75 | 0.18 | 0.18 |
| (1): **ΔT** is the abbreviation for the vertical temperature method at different heights used to calculate stability categories. | | | | |

The KNPS DCFs in § 12 have been calculated using the 10 m stack height concentrations and meteorological stability categories based on the vertical temperature difference between 10 m and 50 m, the heights recommended by the U.S. NRC Regulatory Guide 1.23 used to assign hourly atmospheric stability class values [14]. Normal airborne discharges from KNPS are from the main stack with an effective height of 64 m and X/Q dispersion factors supplied by the KNPS weather station are based on the vertical temperature difference between 10 m and 50 m [4].

It can therefore be concluded that a high degree of conservatism is included in the DCF values calculated for KNPS and included in Appendix 2.

# 6 Land Cover and Soil Types

## 6.1 Land Cover

The type of land cover determines the roughness length parameter required for modelling atmospheric dispersion. The roughness length is a numerical representation of the mechanical turbulence created as the air passes over obstructions on the land surface. It considers the type of surface (e.g., water, agricultural areas, forests, and cities), and determines the deposition of radioactivity on surface areas. The parameter values available in PLUME are listed in Table 6-1.

**Table 6-1:** Surface types and roughness parameter values

| Terrain | Roughness length $z_0$ (m) |
|---|---|
| Sea, very short grass | 0.01 |
| Open grassland | 0.04 |
| Low lying crops, e.g. root crops | 0.1 |
| Agricultural areas | 0.3 |

| Terrain | Roughness length $z_0$ (m) |
|---|---|
| Parks, open suburbia | 0.4 |
| Cities, woodlands | 1 to 4 |

A land cover representative of natural vegetation and agricultural areas in the Duynefontyn area (0.3) was selected. Vegetation consists mainly of fynbos between the discharge point (KNPS) and the nearest residential area and human settlement in the direction of wind sectors 5, 6, and 7 shown in Figure 5-1.

## 6.2 Soil Types

The activity concentration of radionuclides in the soil and the corresponding external ground gamma dose is used in the dose calculations. The calculations require information on the soil structure onto which radionuclides are deposited. Soil is then modelled in GRANIS, the soil deposition and external radiation exposure model in PC-CREAM 08. Soil is either modelled as undisturbed soil using five compartments of various soil depths, or well mixed soils typical of agricultural practices, which is represented by a single compartment. Input data for GRANIS, when modelling the environment at the Duynefontyn site, has to consider the following soil characteristics.

The sandy soil of the South African West Coast is characterised by a low soil organic carbon, a low cation exchange capacity, a high risk of nutrient leaching, low structural ability, and high sensitivity to erosion, and crusting. Both chemical stability and physical stability are weak in the soil. The characteristics are due to their sandy texture, the low reactivity of their clays, and to climatic conditions. The dominant minerals are quartz, kaolinite, and iron and aluminium oxides, and due to the low rainfall soil texture, is a composition of an assemblage of solid particles and voids [23].

The bulk density of soil depends greatly on the mineral make-up of soil and the degree of compaction. The density of quartz is around 2.65 g/cm3, but the bulk density of a soil may be less than half that density. Most soils have a bulk density between 1.0 and 1.6 g/cm3. A comparison was carried out of different soil types; the generic soil models available in GRANIS, and a soil composition representative of the sandy soils at the Duynefontyn site. The results are included in Appendix 4. The dose calculation results for Co-58, for example, when using different soil types, are listed in Table 6-2. Soil type categorised as ‘generic, undisturbed, dry’ results in the highest dose.

The external dose calculated with GRANIS is generally a small component of the total dose calculated for all exposure pathways. GRANIS only applies to airborne particulates, e.g., Co-58 and Cs-137. The most important nuclides in respect of public dose demonstrated in § 12, are C-14 and H-3. GRANIS does not apply to these nuclides, and their radiological doses are assessed using models that employ a specific activity approach. This approach is discussed in § 6.4 .

**Table 6-2:** A comparison of different soil types in GRANIS and their impact on dose

| Soil Type in GRANIS | Co-58 dose at a deposition rate of 1 $Bq.m^{-2}.s^{-1}$ ; μSv/yr |
|---|---|
| Soil: high Si content representative of local soils | 6.48E-03 |
| Soil: generic, undisturbed, dry | 7.02E-03 |
| Soil: generic, well mixed, dry | 2.71E-03 |
| Soil: generic, undisturbed, wet | 6.38E-03 |
| Soil: generic, well mixed, wet | 2.24E-03 |

The GRANIS model that is used in Duynefontyn dose calculations and the DCFs is based on the default model for dry and undisturbed soils. It provides conservative results when compared to the high silicon representative of the Duynefontyn area, as well as the wet well-mixed soil model that is more representative of soils for vegetable cultivation.

Appendix 4 includes a further comparison of the effective gamma dose from the surface of soil types from particulate nuclides that could be present in KNPS airborne discharges.

## 6.3 Airborne Discharges and its Transfer in Biota

### 6.3.1. FARMLAND

The environmental concentrations in biota and dose impacts of normal operational discharges are assessed by means of the FARMLAND model in PC-CREAM 08. A summary of FARMLAND characteristics is provided, and a more comprehensive description can be found in [7].

FARMLAND approximates the transfer of nuclides through the terrestrial food compartments of the environment that are relevant to the representative person. The physical processes involved are complex and are simplified by modelling these processes by a series of interconnected compartments, each representing different parts of the food chain. FARMLAND is a dynamic model and has the advantage of being flexible and able to accommodate large differences in the amount of detail included in different parts of the model.

A wide range of radionuclides are included, and all nuclides can be assessed that are required for KNPS DCF values. In FARMLAND, the first radioactive progeny of each discharged radionuclide that does not reach secular equilibrium after one year is modelled explicitly.

The quality of the data used to represent nuclide transfer through the environment can have a significant or less significant impact on the dose and is determined by the importance of a nuclide. Ideally, nuclide environmental transfer and bio-concentration data should be obtained by measurements made in the environmental media being assessed. This is not always practical, and it can involve high costs. Data obtained from the literature, e.g., published by the IAEA, are used to provide an estimate required to determine whether regulatory requirements are met. When the estimated radiation doses to humans approach regulatory dose limits, a more site-specific approach is needed [24]. This is not the situation at KNPS. It is shown in § 13 that the representative person dose from KNPS airborne discharges is approximately a factor 10 less than for the dose from liquid discharges and that the total dose has a large margin relative to the KNPS dose constraint of 250 µSv/yr.

The different foods types consumed by people are large in number, and their relative contribution to the total diet can vary considerably between individuals living in different regions of a country [24]. Limited data are available on the transfer processes of radionuclides in a wide range of food types. However, it is not considered necessary to distinguish between many similar foods when carrying out radiological assessments. The various foods have therefore been grouped into several categories found to be important components of the human diet. These categories are [7]:

- green vegetables;
- grain products;
- root crops including potatoes;
- fruit;
- meat;
- liver;
- milk; and
- milk products.

The animals considered in PC CREAM 08 are cattle and sheep, for which full dynamic models incorporating both transfer through pasture and animal metabolism are provided. FARMLAND does not include transfer models for pigs and chicken, although habit data are included in the habit survey [3]. The intake of radioactivity by pigs and chickens is highly variable depending on feeding practices, particularly as in many instances, they are permanently reared indoors [7].

The developers of FARMLAND assumed that for European conditions, only a small part of the diet would be contaminated and hence the consumption of pork, chicken, and eggs will not contribute significantly to ingestion doses. This may not be true for the representative persons defined for the Duynefontyn site. The application of FARMLAND to the Duynefontyn site compensates for this aspect by assuming higher ingestion rates for beef and mutton so that the meat consumption quantities are conservative when calculating the dose for the representative person. This approach is supported by the fact that the principal radionuclides in respect of food ingestion at Duynefontyn are C-14, H-3 and I-131 and their concentrations per unit mass of meat do not differ significantly for the different meat types. Radioactivity concentrations per unit mass for C-14 and H-3 are the same for beef, mutton, pork, poultry, and eggs at values reported in [7]. It is reported in [24] that the mean transfer coefficients for I-131 are of the same order of magnitude for beef, mutton, pork, and poultry. One can therefore assume that approximately the same dose is received for the same mass consumed by a person from any of these animals.

The habit data for the representative person that are described in [3] also include the consumption of eggs. It is conservatively assumed that all the C-14 and H-3 in eggs originates from KNPS via inhalation by chicken and reports to the eggs. One can assume that in respect of other radionuclides that the hens kept in the potential impact area are mainly fed with commercial feeds not sourced in the 5 km area and therefore not impacted by KNPS discharges. An ingestion dose model for eggs was constructed to account for the two principal nuclides in the airborne discharges, i.e., C-14 and H-3. The model and results are included in Appendix 6, and the DCFs for C-14 and H-3 include the dose contribution from egg consumption.

The models and parameter values used in the dose assessment are specifically for evaluating the transfer of nuclides through food chains following deposition from the atmosphere because of routine, continuous releases to the environment. For other applications, these models may not be adequate and so should be used with care. In particular, no consideration is given to variations in agricultural practice or season of the year, as these are not important for continuous releases [7]. However, these factors can be significant for abnormal short-term releases and extensions to the models to consider these are discussed in § 10.

The transfer factors for the different nuclides include the following complex environmental mechanisms. When nuclides deposit from the atmosphere onto agricultural land, a part is intercepted by the foliage of vegetation, while part will land on the soil. In general, radioactivity is removed from the surfaces of plants by natural processes such as weathering, with a half-life ranging from a few to several tens of days.

The interception and retention of radionuclides on plant surfaces vary according to the physicochemical form of the deposit, the nature of the vegetation, and the prevailing conditions. Much of the external contamination on crops at harvest will be removed before consumption of the edible parts by humans. Washing and removal of outer leaves of green vegetables lead to a reduction in radionuclide concentration, as does the removal of the outer layers of grain in the production of flour. In FARMLAND, the interception factor, retention half times, processing, and preparation losses, together with the transfer coefficients representing translocation for crops (green vegetables, grain, root crops, and fruit) are all chosen to fit available environmental and experimental data. Data for transfer factors are updated regularly by the IAEA, and the input data for the Duynefontyn site will be reviewed periodically against the latest published data. The most recent data published by the IAEA on radionuclide transfer factors in terrestrial and freshwater environments is provided in [24].

The developers of FARMLAND considered the application of the models to different climatic regions [7]. The types of food grown and consumed together with the agricultural practices adopted show strong regional variations. The prevailing climate has a pronounced effect on agriculture and may affect the transfer processes outlined in this section of the report. Differences in the transfer of radioactivity in the food chain between northern and southern France have been considered. Large differences are found in the types of food produced and consumed. For example, there are few cattle in the south, and little butter or cheese from cows' milk are produced or eaten; however, cheese from goats' milk and oils, such as olive oil, are widely produced and eaten. There are also large differences in the times at which crops are planted and harvested and in the feeding regimes for animals.

These differences in agricultural practices could be significant for accidental releases where there is a single deposit at a particular time of year. However, for routine releases that the application of PC-CREAM 08 is intended for, deposition is assumed to be continuous throughout the year, and such differences in agricultural practice are insignificant in estimating concentrations in terrestrial foods [7].

The application of the PC-CREAM 08 models to southern Europe is pertinent since the region is representative of a Mediterranean climate like the Western Cape. It is reported that any differences in transfer parameters due to the various European regions appear to be small compared with the variation due to other factors, such as soil type [7].

The radiological dose from C-14 and H-3 are assessed using models that employ a specific activity approach and is discussed in more detail in § 6.4 .

### 6.4 The Transfer of Tritium and Carbon-14 in the Terrestrial Environment

The transfer of tritium and carbon-14 between the atmosphere and the terrestrial environment is different to other nuclides and more complex. This additional complexity is primarily a consequence of the fundamental roles played by hydrogen and carbon in biological systems. Due to their special behaviour in the environment, a specific activity approach has been adopted in FARMLAND. It is based on the assumption that a steady-state equilibrium has been attained between the atmospheric concentrations of these nuclides and exposed organisms so that the ratio between the nuclide and its stable counterpart is fixed [25].

For a release of C-14 to the atmosphere, the specific activity can be determined by the degree of atmospheric dispersion and the carbon concentration in the atmosphere; the latter is equal to 0.15 g $m^{-3}$ [7]. A similar assumption can be made for H-3, and the specific activity of H-3 taken into the body can be assumed as equal to that in atmospheric water vapour. This is determined similar to C-14, by the degree of atmospheric dispersion with the concentration of water vapour in the atmosphere equal to 8 g $m^{-3}$ (annual average value) [7]. The intake of carbon-14 and H-3 in humans by inhalation and ingestion can be determined from the respective intakes of carbon and water by the various consumption routes.

The activity concentrations in FARMLAND to estimate doses via food ingestion and activity concentrations are based on the PLUME dispersion calculations. Table 6-3 includes those factors relevant to the specific activity in food models in FARMLAND, which were also used for human dose from egg consumption described in Appendix 6.

**Table 6-3:** Specific activity of H-3 and C-14 in foods

| Foodstuff | Water content, % | Carbon content, % | Concentration in food, Bq/kg per Bq/$m^3$ (air concentration) | |
|---|---|---|---|---|
| | | | H-3 | C-14 |
| Grain | 10 | 36 | 12.5 | 2400 |
| Green vegetables | 80 | 8 | 100 | 533 |
| Root vegetables | 80 | 8 | 100 | 533 |
| Fruit | 84.4 | 8 | 100 | 533 |
| Cow's milk | 90 | 4 | 112.5 | 267 |
| Cow/sheep/pig/chicken/meat/eggs | 70 | 12 | 87.5 | 800 |
| Carbon content is taken as being 40% of dry matter | | | | |
| The following atmospheric specific activities are assumed: | | | | |
| 125.0 Bq (H-3) per kg ($H_2O$ per Bq/$m^3$ (H-3) | | | | |

| |
|---|
| 6667.0 Bq(C-14) per kg (C12) per Bq/m$^3$ (C-14) |

### 6.5 FARMLAND Input Data for Duynefontyn

The uncertainties on the nuclide concentrations that are predicted by FARMLAND have not been quantified explicitly. FARMLAND has been developed to provide best estimates of activity concentrations in food with a bias to conservatism where there is a lack of data and knowledge of parameter values is poor. It is expected that FARMLAND will predict activity concentrations in food to within a factor of five with a bias to overestimation [7].

The input data used to calculate KNPS DCFs are provided in the form of a record and referenced § 16.

## 7 Marine Dispersion of Liquid Discharges

### 7.1 Sediment Distribution Coefficients and Bio-concentration Ratios

Exposure pathways and human dose due to radioactive liquid discharges to the sea are sensitive to the nuclide-specific sediment distribution coefficients and the concentration ratios for marine species. Recent data published by the IAEA was consulted, and the data that was used for KNPS DCFs are included in Appendix 5.

### 7.2 Definition of the Local Marine Compartment Used in Doris

Detailed marine dispersion data are available for the Duynefontyn site and specifically for KNPS discharges. The study was carried out by PRDW, and the results of important parameters are included in the DORIS input data [26]. The PRDW study derived dispersion parameter values for three differently sized marine compartments, which are illustrated in Figure 7-1. The data available for the three different compartments are included in Table 7-1.

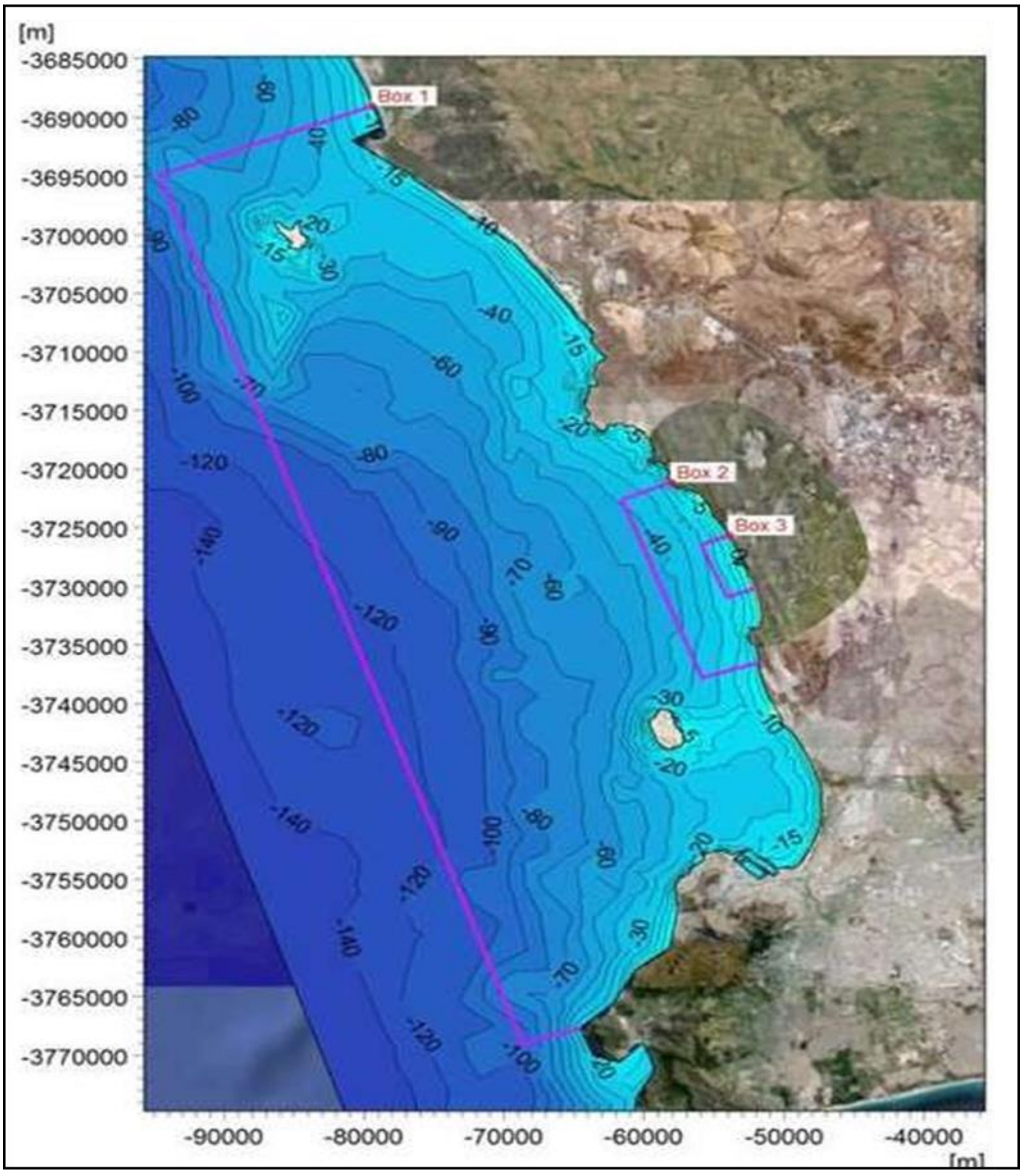


**Figure 7-1:** Marine compartments for which dispersion parameters were derived

**Table 7-1: Marine box model parameters representative of the three marine compartments**

| Parameter | Unit | Value | | |
|---|---|---|---|---|
| | | Box 1 | Box 2 | Box 3 |
| Average water depth | m | 6.60E+01 | 2.30E+01 | 1.10E+01 |
| Coastline length | m | 1.35E+05 | 2.20E+04 | 5.90E+03 |
| Mean suspended sediment load | $t/m^3$ | 4.62E-06 | 4.76E-06 | 5.36E-06 |
| 95th percentile suspended load | $t/m^3$ | 7.70E-06 | 8.65E-06 | 1.24E-05 |
| Net sedimentation rate | $t/m^2/yr$ | 7.30E-04 | 6.60E-06 | 5.80E-05 |
| Sediment density | $t/m^3$ | 4.00E-01 | 4.00E-01 | 4.00E-01 |
| Volume exchange rate (VER) | $m^3/yr$ | 8.70E+12 | 8.80E+11 | 2.1+11 |

The marine compartment data listed in Table 7-2 representing Box 3, provide conservative results when calculating sea and marine biota radioactivity concentrations with DORIS.

**Table 7-2:** DORIS marine compartment parameter values

| DORIS Local compartment factors | Volume ($m^3$) | Depth (m) | Coastline length (m) | Volumetric exchange rate ($m^3/yr$) | Suspended sediment load ($t/m^3$) | Sedimentation Rate ($t/m^2/yr$) | Sediment density ($t/m^3$) | Diffusion rate ($m^2/yr$) |
|---|---|---|---|---|---|---|---|---|
| Design basis assessment | 1.14E+08 | 1.10E+01 | 5.90E+03 | 2.00E+09 | 1.24E-05 | 5.80E-05 | 4E-01 | 3.15E-02 |
| Representative person | 1.14E+08 | 1.10E+01 | 5.90E+03 | 2.5E+10 | 1.24E-05 | 5.80E-05 | 4E-01 | 3.15E-02 |

This approach is supported by the fact that KNPS discharges into the surf-zone and which could result in high concentrations under certain sea conditions. A dispersion test done at KNPS that involved a dye released into the cooling water outfall is illustrated in the left of the composite picture in Figure 7-2. It illustrates outfall flow towards the south in the surf zone. The same effect can be observed in the difference in sea temperature shown on the right of Figure 7-2.

**Figure 7-2:** An illustration of KNPS liquid discharge into the surf zone

The only value in Table 7-1 that is not used in DORIS is the value for the volume exchange rate (VER). The radioactivity concentrations are sensitive to the VER since it is a principal parameter determining the rate at which radioactivity is removed from the marine compartments. Lower VER values result in higher public dose. Two VER values shown in Table 7-2 have been derived based on the calibration of the DORIS results against nuclide concentrations measured by the ESL in Box 3. The higher value is used for design basis dose assessments and the lower value for calculating the dose for a representative person. The basis for the two values is described in § 7.3

## 7.3 Calibrating Box 3 Volume Exchange Rates against KNPS Environmental Surveillance Results

Environmental monitoring data reported by the KNPS Environmental Survey Laboratory (ESL) is used to calibrate the DORIS model. Code calibration is described as a useful process when an environmental model is used for a single site repeatedly; calibration should not be confused with the more comprehensive process of software validation [23].

Calibration between ESL nuclide concentrations measured in white mussel and concentrations predicted by DORIS was done by varying the VER input value to DORIS. White mussel was selected since it serves as an indicator species for KNPS. ESL monitoring results for two important nuclides in the liquid discharges, i.e., Ag-110m and Co-58, are frequently detected, and average annual concentrations are included in Table 7-3 [23]. The mussels are collected at distances of 300 m and 900 m south of the KNPS outfall.

**Table 7-3:** Annual average radioactivity measured in white mussel, Bq/kg (wet mass)

| Year | Bq/kg(wm) 300 m south of the outfall | | Bq/kg(wm) 900 m south of the outfall | |
|---|---|---|---|---|
| **Nuclide** | **Ag-110m** | **Co-58** | **Ag-110m** | **Co-58** |
| 1995 | 14.70 | 0.31 | 7.53 | NR |
| 1996 | 9.03 | NR | 4.80 | NR |
| 1997 | 9.36 | 0.58 | 5.06 | 0.74 |
| 1998 | 8.10 | 0.50 | 5.26 | 0.42 |
| 1999 | 8.38 | 1.29 | 6.25 | 0.84 |
| 2000 | 6.80 | 0.57 | 4.14 | 0.77 |
| 2001 | 6.29 | 1.10 | 4.23 | 0.95 |
| 2002 | 9.21 | 0.52 | 6.60 | 0.40 |
| 2003 | 8.47 | 0.87 | 6.50 | 0.62 |
| 2004 | 8.26 | 0.38 | 4.80 | 0.42 |
| 2005 | 12.30 | 0.37 | 7.34 | 0.34 |
| 2006 | 7.79 | 0.36 | 4.57 | 0.46 |
| 2007 | 6.46 | 0.35 | 3.97 | 0.53 |
| 2008 | 4.95 | 0.34 | 3.35 | 0.30 |
| 2009 | 3.94 | 0.16 | 2.69 | 0.35 |
| 2010 | 4.38 | 0.18 | 3.37 | 0.18 |
| 2011 | 3.55 | 0.12 | 2.86 | NR |
| 2012 | 2.34 | 0.29 | 1.41 | 0.22 |
| 2013 | 1.10 | 0.44 | 0.71 | 0.41 |
| 2014 | 1.02 | 0.29 | 0.48 | 0.81 |
| 2015 | 0.57 | 0.69 | 0.32 | 0.23 |
| 2016 | 0.28 | NR | 0.28 | NR |
| 2017 | NR | NR | 0.17 | 0.23 |
| 2018 | 0.47 | 0.27 | 0.27 | 0.15 |
| 2019 | 0.25 | NR | 0.17 | 0.11 |

**Table 7-4**: Calibrating DORIS using ESL monitoring data for Ag-110m and Co-58

| **Liquid discharge VER = 2.5E+10 m$^3$/yr** | | **2015** | **2016** | **2017** | **2018** | **2019** |
|---|---|---|---|---|---|---|
| Ag-110m | Discharged, Bq/yr | 3.84E+08 | 1.06E+08 | 9.02E+07 | 5.74E+08 | 1.11E+08 |
| | DORIS prediction, Bq/g | 0.81 | 0.23 | 0.19 | 1.22 | 0.24 |
| | ESL Measured Bq/g | 0.57 | 0.28 | 0.17 | 0.47 | 0.25 |
| Co-58 | Discharged, Bq/yr | 1.70E+09 | 7.30E+08 | 2.88E+09 | 5.68E+09 | 8.60E+08 |
| | DORIS prediction, Bq/g | 0.28 | 0.12 | 0.47 | 0.93 | 0.14 |
| | ESL Measured Bq/g | 0.69 | ND | 0.23 | 0.27 | 0.11 |

A higher value for VER equal to 2.9E+09 m$^3$/yr was derived for the IRP (DB) DCFs, using earlier KNPS annual discharge data that are relatively high compared to the period 2015 to 2019.

# 8 Exposure Pathways

## 8.1 Potential Exposure Pathways

The following exposure pathways are considered to be the primary pathways and for which habit data were compiled to characterise the interim representative person discussed in § 9:

- consumption of locally sourced aquatic and terrestrial foods;
- activities and occupancy over beach intertidal substrates (recreational fishing, bait collection, handling of fishing gear and sediment); occupancy of beach areas and seawater during recreational activities such as picnicking, hiking, swimming, surfing, diving; also the frequent cleaning of beach areas to remove seaweed;
- inhalation of airborne discharges;
- external radiation from the airborne plume and deposited airborne particulates on land;
- re-suspension and inhalation of deposited airborne particulates;
- activities and occupancy within the radius of detectable direct radiation from the Duynefontyn site nuclear installations; and
- permanent occupancy of residential buildings (brick as well as temporary constructed dwellings).

The importance of each exposure pathways was assessed for different human settlements that are identified as potential critical groups. Settlements in the sectors SSE to ESE (Figure 7-1) and at distances less than 5 km from KNPS receive the highest exposures when considering the environmental dispersion characteristics and habit data [3]. Most of these exposure pathways can be assessed with PC-CREAM 08, but not all of them. Surface and groundwater and sewage sludge are two examples, and a brief discussion of their importance to dose assessment are provided.

### 8.2 Surface and Groundwater

Consumption of surface water is not included as an exposure pathway. It is an important pathway for radionuclides when discharged to freshwater bodies, e.g., nuclear facilities located at river sites such as in Europe and in the United States. The critical groups investigated in this report have access to municipal water supply.

Groundwater from local site aquifers is abstracted by households in the Duynefontyn Township. Groundwater studies in the Duynefontyn Site Safety Report indicate a very low likelihood of water pollution [29].

No groundwater monitoring is currently done outside the Eskom owner-controlled boundary, and it should be considered for inclusion in the ESL surveys.

### 8.3 Sewage Sludge

Sewage sludge is often applied to land as a soil conditioner. Radionuclides in the sludge give rise to potential exposure pathways. Normally controls are placed on the use of sludge on land to produce crops that may be eaten raw, especially fruit and vegetables. In some countries, ten months between the application of the sludge and harvesting of the crop is required [30].

The ESL carries out extensive monitoring of the Melkbosstrand sewage works (MSW) [28]. Trace quantities of Co-60 were detected in one of the 40 samples collected at the MSW for the year 2019. Two radiopharmaceutical nuclides are frequently measured, i.e. I-131 and Lu-177 and are not attributable to KNPS.

KNPS was notified in the past of the use of sludge from the MSW in the gardens of the Duynefontyn Township and that nuclides potentially originating from KNPS may be present in the sludge. The results of an earlier screening dose assessment of the radioactivity in sewage included in Table 8-3 [31].

**Table 8-1:** Radioactivity and potential dose reported by KNPS in Melkbos sewage sludge

| Sample medium | Nuclide | DCF $Sv.m^2/Bq.h$ | Consumption rate (kg or L per annum) | Activity; (Bq/kg) | Committed Effective Dose for Year (Sv) | Committed Effective Dose for Quarter (Sv) |
|---|---|---|---|---|---|---|
| Sewage sludge | Co-58 | 1.892E-12 | Reference to 'Terrestrial Samples' in ESL report | 3.47 | 4.604E-07 | 1.151E-07 |
| | Co-60 | 4.595E-12 | | 2.02 | 6.509E-07 | 1.627E-07 |
| | | | | **Total** | **1.111E-06** | **2.778E-07** |

These results are extremely conservative when compared to the results when dose coefficients from the EPA Federal Guidance Report No. 12 are applied to the same activity concentrations. The results are shown in Table 8-2 [32].

**Table 8-2:** External dose from soil mixed with contaminated sewage sludge

| Nuclide | Infinite soil thickness Sv per $Bq.s.m^{-3}$ (worst case) | ESL Bq/kg | Exposure time for a full year, s/yr | µSv/yr, infinite soil thickness |
|---|---|---|---|---|
| Co-58 | 3.19E-17 | 3.47 | 31557600 | 0.003 |
| Co-60 | 8.68E-17 | 2.02 | 31557600 | 0.006 |

The potential dose factor from sewage is not included in the current NNR DCFs and is also not included in the new revised DCFs in Appendix 2. It is not expected to have a significant contribution to public dose. A survey is required to determine how much and how frequent sewage sludge from MSW is released into the nearby Duynefontyn public domain, if any. A survey was not possible during the habit survey reported in [3].

Should a more detailed assessment be required, the PC-CREAM 08 model GRANIS can be used. GRANIS, an acronym for Gamma Radiation Above Nuclides In Soil, is mainly used to assess the dose and dose rate on radioactively contaminated soil following deposition of airborne radioactivity. It is also possible to input a set of measured soil nuclide activities directly into GRANIS and to calculate the dose rate [34]. The results of a case study are shown in Table 8-1, indicating very small DCFs for external radiation.

**Table 8-3:** An example of GRANIS results for soil and sewage sludge; Sv/hr

| **Soil**[2] | | | | | | **Sewage sludge**[2] |
|---|---|---|---|---|---|---|
| **Radionuclide**[3] | **1cm** | **5cm** | **15cm** | **30cm** | **1 metre** | **1 metre** |
| $^{55}$Fe | 9.04 $10^{-14}$ | 9.04 $10^{-14}$ | 9.04 $10^{-14}$ | 9.04 $10^{-14}$ | 9.04 $10^{-14}$ | 3.88 $10^{-13}$ |
| $^{60}$Co | 5.64 $10^{-8}$ | 1.72 $10^{-7}$ | 2.90 $10^{-7}$ | 3.45 $10^{-7}$ | 3.65 $10^{-7}$ | 5.49 $10^{-7}$ |
| $^{59}$Ni | 1.28 $10^{-13}$ | 1.28 $10^{-13}$ | 1.28 $10^{-13}$ | 1.28 $10^{-13}$ | 1.28 $10^{-13}$ | 5.52 $10^{-13}$ |
| $^{65}$Zn | 1.32 $10^{-8}$ | 4.01 $10^{-8}$ | 6.70 $10^{-8}$ | 7.87 $10^{-8}$ | 8.26 $10^{-8}$ | 1.25 $10^{-7}$ |
| $^{90}$Sr | 1.38 $10^{-15}$ | 1.39 $10^{-15}$ | 1.39 $10^{-15}$ | 1.39 $10^{-15}$ | 1.39 $10^{-15}$ | 6.70 $10^{-15}$ |
| $^{99}$Mo | 6.20 $10^{-9}$ | 1.77 $10^{-8}$ | 2.68 $10^{-8}$ | 2.95 $10^{-8}$ | 3.01 $10^{-8}$ | 6.17 $10^{-8}$ |
| $^{106}$Ru | 4.81 $10^{-9}$ | 1.43 $10^{-8}$ | 2.29 $10^{-8}$ | 2.60 $10^{-8}$ | 2.67 $10^{-8}$ | 4.31 $10^{-8}$ |
| $^{110m}$Ag | 6.32 $10^{-8}$ | 1.90 $10^{-7}$ | 3.14 $10^{-7}$ | 3.64 $10^{-7}$ | 3.80 $10^{-7}$ | 5.87 $10^{-7}$ |
| $^{137}$Cs | 1.39 $10^{-8}$ | 4.15 $10^{-8}$ | 6.70 $10^{-8}$ | 7.64 $10^{-8}$ | 7.88 $10^{-8}$ | 1.25 $10^{-7}$ |
| $^{144}$Ce | 1.09 $10^{-9}$ | 3.14 $10^{-9}$ | 4.98 $10^{-9}$ | 5.74 $10^{-9}$ | 6.07 $10^{-9}$ | 1.14 $10^{-8}$ |
| $^{210}$Pb | 2.64 $10^{-11}$ | 4.61 $10^{-11}$ | 4.85 $10^{-11}$ | 4.85 $10^{-11}$ | 4.85 $10^{-11}$ | 3.10 $10^{-10}$ |
| $^{210}$Po | 1.97 $10^{-13}$ | 5.91 $10^{-13}$ | 9.67 $10^{-13}$ | 1.12 $10^{-12}$ | 1.16 $10^{-12}$ | 1.80 $10^{-12}$ |
| $^{226}$Ra | 3.94 $10^{-8}$ | 1.19 $10^{-7}$ | 1.98 $10^{-7}$ | 2.33 $10^{-7}$ | 2.47 $10^{-7}$ | 3.84 $10^{-7}$ |
| $^{228}$Ra | 2.20 $10^{-8}$ | 6.62 $10^{-8}$ | 1.09 $10^{-7}$ | 1.26 $10^{-7}$ | 1.32 $10^{-7}$ | 2.07 $10^{-7}$ |
| $^{227}$Ac | 8.86 $10^{-9}$ | 2.52 $10^{-8}$ | 3.78 $10^{-8}$ | 4.11 $10^{-8}$ | 4.17 $10^{-8}$ | 8.62 $10^{-8}$ |
| $^{228}$Th | 7.78 $10^{-8}$ | 2.40 $10^{-7}$ | 4.12 $10^{-7}$ | 5.01 $10^{-7}$ | 5.49 $10^{-7}$ | 8.30 $10^{-7}$ |
| $^{230}$Th | 7.83 $10^{-12}$ | 1.82 $10^{-11}$ | 2.34 $10^{-11}$ | 2.41 $10^{-11}$ | 2.41 $10^{-11}$ | 8.61 $10^{-11}$ |
| $^{232}$Th | 3.89 $10^{-12}$ | 8.19 $10^{-12}$ | 1.00 $10^{-11}$ | 1.03 $10^{-11}$ | 1.03 $10^{-11}$ | 4.14 $10^{-11}$ |
| $^{231}$Pa | 8.35 $10^{-10}$ | 2.38 $10^{-9}$ | 3.59 $10^{-9}$ | 3.92 $10^{-9}$ | 3.96 $10^{-9}$ | 7.79 $10^{-9}$ |
| $^{234}$U | 3.40 $10^{-12}$ | 6.24 $10^{-12}$ | 7.46 $10^{-12}$ | 7.60 $10^{-12}$ | 7.61 $10^{-12}$ | 3.14 $10^{-11}$ |
| $^{235}$U | 3.64 $10^{-9}$ | 1.01 $10^{-8}$ | 1.42 $10^{-8}$ | 1.49 $10^{-8}$ | 1.50 $10^{-8}$ | 3.79 $10^{-8}$ |
| $^{236}$U | 2.23 $10^{-12}$ | 3.48 $10^{-12}$ | 3.94 $10^{-12}$ | 3.99 $10^{-12}$ | 3.99 $10^{-12}$ | 1.82 $10^{-11}$ |
| $^{238}$U | 5.36 $10^{-10}$ | 1.50 $10^{-9}$ | 2.32 $10^{-9}$ | 2.63 $10^{-9}$ | 2.73 $10^{-9}$ | 5.49 $10^{-9}$ |
| $^{237}$Np | 4.98 $10^{-9}$ | 1.40 $10^{-8}$ | 2.07 $10^{-8}$ | 2.23 $10^{-8}$ | 2.26 $10^{-8}$ | 4.92 $10^{-8}$ |
| $^{238}$Pu | 2.14 $10_{-12}$ | 2.57 $10^{-12}$ | 2.71 $10^{-12}$ | 2.72 $10^{-12}$ | 2.72 $10^{-12}$ | 1.32 $10^{-11}$ |
| $^{239}$Pu | 1.75 $10^{-12}$ | 3.54 $10^{-12}$ | 4.73 $10^{-12}$ | 5.02 $10^{-12}$ | 5.06 $10^{-12}$ | 1.46 $10^{-11}$ |
| $^{240}$Pu | 2.22 $10^{-12}$ | 2.91 $10^{-12}$ | 3.25 $10^{-12}$ | 3.35 $10^{-12}$ | 3.38 $10^{-12}$ | 1.45 $10^{-11}$ |
| $^{241}$Pu | 3.31 $10^{-14}$ | 8.47 $10^{-14}$ | 1.10 $10^{-13}$ | 1.13 $10^{-13}$ | 1.13 $10^{-13}$ | 3.84 $10^{-13}$ |
| $^{241}$Am | 3.65 $10^{-10}$ | 7.55 $10^{-10}$ | 8.74 $10^{-10}$ | 8.83 $10^{-10}$ | 8.83 $10^{-10}$ | 4.38 $10^{-9}$ |

(2) : Refers to the soil and sewage sludge composition described in reference [34]

Future land use and habit surveys may indicate several exposure pathways from the application of sewage that could require more detailed assessments. Reference [33] provides information on exposures that include the following scenarios:

- residents of houses built on agricultural fields formerly applied with sludge;

- recreational users of a park where sludge has been used for land reclamation;
- residents of a town near fields upon which sludge has been applied;
- neighbours of a landfill that contains sludge or ash;
- neighbours of a sludge incinerator;
- agricultural workers who operate equipment to apply sludge to agricultural lands; and
- workers at treatment works involved in sampling, transport, and bio-solids loading operations.

## 9 Habit Data and the Representative Person

At the time of compiling this document, the COVID-19 pandemic and resulting lockdown conditions prevented implementation of an extensive habit survey, and it was postponed until such time that lockdown restrictions have been lifted. A report was prepared that presents interim habit data [3]. Eskom will appoint a service provider to conduct the survey as soon as is practicable possible.

Interim habit data were compiled using a variety of sources, and it includes data from earlier habit surveys, observations of current human activities near the site, and draws from other national and international sources. The selection of habit data for the representative person aimed to provide a high level of confidence using a conservative approach, in that it can be used to measure compliance with the National Nuclear Regulatory dose constraint of 250 µSv/yr.

The data was used in the calculation of the revised DCFs. The representative persons for which DCFs were calculated, have the following general habit profiles:

- IRP01: An urban resident living in proximity of the beachfront and site boundary, thus experiencing a combined exposure to liquid and airborne discharge exposure pathways. The types of houses provide a high shielding factor because of their construction and limit exposure pathways that involve inhalation and plume exposure. Terrestrial foodstuff consumption grown locally is limited, consisting mainly of fruit and broadleaf vegetables from a garden patch, as well as chicken and eggs. Seafood consumption consisting of locally caught fish could be high as well as the time spent on the beach and intertidal zone.
- IRP02: A resident in an informal settlement who could be more exposed to pathways from airborne discharges than the urban resident in IRP01. IRP02 may be more self-reliant on food production compared to IRP01. Exposures to liquid discharge pathways are expected to be less when compared to IRP01.
- IRP(DB): A third representative person is constructed for conservative and design basis assessments. High habit data values when compared to IRP01 and IRP02 were selected from the liquid and airborne discharge exposure pathways. This construct is similar to the Maximum

Exposed Individual (MEI) concept currently in use at KNPS, an approach described in the U.S. NRC Regulatory Guide 1.109 [35].

Summaries of input data used in the methodology document are included in Appendix 7.

# 10 Assessment of Short-Term Discharges

## 10.1 Airborne Short-Term Discharges

Short-term radioactivity discharges, also referred to as batch releases, are mainly assessed for airborne discharges. A batch release can result in a public dose that is different from the public dose resulting from the same quantity of radioactivity when assuming a continuous and constant rate of discharge. Rainfall and other short-term meteorological variances in space and time are important factors that may result in higher localised atmospheric concentrations and deposition of radioactivity. Examples of KNPS operational conditions when there is a higher likelihood for batch releases to the atmosphere are:

- during maintenance operations;
- refuelling outages and reactor start-up;
- purging a reactor cooling system; and
- contingencies such as nuclear fuel leaks requiring reactor shutdown accompanied by an operator error causing the release to the atmosphere of the gaseous waste product before adequate decay time has been allowed for short-lived radionuclides.

The approximate frequencies at which batch releases are when the following plant conditions exist:

- During maintenance and testing (maintenance occurs every refuelling outage or 18 months when systems are opened for maintenance and can lead to increased gaseous particulate releases. High iodine releases can be expected about 16 times per year related to ventilation charcoal filter testing);
- Refuelling outages and reactor start-up (every 18 months per unit when the primary system undergoes significant boration for shutdown leading to high discharge of primary noble gases should fuel leaks be present. The shutdown and start-up GCT to atmosphere can also lead to higher tritium releases although the dominant contributor to gaseous tritium is SFP evaporation);
- Purging a reactor cooling system and containment (every 18 months per unit for reactor system and about 20 times per year for containment purging depending on containment leak rates);
- Contingencies such as nuclear fuel leaks requiring reactor shutdown accompanied by an operator error causing the release to the atmosphere of the gaseous waste product before adequate decay

time has been allowed for short-lived radionuclides (the volume of the TEG tanks are very limited which prevents long decay of noble gases and possibly iodine during plant shutdown with a fuel leaker. This may occur once every 3 years for small fuel leaks and once every ten years with larger fuel leaks).

The PC-CREAM 08 atmospheric dispersion model PLUME is based on the Gaussian plume model. Many studies have been published in which the validity and accuracy of the Gaussian plume model have been considered [7]. These studies show that the accuracy of predicted airborne concentrations improves as the duration of discharges increases. Annual average concentrations within a few kilometres of a site with simple terrain are likely to be predicted within a factor of 2, and the uncertainty increases with increasing distance from the site. PLUME is designed for routine, continuous, low-level emissions at a constant rate under steady-state environmental conditions. These circumstances are rarely met in practice. Airborne discharges can fluctuate with time, and environmental conditions vary diurnally and seasonally. Dose calculations for batch releases performed with the radio-ecological models developed for continuous releases, such as those included in PC-CREAM 08, may include large uncertainties.

A study of atmospheric dispersion conditions at the Duynefontyn site indicates that there are times when batch discharges can be carried to high population areas. An example from a study carried out with the CALPUFF code discussed in Appendix 4 is illustrated in Figure 10-1.


**Figure 10-1:** Example of KNPS atmospheric dispersion isopleths during a 24-hour period in winter

It has been suggested that the dose consequences from a short-term discharge that constitutes a large fraction of the total annual airborne discharge at nuclear power plants may be 20 to 100 times larger than the doses estimated using official models based on the assumption that discharges are continuous over a year [36]. The results of an EPRI study regarding short-term discharges to the atmosphere versus continuous releases are reported in [37]. The EPRI study concluded that a realistic increase in dose associated with batch releases is from unity up to a factor of eight higher for the specific site characteristics included in the study. The EPRI report provides a methodology to assess the dose implications of batch releases under different environmental conditions and to provide answers to questions regarding the extent of the dose a person is receiving via batch releases when compared to the assumption of continuous discharges.

The report concludes that the methodology could easily be adapted to other sites and can be used to identify favourable meteorological conditions that would result in minimal impacts from a planned batch release.

The potential higher impact from batch releases to the atmosphere is compensated for as follows in the prospective dose assessment. The dose from atmospheric discharges is based on 10 m release heights instead of the stack height at 64 m effective height. Dose calculations were performed using the same input data but just changing the release height. A release height of 10 m results in approximately 20 times higher dose.

Another environmental factor to consider is that the nuclide concentrations in food products are sensitive to the time of year when airborne discharge occurs, especially in the case of C-14. A $^{14}CO_2$ discharge, whether it occurs during daylight hours or at night, will result in different concentrations in plants. Releases during the growing season, especially close to harvest time result in the highest concentrations. Ingestion pathway doses are dominated by $^{14}CO_2$ and H-3. In the Western Cape, for example, the sowing of wheat occurs until the end of May and harvesting takes place from October until the first part of November [38].

A preliminary investigation was carried out to determine changes in atmospheric dispersion conditions during the growth period when compared to other periods of the year. Indications are that there are such changes, but further investigations may demonstrate that it is not an important contributing factor in determining dose. Atmospheric dispersion isopleths for different periods of the year carried out with the CALPUFF code discussed in Appendix 4 are illustrated in Figure 13-2. The shift in the yellow isopleth during grain growth season indicates an increase in C-14 concentrations to the east and south of Duynefontyn, areas where grain production occurs. It is proposed that should the annual dose assessment results using PLUME indicate a representative person dose significantly above 10 μSv/yr, further investigations be carried out with more refined dispersion models to determine the potential significance of an increase in C-14 concentrations. An annual dose below 10 μSv/yr to the representative person is considered a trivial dose [39].

C-14 January to May (2011) | C-14 Grain Growth Season June to Oct (2011) | C-14 Annual average (2011)

**Figure 10-2:** Seasonal changes in atmospheric dispersion conditions at Duynefontyn

## 10.2 Liquid Short-Term Discharges

Liquid batch discharges from KNPS do not present the same challenges as batch discharges to the atmosphere. Normal operational liquid discharges are regular batch discharges that occur throughout the year and are modelled as continuous discharges. The discharge rate when pumping from a liquid waste storage tank is limited, and it is unlikely that a month's liquid discharge volume can be released into the marine environment over a period of a few hours. Liquids are stored in holding tanks before being discharged, allowing short-lived nuclides to decay. However, since the liquid discharges at KNPS are into the surf zone, consideration should be given to tide and surface current conditions when discharging to the sea. High tide and a south-eastern wind will transport the discharge to the north, away from beach and sea areas south of KNPS where members of the public are located.

## 11 Build-up of Radionuclides in the Environment

The increase in environmental radioactivity concentrations over time because of continuous discharges, referred to as build-up of nuclides, is included in the PC-CREAM 08 dose calculations. Build- up is of particular importance for longer half-life nuclides, e.g., Co-60, Cs-137, and Ni-63. Their contribution to the annual dose increases during the lifetime of a nuclear installation and continues to impart dose after final shutdown. The time integrals of dose for the annual discharge of a radionuclide, say over 60 years, which is the proposed LTO of KNPS, is equated to the annual dose at the end of 60 years.

Since PC-CREAM 08 considers a constant routine discharge for the period for which a dose is assessed, consideration is required of the significance of varying annual discharges in the past and their different build-up, i.e., for KNPS over the period 1984/85 to 2019. illustrates examples of possible scenarios of annual discharges over a period of 4 years.

- Case A represents the dose in years 1 to 4 when radioactivity was only discharged in year 1. A dose is still being received in the following three years because of the slow decay following the discharge in the first year.
- Case B represents the dose when the annual discharge is constant. The build-up of radioactivity takes place, and the dose is assessed accordingly. This is how PC-CREAM 08 calculates dose at the end of year 4.
- Case C represents variable annual discharges, and which is the actual case at KNPS. The dose that is calculated for end-of-year 4 will not reflect the correct dose at the end-of-year 4. The dose may be higher or lower than for Case B, and it depends on the average annual discharge for Case C over 4-year period and whether a correction to the dose calculation in the manner performed for Case B, is required.

Case C becomes a complex exercise. It is proposed to account for varying contributions from the preceding years only when a particular year's dose result, when calculated in a prospective manner for 60 years of operation life, is greater than 10 µSv/yr (the dose that is considered to be trivial). The annual dose for KNPS in its 40$^{th}$ year of operation, for example, is calculated as if its airborne and liquid discharges will continue for a further 60 years.

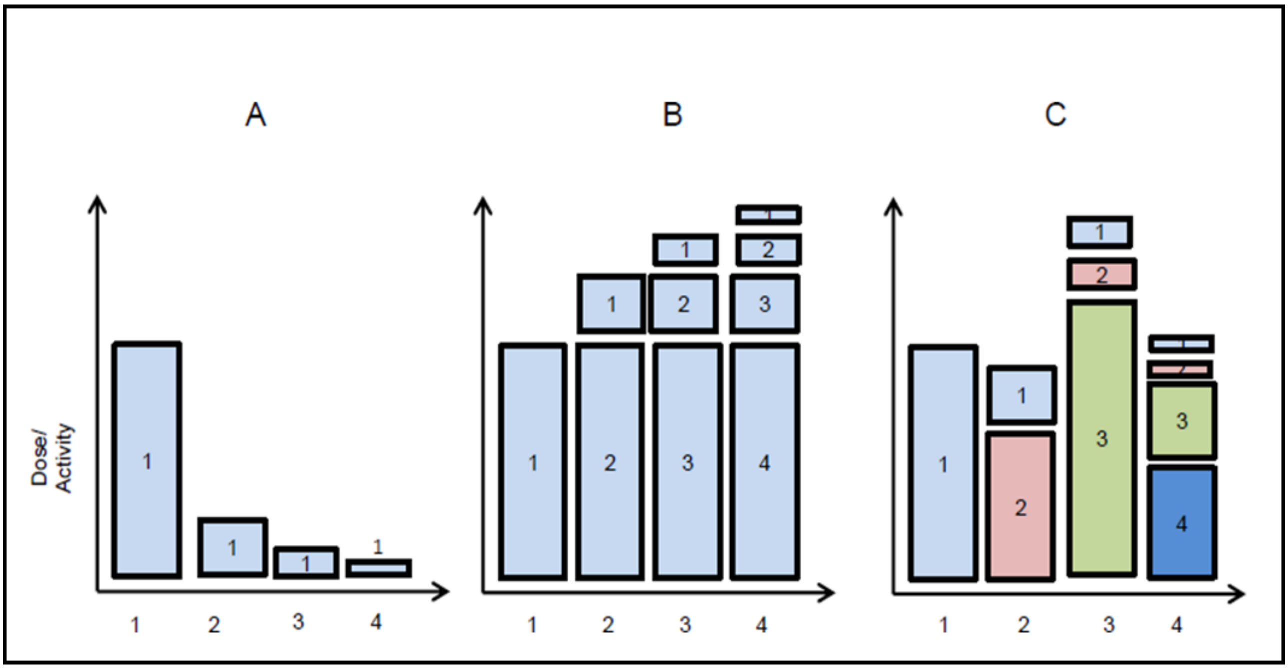


**Figure 11-1:** Categories of discharges

## 12 Dose Conversion Factors

A DCF is a dose value per unit Bq for each of the radionuclides potentially discharged from KNPS, considering the Duynefontyn site environment and habit data. The KNPS Activity Migration Model (AMM) that includes the current DCFs, is being reviewed. The revised DCFs presented in this document are part of the review process. The DCFs are calculated for a 60-year KNPS operational lifetime and account for the proposed LTO.

The DCFs are a function of the critical groups located at or beyond the OCB. Periodic review of the DCFs may be required, especially when significant changes occur in land-use and human settlements. New sources of airborne discharges such as additional NPPs on the Duynefontyn site may require consideration of different atmospheric dispersion factors when compared to KNPS. The characteristics of the local marine compartment that are used to derive DCFs based on liquid discharges are not expected to change for as long as no new developments immediately beyond the northern beach section of the OCB occur. Direct radiation from future nuclear facilities on the site will have to be considered. However, radiation levels are not expected to be measurable beyond the OCB, like the radiation levels measured for KNPS.

The DCFs have been calculated using the PC-CREAM 08 software system of codes and the habit data referred to in § 9. The revised DCFs are included in Appendix 2. It was calculated for three different age groups (adult, child, and infant) for three representative persons for which habit data were compiled (refer § 9). The input and output data files used in PC-CREAM 08 are included as records in § 16.

## 13 Example of a Dose Calculation

Public dose is reported to the NNR. It is calculated using the DCFs in the KNPS AMM actual measured discharge activities. An example of a dose calculation for 2019 using the revised DCFs in Appendix 2 is provided here.

The annual dose to the IRP01 age group ‘child’ from each reported nuclide in the KNPS 2019 discharges are shown in Table 13-1 and Table 13-2.

**Table 13-1:** KNPS 2019 annual dose from airborne discharges

| Nuclide | Airborne DCF, µSv/Bq | Bq/yr | Annual dose, µSv/yr |
|---|---|---|---|
| Ag-110m | 1.46E-10 | 3.42E+05 | 4.99E-05 |
| Ar-41 | 1.34E-14 | 8.20E+10 | 1.10E-03 |
| C-14 | 6.71E-12 | 3.24E+11 | 2.17E+00 |
| Co-58 | 6.12E-12 | 6.59E+06 | 4.03E-05 |
| Co-60 | 2.36E-10 | 1.39E+06 | 3.28E-04 |
| Fe-55 | 2.32E-12 | 4.04E+06 | 9.37E-06 |
| H-3 | 3.07E-14 | 1.01E+13 | 3.10E-01 |
| I-131 | 3.35E-10 | 1.93E+08 | 6.47E-02 |
| I-132 | 2.12E-13 | 3.05E+08 | 6.47E-05 |
| I-133 | 5.42E-12 | 3.40E+08 | 1.84E-03 |
| I-134 | 9.09E-14 | 4.52E+08 | 4.11E-05 |
| I-135 | 6.54E-13 | 3.51E+08 | 2.30E-04 |
| Kr-85 | 1.31E-16 | 5.28E+10 | 6.92E-06 |
| Kr-85m | 2.17E-15 | 3.23E+07 | 7.01E-08 |
| Kr-88 | 2.70E-14 | 1.27E+07 | 3.43E-07 |
| Ni-63 | 4.17E-13 | 5.01E+06 | 2.09E-06 |
| Xe-131m | 1.58E-16 | 1.29E+10 | 2.04E-06 |
| Xe-133 | 5.66E-16 | 1.29E+12 | 7.30E-04 |
| Xe-133m | 4.55E-16 | 2.62E+09 | 1.19E-06 |

| Nuclide | Airborne DCF, µSv/Bq | Bq/yr | Annual dose, µSv/yr |
|---|---|---|---|
| Xe-135 | 3.25E-15 | 8.98E+08 | 2.92E-06 |
| | **Total** | **1.19E+13** | **2.55E+00** |

**Table 13-2:** KNPS 2019 annual dose from liquid discharges (IRP01-Child)

| Nuclide | Liquid DCF, µSv/Bq | Bq/yr | Annual dose, µSv/yr |
|---|---|---|---|
| Ag-110m | 2.61E-10 | 1.11E+08 | 2.90E-02 |
| C-14 | 2.40E-11 | 2.43E+10 | 5.83E-01 |
| Ce-144 | 9.75E-13 | 9.85E+05 | 9.60E-07 |
| Co-57 | 1.51E-12 | 3.25E+06 | 4.91E-06 |
| Co-58 | 3.62E-12 | 8.60E+08 | 3.11E-03 |
| Co-60 | 9.64E-11 | 3.63E+08 | 3.50E-02 |
| Cr-51 | 4.70E-14 | 4.03E+06 | 1.89E-07 |
| Cs-137 | 3.68E-12 | 1.62E+07 | 5.96E-05 |
| Fe-55 | 1.17E-10 | 1.05E+09 | 1.23E-01 |
| H-3 | 3.65E-17 | 2.72E+13 | 9.93E-04 |
| I-131 | 1.04E-12 | 2.38E+05 | 2.48E-07 |
| Mn-54 | 7.85E-12 | 1.01E+07 | 7.93E-05 |
| Na-24 | 8.25E-16 | 2.98E+06 | 2.46E-09 |
| Nb-95 | 7.65E-13 | 2.14E+06 | 1.64E-06 |
| Nd-147 | 7.41E-12 | 3.37E+05 | 2.50E-06 |
| Ni-63 | 5.57E-13 | 1.31E+09 | 7.30E-04 |
| Sb-124 | 6.37E-12 | 3.70E+07 | 2.36E-04 |
| Te-123m | 6.55E-12 | 3.93E+06 | 2.57E-05 |
| Zn-65 | 1.85E-10 | 4.05E+05 | 7.49E-05 |
| Zr-95 | 2.87E-12 | 4.87E+05 | 1.40E-06 |
| Zr-97 | 1.57E-13 | 3.06E+05 | 4.81E-08 |
| | **Total** | **2.72E+13** | **7.75E-01** |

The dose results for all IRPs defined and age groups in [3] are included in Table 13-3 and illustrated in Figure 13-1, Figure 13-2, and Figure 13-3.

**Table 13-3:** KNPS 2019 annual dose for all IRPs considered in the interim habit study

| Discharge | IRP | Adult | Child | Infant |
|---|---|---|---|---|
| Airborne µSv/yr | IRP(DB) | 10.72 | 11.26 | 14.43 |
| | IRP01 | 2.19 | 1.75 | 2.55 |
| | IRP02 | 1.25 | 1.63 | 1.75 |
| Liquid µSv/yr | IRP(DB) | 24.46 | 27.99 | 16.50 |
| | IRP01 | 1.21 | 1.13 | 0.78 |
| | IRP02 | 0.34 | 0.30 | 0.25 |
| IRP total dose 2019, µSv/yr | IRP(DB) | 35.18 | 39.26 | 30.93 |
| | IRP01 | 3.40 | 2.87 | 3.33 |
| | IRP02 | 1.58 | 1.93 | 2.01 |

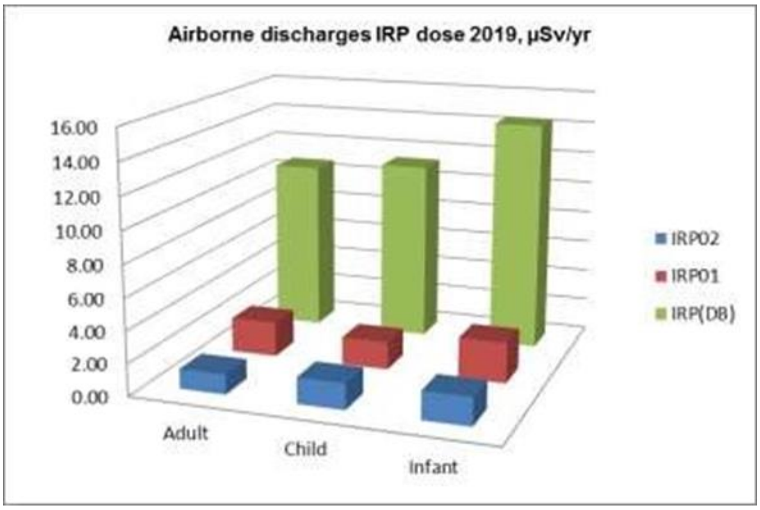


**Figure 13-1:** KNPS IRP dose from airborne discharges, 2019

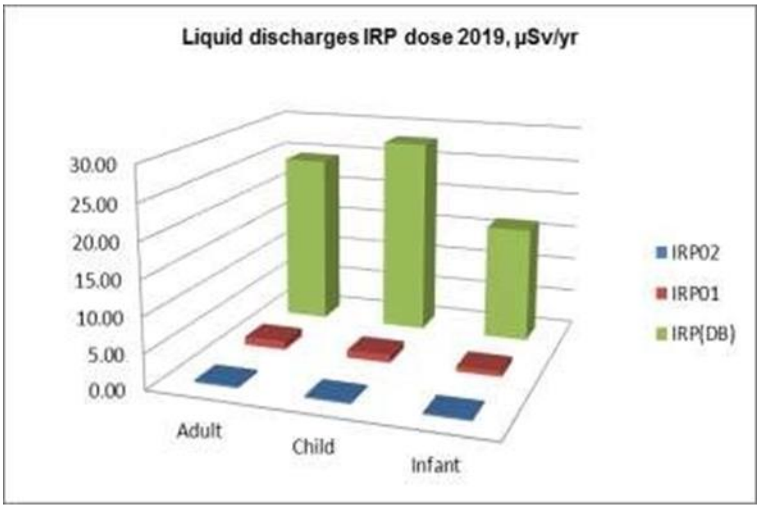


**Figure 13-2:** KNPS IRP dose from liquid discharges, 2019

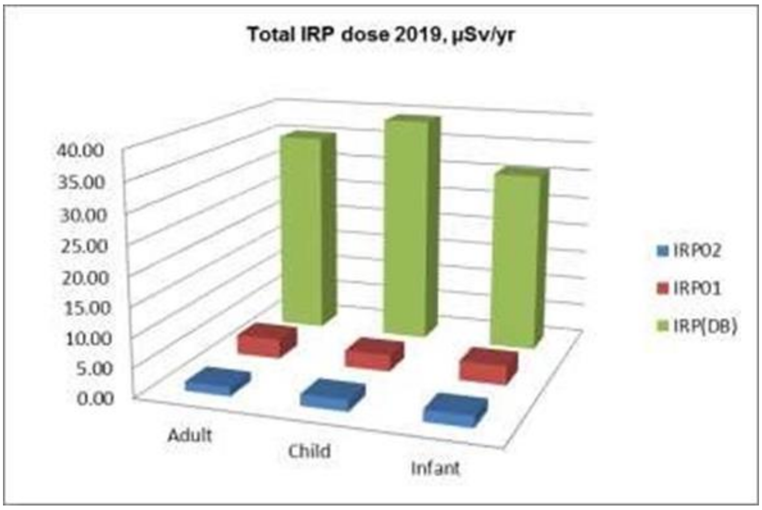


**Figure 13-3:** KNPS IRP total annual dose, 2019

## 14 Validation and Verification

Various V&V studies have been performed by the PC-CREAM 08 software developer, Public Health England (PHE). Reports on the studies have been published, and the information will be reviewed as part of the verification and validation (V&V) to be done in accordance with NNR regulatory requirement [40]. A V&V plan was prepared and submitted to the NNR [41].

## 15 Recommendations and Concluding Remarks

This methodology document will be maintained as a “living” document to:

- include relevant information on international developments in environmental assessments; and
- address future changes in ICRP dose coefficients as recommended by the NNR.

The methodology and example dose calculation demonstrate that the current KNPS dose constraint equal to 250 µSv/yr is met with a large safety margin. Further optimisation in respect of public dose can be achieved when implementing the following recommendations:

- Hard-to-measure (HTM) nuclides may be present at quantities in KNPS discharges that qualify them as principal nuclides, i.e., contributing more than 1 per cent to dose from either liquid of airborne discharges. This is an aspect of the KNPS discharges that should be investigated further to confirm adequate conservatism in their scaling factors used for DCFs.
- Periodic collection and radioanalysis of groundwater samples at locations of the critical groups considered will be considered for inclusion in the KNPS environmental surveys to confirm that it is a negligible exposure pathway.
- The liquid discharges at KNPS are into the surf zone, and consideration should be given to tide and surface current conditions when discharging to the sea. High tide and a south-eastern wind will transport the discharge to the north, away from beach and sea areas south of KNPS where more members of the public are generally located.
- Airborne discharges such as containment purging and filter testing using I-131 should be carried out under favourable atmospheric conditions for dispersion, minimising airborne concentrations at critical group locations.

## 16 Records

Records consist of the input data files in PC-CREAM 08 to calculate DCF values for KNPS. The files which are produced as comma-separated values (csv) by PC-CREAM 08, are the following:

- FARMLAND_DCF_2020
- GRANIS_DCF_2020
- PLUME_DCF_2020
- RESUS_DCF_2020
- Airborne Discharge_DCF_2020
- Liquid Discharge_DCF_2020_DB
- Liquid Discharge_DCF_2020_IRP01
- Liquid Discharge_DCF_2020_IRP02

# A.1. Appendix 1 - PC-CREAM 08 OVERVIEW

## A.1.1. Overview

PC-CREAM 08 is a complex model that is divided into several parts for ease of use. Primarily, the program consists of the 'Models' and 'ASSESSOR' divisions. The 'Models' part includes a series of mathematical models that predict the transfer of radionuclides through the environment and provide estimates of activity concentrations in various environmental media following a continuous release. The output of these models is then used as input to the dose assessment part of the program, namely 'ASSESSOR'.

An overview of each of the models included within PC-CREAM 08 and the dose assessment part of the program is given in the sections that follow. Further detail of the models and data are given in the references provided [5].

## A.1.2. PLUME

PLUME is the atmospheric dispersion model used within PC-CREAM 08. It is a Gaussian plume model that considers the meteorological conditions during the release, the roughness of the land surface, and the physical characteristics of the radionuclides being released. The model calculates activity concentrations in air, deposition rates, and external gamma dose rates from radionuclides in the cloud (cloud gamma) at various distances downwind of the release point. The output from the model can be used as input to ASSESSOR, which combines these results with site-specific meteorological data and actual release rates to calculate actual activity concentrations in air, deposition rates, and airborne (cloud) gamma dose rates downwind of the release point. The deposition rates from PLUME are used to scale the results from the other models, namely RESUS, GRANIS, and FARMLAND to estimate doses from various exposure routes arising from the discharge of radionuclides to the atmosphere.

## A.1.3. RESUS

RESUS can be used to estimate activity concentrations in air arising from the resuspension of previously deposited radionuclides. The activity concentrations, which are calculated for a user-defined deposition rate, are inputted to ASSESSOR, which scales them by the actual deposition rate predicted by PLUME at various locations downwind of the discharge point and combines them with habit data to calculate doses.

### A.1.4. GRANIS

External exposure to gamma radiation from radionuclides deposited on the ground is calculated using the GRANIS model. GRANIS models the transfer of radionuclides through the soil and considers the shielding properties of the soil when estimating doses one metre above the soil surface. The doses are calculated based on a user-defined deposition rate. GRANIS is the only model in PC-CREAM 08 that includes some organ doses as well as effective doses. Effective doses are inputted to ASSESSOR, which scales them by the actual deposition rate at various locations downwind of the discharge point and combines them with habit data to estimate actual exposures.

### A.1.5. FARMLAND

FARMLAND is a suite of models that can be used to predict the transfer of radionuclides into terrestrial foods following deposition onto the ground. The food categories considered are those that are most important in the human diet, namely, green vegetables, root vegetables, fruit, grain, cow milk, cow milk products, cow meat, cow liver, sheep meat, and sheep liver. Activity concentrations in each food type are calculated for a user-defined deposition rate. These activity concentrations are inputted to ASSESSOR, which scales them by the actual deposition rate at various locations downwind of the discharge point and combines them with habit data to calculate ingestion doses.

### A.1.6. DORIS

The marine dispersion model used in PC-CREAM 08 is based closely on the MARINA II model. The model can be used to predict the activity concentrations in seawater, sediments, and marine biota for user-defined discharge rates. These activity concentrations are inputted to ASSESSOR, which scales them by the actual discharge rate and combines them with habit data to calculate doses from ingestion of marine foods, external exposure to beach sediments, and inhalation of sea spray.

### A.1.7. ASSESSOR

Once activity concentrations in environmental media have been calculated using the various models, they can be used in ASSESSOR, the dose assessment part of PC-CREAM 08, to calculate effective doses. There are five parts of ASSESSOR to calculate individual and collective doses from discharges to the atmosphere and sea and individual doses from discharges into rivers. Each part of ASSESSOR displays all the model runs that are available for use, including the default set.

The results of these models are combined with actual discharge rates, site-specific data, habit data, and DCFs to calculate effective doses for the most important exposure pathways. The DCFs used are provided in data tables.

To calculate external effective dose from exposure to beta radiation in the plume (cloud beta), ASSESSOR uses a set of dose coefficients that gives the skin equivalent dose rate per unit air concentration assuming total immersion in the contaminated air. Similarly, the external effective dose from exposure to beta radiation on the ground (deposited from the atmosphere or as part of aquatic sediments) is calculated using a set of dose coefficients that gives the skin equivalent dose rate per unit deposition at 80 cm above a uniformly contaminated surface. A slightly different approach is used to estimate the external beta and gamma exposures to radionuclides in contaminated fishing gear; these are calculated using empirical formulae and the mean energy of the beta and gamma radiation. The same mean gamma energies are also used to calculate the external gamma dose above aquatic sediments.

## A.2. Appendix 2 - DCF AIRBORNE AND LIQUID DISCHARGES

**Table A2- 1:** DCF Airborne Discharges µSv/yr per Bq/yr

| Radionuclide | IRP(DB) | | | | IRP01 | | | | IRP02 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adult | Child | Infant | | Adult | Child | Infant | | Adult | Child | Infant |
| Ag-110m | 4.14E-10 | 4.94E-10 | 1.09E-09 | | 8.29E-11 | 8.79E-11 | 1.46E-10 | | 3.93E-11 | 4.17E-11 | 6.29E-11 |
| Ar-41 | 2.57E-14 | 2.57E-14 | 2.57E-14 | | 1.34E-14 | 1.34E-14 | 1.34E-14 | | 1.03E-14 | 1.03E-14 | 1.03E-14 |
| As-76 | 4.77E-13 | 6.15E-13 | 9.41E-13 | | 3.54E-13 | 4.37E-13 | 4.97E-13 | | 1.38E-13 | 1.75E-13 | 2.29E-13 |
| Ba-139 | 2.18E-14 | 2.62E-14 | 3.09E-14 | | 2.04E-14 | 2.47E-14 | 2.90E-14 | | 6.84E-15 | 8.21E-15 | 9.68E-15 |
| Ba-140 | 7.52E-12 | 8.25E-12 | 1.25E-11 | | 4.84E-12 | 4.94E-12 | 5.38E-12 | | 2.22E-12 | 2.44E-12 | 3.18E-12 |
| Be-7 | 7.09E-13 | 7.64E-13 | 1.34E-12 | | 2.78E-13 | 2.91E-13 | 3.77E-13 | | 1.36E-13 | 1.44E-13 | 1.77E-13 |
| Br-82 | 1.01E-12 | 1.07E-12 | 1.48E-12 | | 7.35E-13 | 7.88E-13 | 1.07E-12 | | 3.24E-13 | 3.45E-13 | 4.50E-13 |
| Br-84 | 4.06E-14 | 4.36E-14 | 4.61E-14 | | 2.64E-14 | 2.94E-14 | 3.18E-14 | | 1.28E-14 | 1.36E-14 | 1.43E-14 |
| C-14 | 3.08E-11 | 3.26E-11 | 4.12E-11 | | 5.80E-12 | 4.56E-12 | 6.71E-12 | | 3.38E-12 | 4.60E-12 | 4.77E-12 |
| Ce-141 | 1.91E-12 | 2.03E-12 | 2.77E-12 | | 1.51E-12 | 1.50E-12 | 1.38E-12 | | 5.83E-13 | 6.19E-13 | 7.28E-13 |
| Ce-144 | 2.55E-11 | 3.05E-11 | 5.43E-11 | | 1.71E-11 | 1.78E-11 | 1.90E-11 | | 6.59E-12 | 7.27E-12 | 9.33E-12 |
| Co-57 | 3.81E-12 | 4.20E-12 | 4.93E-12 | | 2.34E-12 | 2.37E-12 | 2.41E-12 | | 1.21E-12 | 1.28E-12 | 1.35E-12 |
| Co-58 | 9.63E-12 | 1.02E-11 | 1.14E-11 | | 6.01E-12 | 6.04E-12 | 6.12E-12 | | 3.11E-12 | 3.23E-12 | 3.38E-12 |
| Co-60 | 3.72E-10 | 3.83E-10 | 3.98E-10 | | 2.35E-10 | 2.36E-10 | 2.36E-10 | | 1.25E-10 | 1.27E-10 | 1.28E-10 |
| Cr-51 | 1.56E-13 | 1.71E-13 | 2.28E-13 | | 9.14E-14 | 9.65E-14 | 1.07E-13 | | 4.63E-14 | 5.04E-14 | 6.19E-14 |
| Cs-134 | 5.90E-10 | 3.55E-10 | 3.11E-10 | | 1.59E-10 | 1.12E-10 | 1.06E-10 | | 8.38E-11 | 6.56E-11 | 5.79E-11 |
| Cs-136 | 1.67E-11 | 1.61E-11 | 2.52E-11 | | 5.12E-12 | 5.01E-12 | 6.65E-12 | | 2.53E-12 | 2.62E-12 | 3.46E-12 |
| Cs-137 | 5.98E-10 | 4.21E-10 | 3.93E-10 | | 2.12E-10 | 1.76E-10 | 1.72E-10 | | 1.12E-10 | 9.83E-11 | 9.28E-11 |
| Cs-138 | 4.88E-14 | 5.17E-14 | 5.39E-14 | | 2.91E-14 | 3.20E-14 | 3.41E-14 | | 1.57E-14 | 1.65E-14 | 1.71E-14 |
| Cu-64 | 8.26E-14 | 9.49E-14 | 1.51E-13 | | 7.23E-14 | 8.28E-14 | 1.29E-13 | | 2.74E-14 | 3.13E-14 | 4.81E-14 |
| Fe-55 | 2.75E-11 | 7.17E-11 | 1.27E-10 | | 9.59E-13 | 1.69E-12 | 2.32E-12 | | 5.57E-13 | 1.15E-12 | 1.55E-12 |
| Fe-59 | 2.02E-11 | 3.30E-11 | 6.36E-11 | | 6.03E-12 | 6.25E-12 | 6.71E-12 | | 3.00E-12 | 3.40E-12 | 3.99E-12 |
| H-3 | 6.54E-14 | 5.80E-14 | 7.44E-14 | | 2.94E-14 | 2.43E-14 | 3.07E-14 | | 1.44E-14 | 1.30E-14 | 1.77E-14 |
| Hf-181 | 5.46E-12 | 5.78E-12 | 6.80E-12 | | 3.91E-12 | 3.86E-12 | 3.68E-12 | | 1.74E-12 | 1.84E-12 | 2.01E-12 |
| Hg-203 | 1.00E-11 | 1.13E-11 | 2.83E-11 | | 2.93E-12 | 3.08E-12 | 5.54E-12 | | 1.24E-12 | 1.43E-12 | 2.51E-12 |
| I-129 | 2.24E-08 | 2.60E-08 | 2.39E-08 | | 3.36E-09 | 3.35E-09 | 3.48E-09 | | 1.47E-09 | 2.17E-09 | 1.63E-09 |
| I-130 | 1.60E-12 | 1.84E-12 | 3.15E-12 | | 1.06E-12 | 1.21E-12 | 1.81E-12 | | 4.43E-13 | 5.26E-13 | 8.82E-13 |
| I-131 | 3.65E-10 | 5.26E-10 | 1.67E-09 | | 7.59E-11 | 1.08E-10 | 3.35E-10 | | 2.80E-11 | 4.53E-11 | 1.38E-10 |
| I-132 | 2.68E-13 | 2.85E-13 | 3.22E-13 | | 1.75E-13 | 1.90E-13 | 2.12E-13 | | 7.62E-14 | 8.13E-14 | 9.16E-14 |
| I-133 | 2.45E-12 | 3.37E-12 | 9.94E-12 | | 1.65E-12 | 2.18E-12 | 5.42E-12 | | 6.15E-13 | 9.10E-13 | 2.64E-12 |
| I-134 | 1.27E-13 | 1.33E-13 | 1.39E-13 | | 8.08E-14 | 8.60E-14 | 9.09E-14 | | 3.48E-14 | 3.62E-14 | 3.79E-14 |
| I-135 | 6.49E-13 | 7.39E-13 | 1.07E-12 | | 4.35E-13 | 5.02E-13 | 6.54E-13 | | 1.84E-13 | 2.13E-13 | 3.06E-13 |
| Kr-85 | 2.51E-16 | 2.51E-16 | 2.51E-16 | | 1.31E-16 | 1.31E-16 | 1.31E-16 | | 9.15E-17 | 9.15E-17 | 9.15E-17 |
| Kr-85m | 4.17E-15 | 4.17E-15 | 4.17E-15 | | 2.17E-15 | 2.17E-15 | 2.17E-15 | | 1.71E-15 | 1.71E-15 | 1.71E-15 |
| Kr-87 | 1.58E-14 | 1.58E-14 | 1.58E-14 | | 8.20E-15 | 8.20E-15 | 8.20E-15 | | 6.10E-15 | 6.10E-15 | 6.10E-15 |
| Kr-88 | 4.62E-14 | 4.71E-14 | 4.81E-14 | | 2.52E-14 | 2.61E-14 | 2.70E-14 | | 2.05E-14 | 2.10E-14 | 2.14E-14 |
| La-140 | 1.02E-12 | 1.15E-12 | 1.38E-12 | | 7.74E-13 | 8.75E-13 | 9.32E-13 | | 3.43E-13 | 3.93E-13 | 4.69E-13 |
| Mn-54 | 3.16E-11 | 3.27E-11 | 3.59E-11 | | 1.89E-11 | 1.89E-11 | 1.91E-11 | | 1.00E-11 | 1.01E-11 | 1.03E-11 |
| Mn-56 | 9.79E-14 | 1.14E-13 | 1.22E-13 | | 7.35E-14 | 8.95E-14 | 9.56E-14 | | 3.44E-14 | 3.97E-14 | 4.22E-14 |
| Mo-99 | 5.62E-13 | 6.32E-13 | 8.66E-13 | | 4.45E-13 | 4.98E-13 | 5.49E-13 | | 1.72E-13 | 1.96E-13 | 2.39E-13 |
| Na-24 | 4.70E-13 | 5.16E-13 | 5.40E-13 | | 3.25E-13 | 3.70E-13 | 3.82E-13 | | 1.65E-13 | 1.81E-13 | 1.89E-13 |
| Nb-94 | 8.78E-10 | 8.79E-10 | 8.83E-10 | | 5.62E-10 | 5.62E-10 | 5.61E-10 | | 3.00E-10 | 3.00E-10 | 3.00E-10 |
| Nb-95 | 4.12E-12 | 4.25E-12 | 4.62E-12 | | 2.72E-12 | 2.71E-12 | 2.66E-12 | | 1.35E-12 | 1.40E-12 | 1.47E-12 |
| Nd-147 | 1.39E-12 | 1.48E-12 | 1.92E-12 | | 1.14E-12 | 1.14E-12 | 1.06E-12 | | 4.42E-13 | 4.84E-13 | 6.06E-13 |
| Ni-59 | 3.14E-13 | 3.66E-13 | 8.37E-13 | | 9.18E-14 | 9.33E-14 | 1.61E-13 | | 4.01E-14 | 5.50E-14 | 9.77E-14 |
| Ni-63 | 7.79E-13 | 9.31E-13 | 2.01E-12 | | 2.76E-13 | 2.74E-13 | 4.17E-13 | | 1.13E-13 | 1.48E-13 | 2.41E-13 |
| Np-239 | 4.46E-13 | 4.73E-13 | 5.98E-13 | | 3.98E-13 | 4.11E-13 | 4.31E-13 | | 1.48E-13 | 1.61E-13 | 2.02E-13 |

| Radionuclide | IRP(DB) | | | IRP01 | | | IRP02 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Adult | Child | Infant | Adult | Child | Infant | Adult | Child | Infant |
| P-32 | 5.66E-11 | 7.70E-11 | 2.47E-10 | 1.03E-11 | 1.45E-11 | 4.56E-11 | 4.16E-12 | 6.11E-12 | 1.86E-11 |
| Pr-143 | 1.27E-12 | 1.38E-12 | 1.92E-12 | 1.07E-12 | 1.10E-12 | 1.06E-12 | 4.06E-13 | 4.63E-13 | 6.27E-13 |
| Pr-144 | 5.14E-15 | 6.32E-15 | 7.34E-15 | 4.55E-15 | 5.72E-15 | 6.72E-15 | 1.17E-15 | 1.43E-15 | 1.66E-15 |
| Rb-88 | 1.29E-14 | 1.43E-14 | 1.56E-14 | 8.47E-15 | 9.81E-15 | 1.11E-14 | 3.37E-15 | 3.67E-15 | 3.98E-15 |
| Rb-89 | 2.87E-14 | 2.99E-14 | 3.20E-14 | 1.64E-14 | 1.73E-14 | 1.81E-14 | 7.42E-15 | 7.69E-15 | 8.02E-15 |
| Rh-105 | 2.39E-13 | 2.77E-13 | 5.44E-13 | 2.02E-13 | 2.31E-13 | 4.04E-13 | 7.30E-14 | 8.55E-14 | 1.56E-13 |
| Rh-106 | 2.64E-20 | 2.64E-20 | 2.64E-20 | 1.37E-20 | 1.37E-20 | 1.37E-20 | 1.97E-23 | 1.97E-23 | 1.97E-23 |
| Ru-103 | 3.44E-12 | 3.52E-12 | 3.88E-12 | 2.45E-12 | 2.45E-12 | 2.35E-12 | 1.15E-12 | 1.19E-12 | 1.29E-12 |
| Ru-105 | 1.13E-13 | 1.30E-13 | 1.71E-13 | 9.24E-14 | 1.08E-13 | 1.34E-13 | 3.79E-14 | 4.36E-14 | 5.49E-14 |
| Ru-106 | 2.58E-11 | 2.77E-11 | 3.63E-11 | 1.89E-11 | 1.91E-11 | 1.95E-11 | 8.14E-12 | 8.84E-12 | 1.11E-11 |
| Sb-122 | 1.10E-12 | 1.50E-12 | 2.95E-12 | 5.61E-13 | 6.54E-13 | 7.52E-13 | 2.32E-13 | 2.86E-13 | 4.05E-13 |
| Sb-124 | 3.20E-11 | 4.18E-11 | 7.87E-11 | 1.18E-11 | 1.20E-11 | 1.29E-11 | 5.90E-12 | 6.30E-12 | 7.29E-12 |
| Sb-125 | 5.65E-11 | 6.45E-11 | 9.51E-11 | 2.79E-11 | 2.78E-11 | 2.89E-11 | 1.46E-11 | 1.50E-11 | 1.57E-11 |
| Sb-126 | 1.11E-11 | 1.44E-11 | 2.54E-11 | 4.28E-12 | 4.56E-12 | 4.75E-12 | 2.11E-12 | 2.31E-12 | 2.68E-12 |
| Sb-127 | 2.01E-12 | 2.64E-12 | 5.32E-12 | 9.75E-13 | 1.04E-12 | 1.10E-12 | 4.04E-13 | 4.59E-13 | 6.10E-13 |
| Se-75 | 6.13E-10 | 1.06E-09 | 1.82E-09 | 4.46E-11 | 6.27E-11 | 9.52E-11 | 2.36E-11 | 3.60E-11 | 5.23E-11 |
| Sn-113 | 6.93E-12 | 7.87E-12 | 1.28E-11 | 3.80E-12 | 3.88E-12 | 4.44E-12 | 1.82E-12 | 1.98E-12 | 2.35E-12 |
| Sn-123 | 1.06E-11 | 1.34E-11 | 3.12E-11 | 4.85E-12 | 5.11E-12 | 7.26E-12 | 1.96E-12 | 2.44E-12 | 3.83E-12 |
| Sr-89 | 7.21E-12 | 9.22E-12 | 1.90E-11 | 3.54E-12 | 3.73E-12 | 4.94E-12 | 1.43E-12 | 1.84E-12 | 2.84E-12 |
| Sr-90 | 3.60E-10 | 5.03E-10 | 5.05E-10 | 7.38E-11 | 8.06E-11 | 8.07E-11 | 3.62E-11 | 6.28E-11 | 5.56E-11 |
| Sr-91 | 2.27E-13 | 2.66E-13 | 2.97E-13 | 1.91E-13 | 2.29E-13 | 2.45E-13 | 7.80E-14 | 9.22E-14 | 1.02E-13 |
| Sr-92 | 1.26E-13 | 1.53E-13 | 1.77E-13 | 1.05E-13 | 1.31E-13 | 1.48E-13 | 4.40E-14 | 5.33E-14 | 6.12E-14 |
| Tc-99m | 1.40E-14 | 1.57E-14 | 1.63E-14 | 1.09E-14 | 1.25E-14 | 1.25E-14 | 4.84E-15 | 5.41E-15 | 5.52E-15 |
| Te-123m | 1.34E-11 | 1.86E-11 | 3.35E-11 | 4.34E-12 | 4.39E-12 | 6.63E-12 | 2.23E-12 | 3.24E-12 | 4.58E-12 |
| Te-127m | 1.93E-11 | 3.08E-11 | 6.34E-11 | 5.76E-12 | 6.33E-12 | 1.12E-11 | 2.86E-12 | 4.94E-12 | 8.05E-12 |
| U-237 | 9.88E-13 | 1.04E-12 | 1.61E-12 | 7.69E-13 | 7.61E-13 | 7.66E-13 | 2.87E-13 | 3.02E-13 | 3.79E-13 |
| W-187 | 2.25E-13 | 2.82E-13 | 5.20E-13 | 1.82E-13 | 2.34E-13 | 4.23E-13 | 7.43E-14 | 9.48E-14 | 1.71E-13 |
| Xe-127 | 6.63E-15 | 6.63E-15 | 6.63E-15 | 3.45E-15 | 3.45E-15 | 3.45E-15 | 2.81E-15 | 2.81E-15 | 2.81E-15 |
| Xe-131m | 3.05E-16 | 3.05E-16 | 3.05E-16 | 1.58E-16 | 1.58E-16 | 1.58E-16 | 1.18E-16 | 1.18E-16 | 1.18E-16 |
| Xe-133 | 1.09E-15 | 1.09E-15 | 1.09E-15 | 5.66E-16 | 5.66E-16 | 5.66E-16 | 4.48E-16 | 4.48E-16 | 4.48E-16 |
| Xe-133m | 8.74E-16 | 8.74E-16 | 8.74E-16 | 4.55E-16 | 4.55E-16 | 4.55E-16 | 3.54E-16 | 3.54E-16 | 3.54E-16 |
| Xe-135 | 6.25E-15 | 6.25E-15 | 6.25E-15 | 3.25E-15 | 3.25E-15 | 3.25E-15 | 2.60E-15 | 2.60E-15 | 2.60E-15 |
| Xe-135m | 5.58E-15 | 5.58E-15 | 5.58E-15 | 2.90E-15 | 2.90E-15 | 2.90E-15 | 1.53E-15 | 1.53E-15 | 1.53E-15 |
| Xe-137 | 5.95E-16 | 5.95E-16 | 5.95E-16 | 3.10E-16 | 3.10E-16 | 3.10E-16 | 5.35E-17 | 5.35E-17 | 5.35E-17 |
| Xe-138 | 2.44E-14 | 2.51E-14 | 2.56E-14 | 1.36E-14 | 1.43E-14 | 1.49E-14 | 9.24E-15 | 9.55E-15 | 9.78E-15 |
| Y-90 | 7.91E-13 | 9.80E-13 | 1.52E-12 | 6.68E-13 | 8.02E-13 | 9.30E-13 | 2.53E-13 | 3.32E-13 | 5.12E-13 |
| Y-91 | 5.98E-12 | 7.08E-12 | 1.09E-11 | 4.31E-12 | 4.31E-12 | 4.47E-12 | 1.69E-12 | 2.01E-12 | 2.69E-12 |
| Y-92 | 8.03E-14 | 1.03E-13 | 1.22E-13 | 7.31E-14 | 9.49E-14 | 1.10E-13 | 2.67E-14 | 3.42E-14 | 4.05E-14 |
| Zn-65 | 1.04E-10 | 1.05E-10 | 2.24E-10 | 2.27E-11 | 2.29E-11 | 4.12E-11 | 1.04E-11 | 1.15E-11 | 1.87E-11 |
| Zr-95 | 1.40E-11 | 1.44E-11 | 1.54E-11 | 9.32E-12 | 9.24E-12 | 9.06E-12 | 4.65E-12 | 4.76E-12 | 4.90E-12 |
| Zr-97 | 5.50E-13 | 6.79E-13 | 7.73E-13 | 4.62E-13 | 5.81E-13 | 5.90E-13 | 1.86E-13 | 2.33E-13 | 2.64E-13 |
| Total | 2.72E-08 | 3.13E-08 | 3.23E-08 | 5.03E-09 | 5.01E-09 | 5.52E-09 | 2.32E-09 | 3.07E-09 | 2.68E-09 |

**Table A2- 2:** DCF Liquid Discharges µSv/yr per Bq/yr

| Radionuclide | IRP(DB) | | | | IRP01 | | | | IRP02 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adult | Child | Infant | | Adult | Child | Infant | | Adult | Child | Infant |
| Ag-110m | 9.92E-09 | 1.05E-08 | 1.15E-08 | | 5.34E-10 | 5.65E-10 | 2.61E-10 | | 3.80E-11 | 4.36E-11 | 3.74E-11 |
| Ar-41 | 4.83E-18 | 1.88E-18 | 1.79E-18 | | 4.55E-18 | 1.77E-18 | 1.69E-18 | | 8.53E-19 | 5.07E-19 | 1.69E-19 |
| As-76 | 3.03E-12 | 5.26E-12 | 3.98E-12 | | 1.04E-12 | 1.32E-12 | 2.16E-12 | | 4.80E-13 | 6.16E-13 | 9.57E-13 |
| Ba-139 | 3.74E-16 | 6.48E-16 | 7.38E-16 | | 1.38E-16 | 1.64E-16 | 2.77E-16 | | 5.95E-17 | 7.22E-17 | 1.17E-16 |
| Ba-140 | 5.11E-12 | 5.72E-12 | 5.46E-12 | | 3.13E-13 | 2.20E-13 | 2.37E-13 | | 6.97E-14 | 6.60E-14 | 6.14E-14 |
| Be-7 | 8.82E-14 | 5.57E-14 | 4.88E-14 | | 7.74E-15 | 3.49E-15 | 3.52E-15 | | 1.61E-15 | 1.12E-15 | 6.36E-16 |
| Br-82 | 2.86E-12 | 3.98E-12 | 4.47E-12 | | 3.92E-13 | 3.92E-13 | 1.92E-13 | | 2.85E-14 | 3.38E-14 | 8.78E-15 |
| Br-84 | 7.67E-15 | 1.11E-14 | 1.65E-14 | | 2.12E-15 | 2.21E-15 | 1.43E-15 | | 1.52E-16 | 1.89E-16 | 6.44E-17 |
| C-14 | 7.83E-10 | 8.02E-10 | 4.37E-10 | | 3.73E-11 | 3.03E-11 | 2.40E-11 | | 1.23E-11 | 1.03E-11 | 9.48E-12 |
| Ce-141 | 2.32E-12 | 1.68E-12 | 1.66E-12 | | 2.39E-13 | 1.19E-13 | 1.05E-13 | | 4.27E-14 | 2.79E-14 | 9.58E-15 |
| Ce-144 | 2.75E-11 | 1.82E-11 | 1.82E-11 | | 2.29E-12 | 1.09E-12 | 9.75E-13 | | 4.19E-13 | 2.64E-13 | 9.05E-14 |
| Co-57 | 3.83E-11 | 3.92E-11 | 2.50E-11 | | 2.81E-12 | 1.91E-12 | 1.51E-12 | | 4.91E-13 | 4.09E-13 | 1.49E-13 |
| Co-58 | 9.24E-11 | 9.58E-11 | 5.64E-11 | | 6.85E-12 | 4.88E-12 | 3.62E-12 | | 1.16E-12 | 9.98E-13 | 3.56E-13 |
| Co-60 | 2.79E-09 | 1.60E-09 | 1.23E-09 | | 2.37E-10 | 1.09E-10 | 9.64E-11 | | 4.39E-11 | 2.85E-11 | 9.59E-12 |
| Cr-51 | 8.77E-13 | 1.11E-12 | 6.53E-13 | | 5.81E-14 | 4.63E-14 | 4.70E-14 | | 1.29E-14 | 1.33E-14 | 9.18E-15 |
| Cs-134 | 1.52E-10 | 7.70E-11 | 3.75E-11 | | 9.42E-12 | 3.89E-12 | 2.78E-12 | | 2.75E-12 | 1.35E-12 | 6.27E-13 |
| Cs-136 | 8.21E-12 | 8.77E-12 | 5.15E-12 | | 8.24E-13 | 6.57E-13 | 6.33E-13 | | 2.97E-13 | 2.57E-13 | 2.54E-13 |
| Cs-137 | 1.64E-10 | 7.78E-11 | 4.84E-11 | | 1.11E-11 | 4.52E-12 | 3.68E-12 | | 2.75E-12 | 1.46E-12 | 6.31E-13 |
| Cs-138 | 7.50E-16 | 1.07E-15 | 9.89E-16 | | 4.50E-16 | 4.90E-16 | 7.58E-16 | | 1.75E-16 | 1.95E-16 | 3.21E-16 |
| Cu-64 | 1.62E-11 | 1.93E-11 | 2.61E-11 | | 7.16E-12 | 8.57E-12 | 4.85E-12 | | 4.98E-13 | 6.52E-13 | 6.97E-13 |
| Fe-55 | 3.03E-09 | 6.30E-09 | 3.87E-09 | | 1.40E-10 | 2.68E-10 | 1.17E-10 | | 1.35E-11 | 2.96E-11 | 1.33E-11 |
| Fe-59 | 1.27E-08 | 2.07E-08 | 1.61E-08 | | 7.47E-10 | 1.12E-09 | 6.18E-10 | | 7.21E-11 | 1.24E-10 | 7.00E-11 |
| H-3 | 1.25E-15 | 1.19E-15 | 6.94E-16 | | 5.87E-17 | 4.42E-17 | 3.65E-17 | | 1.93E-17 | 1.50E-17 | 1.44E-17 |
| Hf-181 | 1.97E-11 | 1.30E-11 | 8.90E-12 | | 1.97E-12 | 9.11E-13 | 8.56E-13 | | 3.65E-13 | 2.42E-13 | 6.96E-14 |
| Hg-203 | 2.39E-09 | 2.47E-09 | 3.31E-09 | | 1.64E-10 | 1.79E-10 | 7.21E-11 | | 4.39E-12 | 5.58E-12 | 1.01E-12 |
| I-129 | 3.55E-10 | 5.90E-10 | 3.17E-10 | | 2.73E-12 | 2.78E-12 | 1.45E-12 | | 1.07E-12 | 1.12E-12 | 5.94E-13 |
| I-130 | 2.23E-13 | 4.92E-13 | 8.94E-13 | | 1.55E-14 | 2.09E-14 | 3.67E-14 | | 6.04E-15 | 8.40E-15 | 1.50E-14 |
| I-131 | 2.54E-11 | 5.79E-11 | 9.30E-11 | | 4.78E-13 | 6.67E-13 | 1.04E-12 | | 1.87E-13 | 2.69E-13 | 4.25E-13 |
| I-132 | 6.19E-15 | 1.27E-14 | 2.29E-14 | | 5.63E-16 | 7.01E-16 | 1.22E-15 | | 2.18E-16 | 2.82E-16 | 4.97E-16 |
| I-133 | 7.86E-13 | 1.76E-12 | 3.59E-12 | | 4.57E-14 | 6.27E-14 | 1.24E-13 | | 1.79E-14 | 2.53E-14 | 5.08E-14 |
| I-134 | 8.98E-16 | 1.65E-15 | 2.73E-15 | | 8.56E-17 | 9.50E-17 | 1.52E-16 | | 3.31E-17 | 3.82E-17 | 6.20E-17 |
| I-135 | 5.63E-14 | 1.28E-13 | 2.40E-13 | | 4.51E-15 | 6.24E-15 | 1.13E-14 | | 1.75E-15 | 2.51E-15 | 4.63E-15 |
| Kr-85 | 5.51E-15 | 2.20E-15 | 1.85E-15 | | 4.21E-16 | 1.66E-16 | 1.49E-16 | | 8.54E-17 | 4.46E-17 | 1.49E-17 |
| Kr-85m | 4.04E-18 | 1.58E-18 | 1.48E-18 | | 3.28E-18 | 1.28E-18 | 1.22E-18 | | 6.19E-19 | 3.64E-19 | 1.22E-19 |
| Kr-87 | 1.50E-18 | 5.81E-19 | 5.53E-19 | | 1.43E-18 | 5.55E-19 | 5.30E-19 | | 2.68E-19 | 1.59E-19 | 5.30E-20 |

| Radionuclide | IRP(DB) | | | | IRP01 | | | | IRP02 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adult | Child | Infant | | Adult | Child | Infant | | Adult | Child | Infant |
| Kr-88 | 3.86E-15 | 5.64E-15 | 5.46E-15 | | 2.14E-15 | 2.37E-15 | 3.86E-15 | | 8.29E-16 | 9.44E-16 | 1.63E-15 |
| La-140 | 9.03E-13 | 9.16E-13 | 8.48E-13 | | 2.75E-13 | 1.77E-13 | 1.45E-13 | | 4.65E-14 | 3.65E-14 | 1.59E-14 |
| Mn-54 | 2.20E-10 | 1.03E-10 | 8.22E-11 | | 2.05E-11 | 8.43E-12 | 7.85E-12 | | 3.82E-12 | 2.36E-12 | 7.69E-13 |
| Mn-56 | 6.42E-14 | 9.16E-14 | 3.95E-14 | | 2.37E-14 | 2.67E-14 | 2.46E-14 | | 3.96E-15 | 5.37E-15 | 1.73E-15 |
| Mo-99 | 3.01E-12 | 4.30E-12 | 3.13E-12 | | 3.77E-13 | 3.90E-13 | 4.25E-13 | | 9.33E-14 | 1.09E-13 | 9.33E-14 |
| Na-24 | 2.02E-15 | 1.77E-15 | 1.64E-15 | | 1.11E-15 | 7.33E-16 | 8.25E-16 | | 2.80E-16 | 2.41E-16 | 2.68E-16 |
| Nb-94 | 6.42E-09 | 2.50E-09 | 2.38E-09 | | 5.36E-10 | 2.08E-10 | 1.99E-10 | | 1.00E-10 | 5.97E-11 | 1.99E-11 |
| Nb-95 | 1.70E-11 | 7.59E-12 | 7.06E-12 | | 2.02E-12 | 8.06E-13 | 7.65E-13 | | 3.77E-13 | 2.28E-13 | 7.63E-14 |
| Nd-147 | 1.01E-10 | 1.53E-10 | 5.08E-11 | | 6.37E-12 | 7.55E-12 | 7.41E-12 | | 1.12E-12 | 1.63E-12 | 2.44E-13 |
| Ni-59 | 6.58E-12 | 6.60E-12 | 5.33E-12 | | 3.63E-13 | 2.59E-13 | 2.91E-13 | | 9.08E-14 | 8.15E-14 | 8.82E-14 |
| Ni-63 | 1.04E-11 | 1.45E-11 | 1.11E-11 | | 4.42E-13 | 4.84E-13 | 5.57E-13 | | 1.37E-13 | 1.57E-13 | 2.02E-13 |
| Np-239 | 8.51E-13 | 1.23E-12 | 6.68E-13 | | 1.35E-13 | 1.64E-13 | 1.25E-13 | | 1.56E-14 | 2.34E-14 | 1.15E-15 |
| P-32 | 2.11E-09 | 3.57E-09 | 3.49E-09 | | 1.89E-10 | 2.47E-10 | 3.80E-10 | | 6.98E-11 | 9.33E-11 | 1.58E-10 |
| Pr-143 | 3.82E-13 | 4.33E-13 | 4.39E-13 | | 3.86E-14 | 3.45E-14 | 2.30E-14 | | 5.03E-15 | 4.27E-15 | 1.69E-15 |
| Pr-144 | 2.31E-17 | 2.77E-17 | 3.14E-17 | | 1.15E-17 | 1.20E-17 | 8.24E-18 | | 9.87E-19 | 1.16E-18 | 5.42E-19 |
| Rb-88 | 4.04E-16 | 5.93E-16 | 5.74E-16 | | 2.43E-16 | 2.72E-16 | 4.43E-16 | | 9.49E-17 | 1.08E-16 | 1.88E-16 |
| Rb-89 | 6.15E-16 | 8.07E-16 | 9.80E-16 | | 1.38E-16 | 1.53E-16 | 2.03E-16 | | 4.47E-17 | 4.98E-17 | 8.12E-17 |
| Rh-105 | 1.26E-12 | 2.05E-12 | 1.21E-12 | | 1.92E-13 | 2.37E-13 | 2.15E-13 | | 2.94E-14 | 4.53E-14 | 9.08E-16 |
| Rh-106 | 2.69E-23 | 1.05E-23 | 9.87E-24 | | 2.67E-23 | 1.04E-23 | 9.87E-24 | | 5.04E-24 | 2.96E-24 | 9.87E-25 |
| Ru-103 | 9.50E-12 | 9.85E-12 | 9.31E-12 | | 6.53E-13 | 3.64E-13 | 3.10E-13 | | 1.14E-13 | 8.26E-14 | 2.08E-14 |
| Ru-105 | 1.89E-13 | 3.08E-13 | 2.04E-13 | | 2.86E-14 | 3.45E-14 | 3.03E-14 | | 4.20E-15 | 6.31E-15 | 2.21E-16 |
| Ru-106 | 8.79E-11 | 1.15E-10 | 1.15E-10 | | 3.75E-12 | 2.62E-12 | 2.19E-12 | | 6.21E-13 | 5.26E-13 | 1.07E-13 |
| Sb-122 | 7.19E-12 | 1.28E-11 | 9.70E-12 | | 1.59E-12 | 2.06E-12 | 3.37E-12 | | 7.31E-13 | 9.60E-13 | 1.49E-12 |
| Sb-124 | 5.58E-11 | 9.23E-11 | 6.66E-11 | | 3.45E-12 | 4.13E-12 | 6.37E-12 | | 1.54E-12 | 1.91E-12 | 2.80E-12 |
| Sb-125 | 5.19E-11 | 7.61E-11 | 6.58E-11 | | 2.09E-12 | 1.96E-12 | 2.75E-12 | | 8.00E-13 | 8.66E-13 | 1.14E-12 |
| Sb-126 | 3.01E-11 | 4.98E-11 | 3.33E-11 | | 2.98E-12 | 3.58E-12 | 5.16E-12 | | 1.36E-12 | 1.67E-12 | 2.28E-12 |
| Sb-127 | 1.29E-11 | 2.22E-11 | 1.95E-11 | | 2.06E-12 | 2.59E-12 | 4.21E-12 | | 9.05E-13 | 1.15E-12 | 1.84E-12 |
| Se-75 | 8.90E-10 | 1.53E-09 | 8.66E-10 | | 4.77E-11 | 6.49E-11 | 5.74E-11 | | 1.64E-11 | 2.30E-11 | 2.29E-11 |
| Sn-113 | 3.84E-10 | 5.90E-10 | 4.93E-10 | | 2.55E-11 | 3.06E-11 | 3.76E-11 | | 8.03E-12 | 1.03E-11 | 1.45E-11 |
| Sn-123 | 1.05E-09 | 1.69E-09 | 1.56E-09 | | 6.62E-11 | 8.51E-11 | 1.17E-10 | | 2.18E-11 | 2.89E-11 | 4.62E-11 |
| Sr-89 | 2.07E-12 | 2.64E-12 | 3.56E-12 | | 1.33E-13 | 1.71E-13 | 9.17E-14 | | 9.90E-15 | 1.35E-14 | 1.58E-14 |
| Sr-90 | 2.87E-11 | 3.51E-11 | 1.86E-11 | | 1.46E-12 | 1.80E-12 | 3.81E-13 | | 1.09E-13 | 1.43E-13 | 6.58E-14 |
| Sr-91 | 5.70E-14 | 6.46E-14 | 7.56E-14 | | 1.13E-14 | 1.15E-14 | 6.83E-15 | | 9.66E-16 | 1.01E-15 | 1.01E-15 |
| Sr-92 | 1.41E-14 | 1.74E-14 | 2.06E-14 | | 6.42E-15 | 7.13E-15 | 4.46E-15 | | 4.98E-16 | 6.18E-16 | 3.67E-16 |
| Tc-99m | 4.00E-14 | 7.07E-14 | 1.02E-13 | | 4.76E-15 | 5.34E-15 | 3.19E-15 | | 4.65E-16 | 5.73E-16 | 5.57E-16 |
| Te-123m | 1.16E-10 | 1.88E-10 | 2.06E-10 | | 4.49E-12 | 5.27E-12 | 6.55E-12 | | 1.47E-12 | 1.79E-12 | 2.58E-12 |

| Radionuclide | IRP(DB) | | | | IRP01 | | | | IRP02 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adult | Child | Infant | | Adult | Child | Infant | | Adult | Child | Infant |
| Te-127m | 1.88E-10 | 3.45E-10 | 4.16E-10 | | 7.34E-12 | 9.76E-12 | 1.34E-11 | | 2.41E-12 | 3.31E-12 | 5.28E-12 |
| U-237 | 2.24E-13 | 3.54E-13 | 3.61E-13 | | 1.62E-14 | 1.84E-14 | 1.51E-14 | | 2.28E-15 | 3.01E-15 | 1.42E-15 |
| W-187 | 2.41E-11 | 2.64E-11 | 4.90E-11 | | 9.01E-12 | 1.06E-11 | 3.91E-12 | | 6.30E-14 | 7.24E-14 | 3.92E-14 |
| Xe-127 | 3.11E-14 | 1.21E-14 | 1.15E-14 | | 3.36E-15 | 1.30E-15 | 1.25E-15 | | 6.29E-16 | 3.75E-16 | 1.25E-16 |
| Xe-131m | 8.71E-16 | 3.42E-16 | 3.12E-16 | | 1.38E-16 | 5.38E-17 | 5.04E-17 | | 2.66E-17 | 1.51E-17 | 5.04E-18 |
| Xe-133 | 5.43E-16 | 2.12E-16 | 1.98E-16 | | 1.32E-16 | 5.14E-17 | 4.88E-17 | | 2.51E-17 | 1.46E-17 | 4.88E-18 |
| Xe-133m | 4.22E-16 | 1.64E-16 | 1.54E-16 | | 1.08E-16 | 4.19E-17 | 3.96E-17 | | 2.04E-17 | 1.19E-17 | 3.96E-18 |
| Xe-135 | 2.35E-17 | 9.16E-18 | 8.67E-18 | | 1.81E-17 | 7.02E-18 | 6.70E-18 | | 3.41E-18 | 2.01E-18 | 6.70E-19 |
| Xe-135m | 7.12E-19 | 2.76E-19 | 2.62E-19 | | 5.51E-19 | 2.14E-19 | 2.05E-19 | | 1.04E-19 | 6.13E-20 | 2.05E-20 |
| Xe-137 | 0.00E+00 | 0.00E+00 | 0.00E+00 | | 0.00E+00 | 0.00E+00 | 0.00E+00 | | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Xe-138 | 3.30E-16 | 4.72E-16 | 4.34E-16 | | 1.96E-16 | 2.14E-16 | 3.30E-16 | | 7.63E-17 | 8.50E-17 | 1.40E-16 |
| Y-90 | 1.14E-12 | 1.58E-12 | 1.66E-12 | | 2.04E-13 | 2.51E-13 | 1.53E-13 | | 1.53E-14 | 2.18E-14 | 7.00E-15 |
| Y-91 | 5.75E-12 | 6.79E-12 | 7.20E-12 | | 3.83E-13 | 3.59E-13 | 2.39E-13 | | 4.38E-14 | 4.11E-14 | 1.35E-14 |
| Y-92 | 1.40E-14 | 1.80E-14 | 2.01E-14 | | 6.31E-15 | 7.07E-15 | 4.59E-15 | | 4.97E-16 | 6.34E-16 | 2.15E-16 |
| Zn-65 | 1.04E-08 | 9.21E-09 | 1.01E-08 | | 5.98E-10 | 5.58E-10 | 1.85E-10 | | 1.66E-11 | 1.78E-11 | 2.73E-12 |
| Zr-95 | 7.48E-11 | 3.40E-11 | 2.90E-11 | | 7.50E-12 | 3.04E-12 | 2.87E-12 | | 1.40E-12 | 8.55E-13 | 2.75E-13 |
| Zr-97 | 6.89E-13 | 1.00E-12 | 4.80E-13 | | 1.73E-13 | 1.78E-13 | 1.57E-13 | | 2.87E-14 | 3.66E-14 | 3.80E-15 |
| **Total** | **5.48E-08** | **6.38E-08** | **5.72E-08** | | **3.45E-09** | **3.56E-09** | **2.26E-09** | | **4.45E-10** | **5.01E-10** | **4.29E-10** |

## A.3. Appendix 3 - Plume Modelling Results and its Representativeness of Duynefontyn

The Duynefontyn site is regarded as a complex terrain in respect of atmospheric dispersion because of the characteristics typical of coastal sites such as stagnation, inversion, recirculation, and fumigation conditions. The PLUME code is acceptable for atmospheric transport of continuous radioactive discharges over long periods and over simple terrain. The simple Gaussian model is considered not applicable for releases from sources near buildings or at coastal sites and does not include the effects of plume rise.

The dispersion coefficients calculated by PLUME for a specific year's meteorological data were compared to values of a more advanced dispersion code capable of treating a complex terrain and its impact on atmospheric dispersion. A Lagrangian puff model, CALPUFF, was used to compare dispersion coefficients with those of PLUME. CALPUFF is an advanced non-steady-state meteorological and air quality modelling system developed by Exponents Scientists and can account for the Duynefontyn site characteristics and building wake effects [42]. The model has been adopted by the U.S. Environmental Protection Agency (U.S. EPA) in its guideline on air quality models as the preferred model for assessing long-range transport of pollutants and sensitive land areas referred to as Federal Class I areas. It is also used on a case-by-case basis for certain near-field applications involving complex meteorological conditions, such as coastal sites.

The modelling system consists of three main components and a set of pre-processing and post-processing programs. The main components of the modelling system are CALMET (a diagnostic three- dimensional meteorological model), CALPUFF (an air quality dispersion model), and CALPOST (a post- processing package). In addition to these components, several other processors are used to prepare geophysical (land use and terrain) data and meteorological data that include interfaces to other models such as the weather research and forecasting (WRF) model.

The WRF model is a mesoscale numerical weather prediction system designed to serve both atmospheric research and operational forecasting needs. Data for the Duynefontyn site was obtained from the Canadian company Lakes Environmental who provides meteorological data for a large international client base for purposes of regulatory air quality compliance studies [42]. CALMET-ready WRF data is generated, consisting of three-dimensional data spanning many vertical layers and covering a horizontal grid and domain specified by the client.

The data parameters for the Duynefontyn site are based on 4 km grid resolutions (recommended for complex terrain sites). The layout of KNPS and its stack discharge characteristics were modelled to include building wake effects.

A meteorological data file was prepared for PLUME, as described in [4]. Dispersion coefficients were determined for various distances in the 16 sectors illustrated in Figure 7-1 and for three different discharge heights; 10 m, 20 m and 64 m. CALPUFF was run using meteorological data for the same year and included actual KNPS stack data and also allowing for building downwash effects.

It was determined that using a 10 m stack height for discharges and a surface roughness length of 0.3 as input data to PLUME corresponds well with CALPUFF results. The dispersion coefficients (X/Q) calculated with PLUME are listed in Table A2-1. The values for wind sector 5, where nearest members of the public are located at approximately 2 km from the discharge point (KNPS stack), agree well with the X/Q value equal to 1E-07 calculated with CALPUFF. The CALPUFF results are illustrated in Figure A3-1 and Figure A3-2.

| | 400 m | | | 800 m | | | 1000 m | | | 2000 m | | | 5000 m | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sector** | **10 m** | **20 m** | **63 m** | **10 m** | **20 m** | **63 m** | **10 m** | **20 m** | **63 m** | **10 m** | **20 m** | **63 m** | **10 m** | **20 m** | **63 m** |
| 1 | 4.02E-06 | 2.05E-06 | 3.66E-07 | 1.27E-06 | 7.98E-07 | 1.92E-07 | 8.53E-07 | 5.72E-07 | 1.54E-07 | 2.63E-07 | 1.97E-07 | 7.35E-08 | 5.66E-08 | 4.53E-08 | 2.29E-08 |
| 2 | 3.57E-06 | 1.30E-06 | 1.13E-07 | 1.33E-06 | 7.18E-07 | 8.99E-08 | 9.27E-07 | 5.56E-07 | 8.31E-08 | 3.09E-07 | 2.21E-07 | 5.41E-08 | 7.01E-08 | 5.50E-08 | 2.25E-08 |
| 3 | 3.45E-06 | 1.55E-06 | 2.34E-07 | 1.16E-06 | 6.90E-07 | 1.33E-07 | 7.89E-07 | 5.10E-07 | 1.10E-07 | 2.54E-07 | 1.87E-07 | 5.75E-08 | 5.59E-08 | 4.45E-08 | 2.08E-08 |
| 4 | 3.77E-06 | 1.82E-06 | 2.50E-07 | 1.21E-06 | 7.63E-07 | 1.56E-07 | 8.18E-07 | 5.52E-07 | 1.32E-07 | 2.55E-07 | 1.92E-07 | 6.96E-08 | 5.44E-08 | 4.37E-08 | 2.25E-08 |
| 5 | 2.91E-06 | 1.50E-06 | 3.15E-07 | 8.83E-07 | 5.71E-07 | 1.38E-07 | 5.87E-07 | 4.05E-07 | 1.07E-07 | 1.82E-07 | 1.38E-07 | 5.08E-08 | 3.92E-08 | 3.17E-08 | 1.70E-08 |
| 6 | 2.44E-06 | 1.32E-06 | 2.25E-07 | 7.37E-07 | 4.93E-07 | 1.35E-07 | 4.90E-07 | 3.46E-07 | 1.07E-07 | 1.48E-07 | 1.14E-07 | 4.71E-08 | 3.06E-08 | 2.48E-08 | 1.37E-08 |
| 7 | 2.84E-06 | 1.55E-06 | 2.39E-07 | 8.47E-07 | 5.75E-07 | 1.56E-07 | 5.62E-07 | 4.02E-07 | 1.26E-07 | **1.69E-07** | **1.31E-07** | **5.64E-08** | 3.47E-08 | 2.82E-08 | 1.62E-08 |
| 8 | 2.65E-06 | 1.32E-06 | 1.68E-07 | 8.39E-07 | 5.46E-07 | 1.20E-07 | 5.63E-07 | 3.91E-07 | 1.01E-07 | 1.74E-07 | 1.33E-07 | 5.09E-08 | 3.59E-08 | 2.91E-08 | 1.58E-08 |
| 9 | 2.94E-06 | 1.40E-06 | 1.79E-07 | 9.39E-07 | 6.05E-07 | 1.17E-07 | 6.31E-07 | 4.36E-07 | 9.97E-08 | 1.97E-07 | 1.50E-07 | 5.41E-08 | 4.11E-08 | 3.33E-08 | 1.81E-08 |
| 10 | 2.46E-06 | 7.76E-07 | 3.17E-08 | 9.42E-07 | 5.04E-07 | 4.23E-08 | 6.55E-07 | 3.96E-07 | 4.29E-08 | 2.25E-07 | 1.61E-07 | 3.36E-08 | 5.07E-08 | 4.01E-08 | 1.67E-08 |
| 11 | 5.28E-06 | 8.84E-07 | 1.75E-08 | 2.51E-06 | 9.76E-07 | 3.03E-08 | 1.82E-06 | 8.73E-07 | 3.45E-08 | 6.59E-07 | 4.32E-07 | 3.88E-08 | 1.65E-07 | 1.25E-07 | 3.36E-08 |
| 12 | 5.92E-06 | 1.08E-06 | 1.63E-08 | 2.73E-06 | 1.12E-06 | 2.92E-08 | 1.97E-06 | 9.79E-07 | 3.85E-08 | 7.09E-07 | 4.70E-07 | 4.89E-08 | 1.75E-07 | 1.34E-07 | 3.85E-08 |
| 13 | 3.33E-06 | 7.14E-07 | 6.91E-09 | 1.45E-06 | 6.50E-07 | 2.02E-08 | 1.03E-06 | 5.49E-07 | 2.68E-08 | 3.69E-07 | 2.51E-07 | 3.24E-08 | 8.87E-08 | 6.85E-08 | 2.24E-08 |
| 14 | 4.13E-06 | 1.16E-06 | 2.94E-08 | 1.62E-06 | 8.47E-07 | 4.35E-08 | 1.13E-06 | 6.74E-07 | 5.09E-08 | 3.92E-07 | 2.80E-07 | 5.14E-08 | 8.90E-08 | 7.04E-08 | 2.90E-08 |

| | 400 m | | | 800 m | | | 1000 m | | | 2000 m | | | 5000 m | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sector | 10 m | 20 m | 63 m | 10 m | 20 m | 63 m | 10 m | 20 m | 63 m | 10 m | 20 m | 63 m | 10 m | 20 m | 63 m |
| 15 | 6.33E-06 | 2.90E-06 | 1.35E-07 | 2.06E-06 | 1.36E-06 | 2.04E-07 | 1.39E-06 | 9.82E-07 | 2.00E-07 | 4.28E-07 | 3.33E-07 | 1.28E-07 | 8.54E-08 | 6.98E-08 | 4.06E-08 |
| 16 | 5.76E-06 | 3.54E-06 | 6.25E-07 | 1.59E-06 | 1.17E-06 | 3.91E-07 | 1.03E-06 | 7.86E-07 | 3.05E-07 | 2.94E-07 | 2.36E-07 | 1.24E-07 | 5.71E-08 | 4.72E-08 | 3.07E-08 |

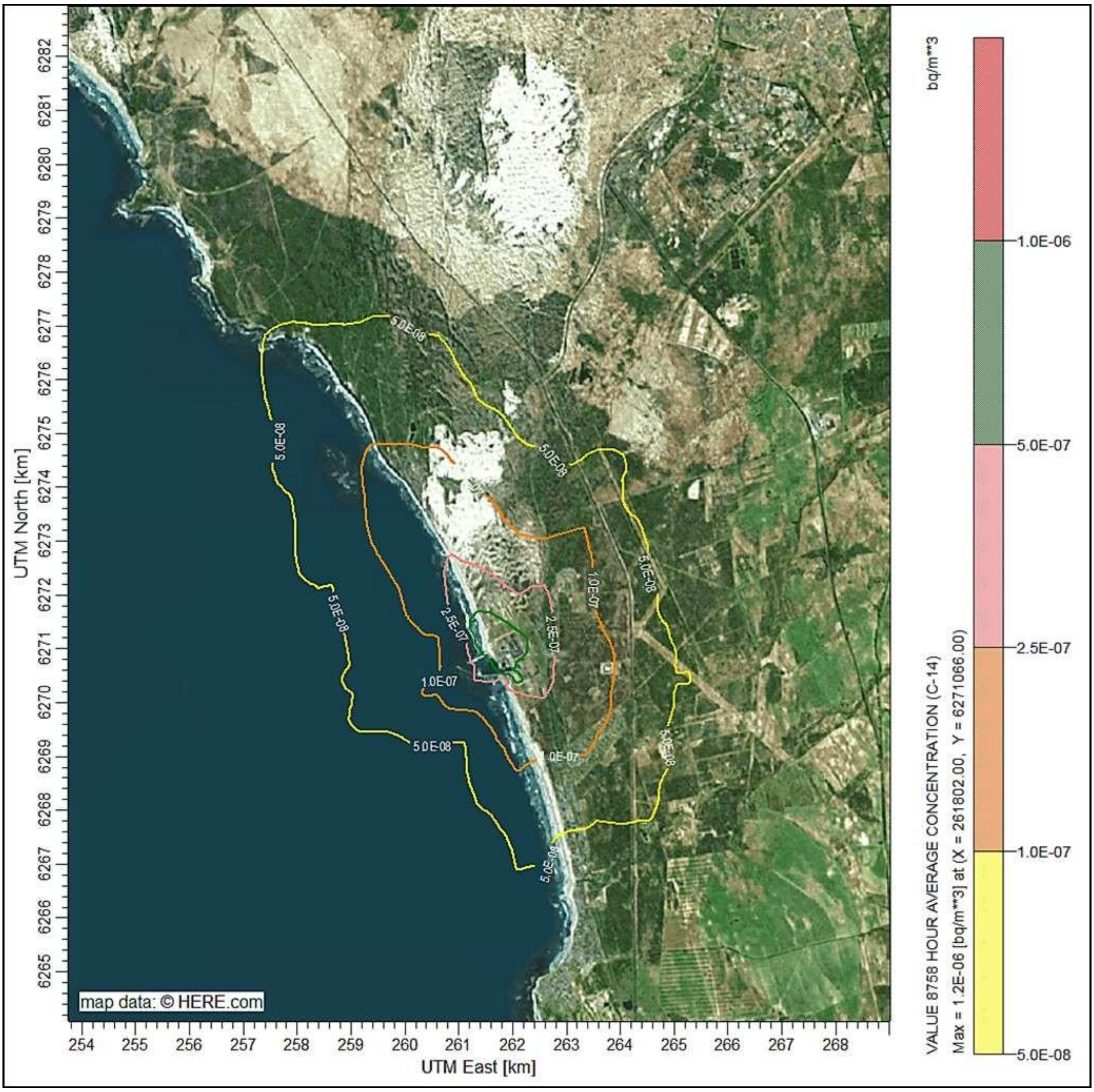


**Figure A3-1:** CALPUFF Annual X/Q (2011)

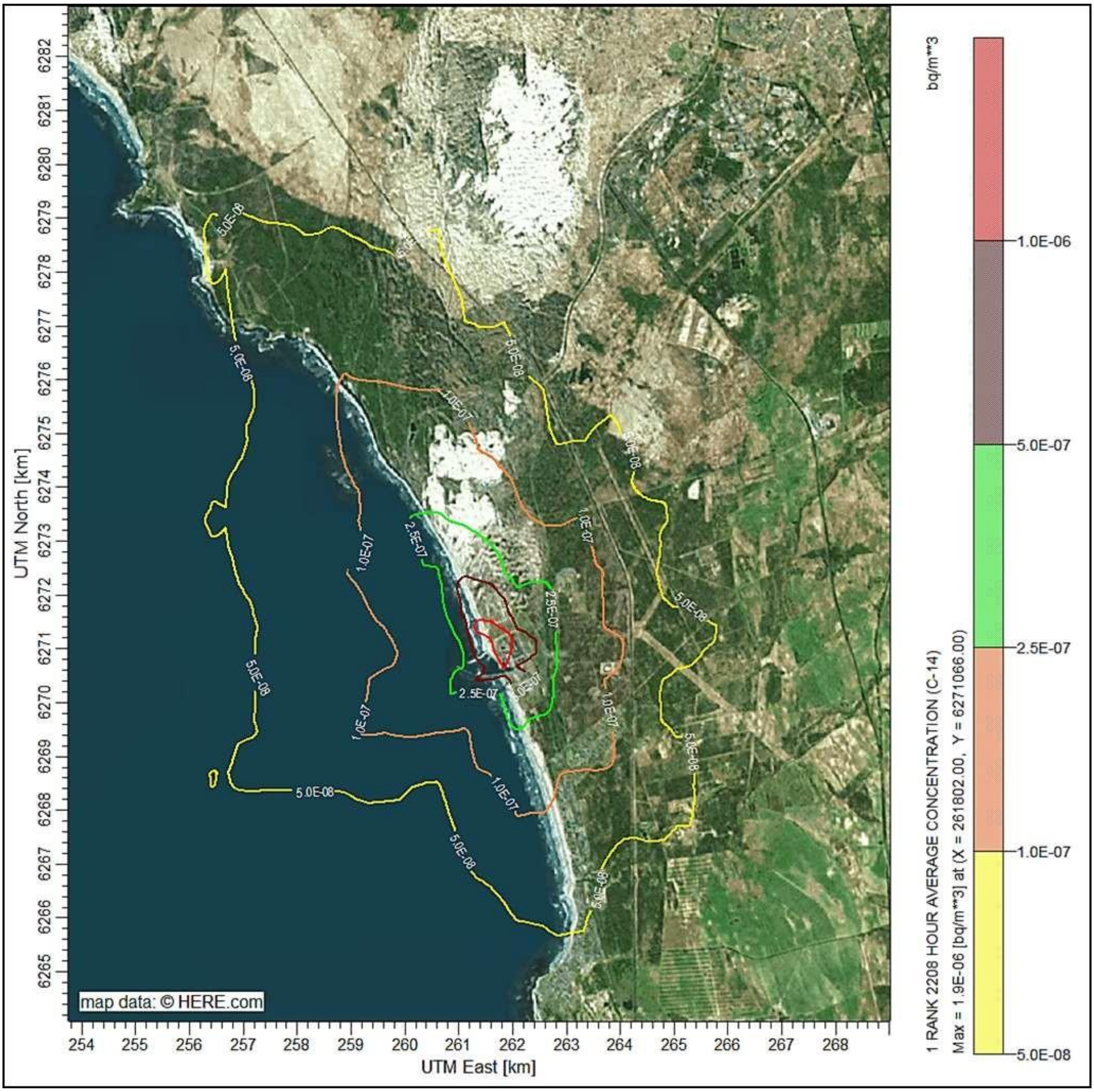


**Figure A3-2:** Quarterly X/Q (2011)

## A.4. Appendix 4 - GRANIS Model Soil Type Sensitivity

**Name:** GRANIS_Dcf_2020_FirDoc 238_49 3
**Description:** Nuclides_plus_Nov20_Dry Soil Hi Si
**Type:** Atmosphere Granis Model
**Date:** 05/12/2020 13:41

PC Cream version: 1.5.1.92
Database version: 2.0.0 update version

Result type: Gamma dose
Instantaneous / Integrals: Integrals
Select organ: effective

View Table

**Integrated dose (effective) 1 m above the ground (Sv) for deposition rate over one year of 1.00E+0 Bq/m2/s**

| Radionuclide | Time (y) 1 | 40 | 60 | 80 |
|---|---|---|---|---|
| Co-58 | 1.26E-01 | 1.71E-01 | 1.71E-01 | 1.71E-01 |
| Co-60 | 7.26E-01 | 7.58E+00 | 7.59E+00 | 7.59E+00 |
| Cr-51 | 1.98E-03 | 2.22E-03 | 2.22E-03 | 2.22E-03 |
| Cs-134 | 4.36E-01 | 2.35E+00 | 2.35E+00 | 2.35E+00 |
| Cs-136 | 6.76E-02 | 7.12E-02 | 7.12E-02 | 7.12E-02 |
| Cs-137 | 1.85E-01 | 4.32E+00 | 4.67E+00 | 4.80E+00 |
| Ba-137m (Cs-137) | 2.72E-06 | 2.72E-06 | 2.72E-06 | 2.72E-06 |
| Cs-138 | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 |
| Cu-64 | 2.61E-04 | 2.61E-04 | 2.61E-04 | 2.61E-04 |
| Fe-55 | 5.10E-07 | 2.39E-06 | 2.39E-06 | 2.39E-06 |
| Fe-59 | 1.07E-01 | 1.29E-01 | 1.29E-01 | 1.29E-01 |
| H-3 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Hf-181 | 4.91E-02 | 5.87E-02 | 5.87E-02 | 5.87E-02 |
| Hg-203 | 2.25E-02 | 2.74E-02 | 2.74E-02 | 2.74E-02 |
| I-129 | 1.49E-03 | 1.68E-02 | 1.72E-02 | 1.73E-02 |
| I-130 | 2.83E-03 | 2.83E-03 | 2.83E-03 | 2.83E-03 |
| I-131 | 7.74E-03 | 8.00E-03 | 8.00E-03 | 8.00E-03 |
| Xe-131m (I-131) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| I-132 | 5.56E-04 | 5.56E-04 | 5.56E-04 | 5.56E-04 |

**Name:** GRANIS_Dcf_2020_FirDoc 238_49

**Description:** Nuclides_plus_Nov20_Generic Dry Soil Undisturbed

**Type:** Atmosphere Granis Model

**Date:** 11/11/2020 19:51

PC Cream version: 1.5.1.92

Database version: 2.0.0 update version

Result type: Gamma dose

Instantaneous / Integrals: Integrals

Select organ: effective

View Table

**Integrated dose (effective) 1 m above the ground (Sv) for deposition rate over one year of 1.00E+0 Bq/m2/s**

| Radionuclide | Time (y) 1 | 40 | 60 | 80 |
|---|---|---|---|---|
| Co-58 | 1.31E-01 | 1.78E-01 | 1.78E-01 | 1.78E-01 |
| Co-60 | 7.55E-01 | 7.86E+00 | 7.87E+00 | 7.87E+00 |
| Cr-51 | 2.06E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 |
| Cs-134 | 4.54E-01 | 2.44E+00 | 2.44E+00 | 2.44E+00 |
| Cs-136 | 7.03E-02 | 7.41E-02 | 7.41E-02 | 7.41E-02 |
| Cs-137 | 1.93E-01 | 4.48E+00 | 4.83E+00 | 4.97E+00 |
| Ba-137m (Cs-137) | 2.83E-06 | 2.83E-06 | 2.83E-06 | 2.83E-06 |
| Cs-138 | 1.33E-04 | 1.33E-04 | 1.33E-04 | 1.33E-04 |
| Cu-64 | 2.72E-04 | 2.72E-04 | 2.72E-04 | 2.72E-04 |
| Fe-55 | 9.16E-07 | 4.30E-06 | 4.30E-06 | 4.30E-06 |
| Fe-59 | 1.11E-01 | 1.34E-01 | 1.34E-01 | 1.34E-01 |
| H-3 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Hf-181 | 5.13E-02 | 6.14E-02 | 6.14E-02 | 6.14E-02 |
| Hg-203 | 2.35E-02 | 2.87E-02 | 2.87E-02 | 2.87E-02 |
| I-129 | 2.09E-03 | 2.43E-02 | 2.49E-02 | 2.51E-02 |
| I-130 | 2.94E-03 | 2.95E-03 | 2.95E-03 | 2.95E-03 |
| I-131 | 8.09E-03 | 8.36E-03 | 8.36E-03 | 8.36E-03 |
| Xe-131m (I-131) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| I-132 | 5.78E-04 | 5.78E-04 | 5.78E-04 | 5.78E-04 |

**Name:** GRANIS_Dcf_2020_FirDoc 238_49 2
**Description:** Nuclides_plus_Nov20_Generic Wet Soil Well Mix
**Type:** Atmosphere Granis Model
**Date:** 05/12/2020 13:46

PC Cream version: 1.5.1.92

Database version: 2.0.0 update version

Result type: Gamma dose

Instantaneous / Integrals: Integrals

Select organ: effective

View Table

Integrated dose (effective) 1 m above the ground (Sv) for deposition rate over one year of 1.00E+0 Bq/m2/s

| Radionuclide | Time (y) 1 | 40 | 60 | 80 |
|---|---|---|---|---|
| Co-58 | 2.38E-02 | 3.26E-02 | 3.26E-02 | 3.26E-02 |
| Co-60 | 1.52E-01 | 2.28E+00 | 2.29E+00 | 2.29E+00 |
| Cr-51 | 3.24E-04 | 3.63E-04 | 3.63E-04 | 3.63E-04 |
| Cs-134 | 8.27E-02 | 5.39E-01 | 5.39E-01 | 5.39E-01 |
| Cs-136 | 1.28E-02 | 1.35E-02 | 1.35E-02 | 1.35E-02 |
| Cs-137 | 3.48E-02 | 1.63E+00 | 1.95E+00 | 2.13E+00 |
| Ba-137m (Cs-137) | 4.93E-07 | 4.93E-07 | 4.93E-07 | 4.93E-07 |
| Cs-138 | 2.63E-05 | 2.63E-05 | 2.63E-05 | 2.63E-05 |
| Cu-64 | 4.53E-05 | 4.54E-05 | 4.54E-05 | 4.54E-05 |
| Fe-55 | 3.78E-08 | 3.13E-07 | 3.13E-07 | 3.13E-07 |
| Fe-59 | 2.16E-02 | 2.62E-02 | 2.62E-02 | 2.62E-02 |
| H-3 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Hf-181 | 8.17E-03 | 9.81E-03 | 9.81E-03 | 9.81E-03 |
| Hg-203 | 3.57E-03 | 4.37E-03 | 4.37E-03 | 4.37E-03 |
| I-129 | 1.07E-04 | 7.40E-03 | 1.04E-02 | 1.31E-02 |
| I-130 | 5.12E-04 | 5.13E-04 | 5.13E-04 | 5.13E-04 |
| I-131 | 1.29E-03 | 1.33E-03 | 1.33E-03 | 1.33E-03 |
| Xe-131m (I-131) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| I-132 | 1.04E-04 | 1.04E-04 | 1.04E-04 | 1.04E-04 |

## A.5. Appendix 5 - DORIS Sedimentation and Bio-Concentration Factors

**Table A5-1:** Sediment Distribution Coefficients and Bio-concentration Ratios of Nuclides in KNPS Discharges

| Element dependent Parameters | Sediment distribution coefficient, $K_D$ – deep water (Bq/t per Bq/m$^3$) | Sediment distribution coefficient, $K_D$ – coastal water (Bq/t per Bq/m$^3$) | Fish concentration factor (Bq/t per Bq/m$^3$) | Crustaceans concentration factor (Bq/t per Bq/m$^3$) | Molluscs concentration factor (Bq/t per Bq/m$^3$) | Seaweed concentration factor (Bq/t per Bq/m$^3$) |
|---|---|---|---|---|---|---|
| Actinium (Ac) | 2.0E+06 | 2.0E+06 | 5.0E+01 | 1.0E+03 | 1.0E+03 | 1.0E+03 |
| Antimony (Sb) | 5.0E+02 | 1.0E+03 | 6.0E+02 | 2.5E+01 | 3.0E+02 | 2.0E+01 |
| Arsenic (As) | 5.0E+02 | 1.0E+03 | 6.0E+02 | 2.5E+01 | 3.0E+02 | 2.0E+01 |
| Barium (Ba) | 1.0E+04 | 2.0E+03 | 1.0E+01 | 7.0E-01 | 1.0E+01 | 1.0E+02 |
| Beryllium (Be) | 1.0E+04 | 2.0E+03 | 1.0E+01 | 7.0E-01 | 1.0E+01 | 1.0E+02 |
| Bismuth (Bi) | 5.0E+02 | 1.0E+03 | 2.0E+01 | 1.0E+03 | 1.0E+03 | 1.0E+04 |
| Bromine (Br) | 5.0E+02 | 1.0E+03 | 2.0E+01 | 1.0E+03 | 1.0E+03 | 1.0E+04 |
| Caesium (Cs) | 2.0E+03 | 4.0E+03 | 1.0E+02 | 5.0E+01 | 6.0E+01 | 5.0E+01 |
| Carbon (C) | 2.0E+03 | 1.0E+03 | 2.0E+04 | 2.0E+04 | 2.0E+04 | 1.0E+04 |
| Cerium (Ce) | 1.0E+08 | 3.0E+06 | 5.0E+01 | 1.0E+03 | 2.0E+03 | 5.0E+03 |
| Chromium (Cr) | 5.0E+04 | 5.0E+04 | 2.0E+02 | 1.0E+02 | 2.0E+03 | 2.0E+03 |
| Cobalt (Co) | 5.0E+07 | 3.0E+05 | 7.0E+02 | 7.0E+03 | 2.0E+04 | 6.0E+03 |
| Copper (Cu) | 2.0E+04 | 1.0E+04 | 1.0E+04 | 2.0E+05 | 6.0E+04 | 5.0E+03 |
| Hafnium (Hf) | 5.0E+05 | 1.0E+06 | 2.0E+01 | 2.0E+02 | 5.0E+03 | 3.0E+03 |
| Hydrogen (H) | 1.0E+00 | 1.0E+00 | 1.0E+00 | 1.0E+00 | 1.0E+00 | 1.0E+00 |
| Iodine (I) | 2.0E+02 | 7.0E+01 | 9.0E+00 | 3.0E+00 | 1.0E+01 | 1.0E+03 |
| Iron (Fe) | 5.0E+07 | 5.0E+04 | 3.0E+04 | 5.0E+05 | 5.0E+05 | 2.0E+04 |
| Krypton (Kr) | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Lanthanum (La) | 1.0E+08 | 2.0E+06 | 1.0E+02 | 1.0E+03 | 2.0E+03 | 5.0E+03 |
| Lead (Pb) | 3.0E+07 | 1.0E+05 | 2.0E+02 | 9.0E+04 | 5.0E+04 | 1.0E+03 |
| Manganese (Mn) | 2.0E+08 | 2.0E+06 | 1.0E+03 | 5.0E+03 | 5.0E+04 | 6.0E+03 |
| Mercury (Hg) | 2.0E+05 | 7.0E+04 | 1.0E+03 | 3.0E+05 | 8.0E+04 | 2.0E+03 |
| Molybdenum (Mo) | 5.0E+04 | 5.0E+04 | 2.0E+02 | 1.0E+02 | 2.0E+03 | 2.0E+03 |
| Neodymium (Nd) | 2.0E+08 | 2.0E+05 | 4.0E+02 | 5.0E+02 | 5.0E+04 | 6.0E+03 |
| Neptunium (Np) | 1.0E+03 | 1.0E+03 | 1.0E+00 | 1.0E+02 | 4.0E+02 | 5.0E+01 |
| Nickel (Ni) | 1.0E+06 | 2.0E+04 | 1.0E+03 | 1.0E+03 | 2.0E+03 | 2.0E+03 |
| Nobium (Nb) | 2.0E+05 | 8.0E+05 | 3.0E+01 | 2.0E+02 | 1.0E+03 | 3.0E+03 |
| Phosphorus (P) | 1.0E+02 | 1.0E+02 | 3.0E+04 | 2.0E+04 | 2.0E+04 | 2.0E+04 |
| Plutonium (Pu) | 1.0E+05 | 1.0E+05 | 1.0E+02 | 2.0E+02 | 3.0E+03 | 2.0E+03 |
| Praseodymium (Pr) | 2.0E+06 | 5.0E+06 | 3.0E+01 | 1.0E+03 | 1.0E+03 | 1.0E+03 |

| Element dependent Parameters | Sediment distribution coefficient, $K_D$ – deep water (Bq/t per Bq/m$^3$) | Sediment distribution coefficient, $K_D$ – coastal water (Bq/t per Bq/m$^3$) | Fish concentration factor (Bq/t per Bq/m$^3$) | Crustaceans concentration factor (Bq/t per Bq/m$^3$) | Molluscs concentration factor (Bq/t per Bq/m$^3$) | Seaweed concentration factor (Bq/t per Bq/m$^3$) |
|---|---|---|---|---|---|---|
| Promethium (Pm) | 1.0E+06 | 2.0E+06 | 3.0E+02 | 1.0E+03 | 7.0E+03 | 3.0E+03 |
| Protactimium (Pa) | 1.0E+06 | 5.0E+06 | 5.0E+01 | 1.0E+01 | 5.0E+02 | 1.0E+02 |
| Radium (Ra) | 3.0E+04 | 5.0E+03 | 1.0E+02 | 1.0E+02 | 1.0E+02 | 1.0E+02 |
| Rhenium (Re) | 1.0E+03 | 3.0E+02 | 2.0E+00 | 1.0E+02 | 2.0E+03 | 2.0E+03 |
| Rhodium | 1.0E+03 | 3.0E+02 | 2.0E+00 | 1.0E+02 | 2.0E+03 | 2.0E+03 |
| Rubidium (Rb) | 2.0E+03 | 4.0E+03 | 1.0E+02 | 5.0E+01 | 6.0E+01 | 5.0E+01 |
| Ruthenium (Ru) | 1.0E+03 | 4.0E+04 | 2.0E+00 | 1.0E+02 | 5.0E+02 | 2.0E+03 |
| Samarium (Sm) | 1.0E+06 | 3.0E+06 | 3.0E+02 | 4.0E+03 | 7.0E+03 | 3.0E+03 |
| Selenium (Se) | 1.0E+03 | 1.0E+03 | 6.0E+03 | 5.0E+03 | 6.0E+03 | 1.0E+03 |
| Silver (Ag) | 2.0E+04 | 1.0E+04 | 1.0E+04 | 2.0E+05 | 6.0E+04 | 5.0E+03 |
| Sodium (Na) | 1.0E+00 | 1.0E-01 | 1.0E+00 | 1.0E+00 | 3.0E-01 | 6.0E-01 |
| Strontium (Sr) | 2.0E+02 | 8.0E+00 | 3.0E+00 | 5.0E+01 | 1.0E+01 | 5.0E+00 |
| Technitium (Tc) | 1.0E+03 | 1.0E+02 | 8.0E+01 | 1.0E+03 | 5.0E+02 | 3.0E+04 |
| Tellurium (Te) | 1.0E+03 | 1.0E+03 | 1.0E+03 | 1.0E+03 | 1.0E+03 | 1.0E+04 |
| Thallium (Tl) | 1.0E+04 | 2.0E+04 | 5.0E+03 | 1.0E+03 | 5.0E+03 | 1.0E+03 |
| Thorium (Th) | 5.0E+06 | 2.0E+06 | 6.0E+02 | 1.0E+03 | 1.0E+03 | 2.0E+02 |
| Tin (Sn) | 5.0E+04 | 4.0E+06 | 5.0E+05 | 5.0E+05 | 5.0E+05 | 2.0E+04 |
| Tungsten (W) | 5.0E+04 | 3.0E+04 | 9.0E+01 | 5.0E+04 | 6.0E+02 | 2.0E+04 |
| Uranium (U) | 5.0E+02 | 1.0E+03 | 1.0E+00 | 1.0E+01 | 3.0E+01 | 1.0E+02 |
| Xenon (Xe) | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Yttrium (Y) | 2.0E+06 | 9.0E+05 | 2.0E+01 | 1.0E+03 | 1.0E+03 | 1.0E+03 |
| Zinc (Zn) | 2.0E+05 | 7.0E+04 | 1.0E+03 | 3.0E+05 | 8.0E+04 | 2.0E+03 |
| Zirconium (Zr) | 5.0E+05 | 1.0E+06 | 2.0E+01 | 2.0E+02 | 5.0E+03 | 3.0E+03 |

## A.6. Appendix 6 - Egg Consumption Ingestion Dose

**Table A6- 1**: Habit Data – Consumption of Eggs

| Eggs, kg/yr | Adult | 15 yr | 10 yr | 5 yr | 1 yr |
|---|---|---|---|---|---|
| UWC/MM | 43.8 | 8.6 | 43.8 | 2.3 | 11 |
| NNR RG-002 | 15 | 12.75 | 9 | 7.5 | 6 |
| SAFood max | 34.21 | | 29.22 | | 26.26 |
| SAFood avg | 6.09 | | 3.65 | | 3.47 |
| IRP(DB-DCF) | 43.8 | | 43.8 | | 11 |
| IRP01(1) | 34.21 | | 29.22 | | 26.26 |
| IRP02(1) | 34.21 | | 29.22 | | 26.26 |
| (1): The consumption rates of UWC/MM appear to be unrealistically high when considering IRP01 and IRP02 local production, i.e., chickens kept in a backyard. The SAFood max. values are used, though still high. | | | | | |

**Table A6- 2:** KNPS DCF (Egg Consumption)

| Table A6-2: KNPS DCF (Egg Consumption) | | | | |
|---|---|---|---|---|
| **IRP** | **Nuclide** | **Adult** | **Child** | **Infant** |
| IRP(DB-DCF): Eggs Sector 7, 2 km | C-14 | 8.19E-13 | 1.13E-12 | 5.96E-13 |
| | H-3 | 3.71E-15 | 4.86E-15 | 2.55E-15 |
| IRP01: DCF Eggs Sector 8, 2 km | C-14 | 4.87E-13 | 5.74E-13 | 4.57E-13 |
| | H-3 | 2.21E-15 | 2.47E-15 | 1.95E-15 |
| IRP02: DCF Eggs Sector 6, 3.4 km | C-14 | 2.59E-13 | 3.05E-13 | 2.42E-13 |
| | H-3 | 1.17E-15 | 1.31E-15 | 1.04E-15 |

A dynamic tritium model has been developed (Higgins et al., 1996) to predict the independent behaviour of tritium in terrestrial food chains. The model includes the formation of organically bound tritium (OBT) which is less mobile in the environment than tritiated water, the form assumed in the specific activity model. A comparison has been made between the results of the specific activity model and the dynamic model run for a continuous and constant source. The comparison showed that predictions using the dynamic model are generally slightly higher than those for the specific activity model by up to 25% depending on the foodstuff, due mainly to the inclusion of OBT [5].

**Table A6- 3:** Egg DCF

| IRP | Nuclide | Bg/kg per Bq/m³ | Air concentration | Consumption, kg/yr | | | ICRP Ingestion DCF. Sv/Bq | | | Egg DCF µSv/yr | | | C-14 and H-3 weighted DCF(75% tritiated water and 25% OBT) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Bq/m³ | Adult | Child | Infant | Adult | Child | Infant | Adult | Child | Infant | Adult | Child | Infant |
| IRP02:DCF Eggs Sector 6 at 3.4 km | C-14 | 800 | 1.63E-14 | 34.21 | 29.22 | 11 | 5.80E-10 | 8.00E-10 | 1.69E-09 | 2.59E-13 | 3.05E-13 | 2.42E-13 | 2.59E-13 | 3.05E-13 | 2.42E-13 |
| | H-3 (OBT) | 87.5 | 1.63E-14 | 34.21 | 29.22 | 11 | 4.20E-11 | 5.70E-11 | 1.20E-10 | 2.05E-15 | 2.38E-15 | 1.88E-15 | 1.17E-15 | 1.31E-15 | 1.04E-15 |
| | H-3 | 87.5 | 1.63E-14 | 34.21 | 29.22 | 11 | 1.80E-11 | 2.30E-11 | 4.80E-11 | 8.78E-16 | 9.59E-16 | 7.53E-16 | | | |
| IRP(DB-DCF): Eggs Sector 7 at 2 km | C-14 | 800 | 4.01E-14 | 44 | 44 | 11 | 5.80E-10 | 8.00E-10 | 1.69E-09 | 8.19E-13 | 1.13E-12 | 5.96E-13 | 8.19E-13 | 1.13E-12 | 5.96E-13 |
| | H-3 (OBT) | 87.5 | 4.01E-14 | 44 | 44 | 11 | 4.20E-11 | 5.70E-11 | 1.20E-10 | 6.48E-15 | 8.80E-15 | 4.63E-15 | 3.71E-15 | 4.86E-15 | 2.55E-15 |
| | H-3 | 87.5 | 4.01E-14 | 44 | 44 | 11 | 1.80E-11 | 2.30E-11 | 4.80E-11 | 2.78E-15 | 3.55E-15 | 1.85E-15 | | | |
| IRP01:DCF Eggs Sector 8 at 2 km | C-14 | 800 | 3.07E-14 | 34.21 | 29.22 | 11 | 5.80E-10 | 8.00E-10 | 1.69E-09 | 4.87E-13 | 5.74E-13 | 4.57E-13 | 4.87E-13 | 5.74E-13 | 4.57E-13 |
| | H-3 (OBT) | 87.5 | 3.07E-14 | 34.21 | 29.22 | 11 | 4.20E-11 | 5.70E-11 | 1.20E-10 | 3.86E-15 | 4.47E-15 | 3.55E-15 | 2.21E-15 | 2.47E-15 | 1.95E-15 |
| | H-3 | 87.5 | 3.07E-14 | 34.21 | 29.22 | 11 | 1.80E-11 | 2.30E-11 | 4.80E-11 | 1.65E-15 | 1.81E-15 | 1.42E-15 | | | |

## A.7. Appendix 7 - PC-CREAM 08 input data used in the methodology document

**Table A7- 1**: Occupancy, consumption, and delay times factors

| Occupancy | Receptor number | Time at location (h/y) | Fraction of time spent indoors | Cloud gamma location factor | Deposited gamma location factor | Cloud beta location factor | Deposited beta location factor | Inhalation location factor |
|---|---|---|---|---|---|---|---|---|
| Infant | IRP(DBA) | 8.76E+03 | 0.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 |
| | IRP01 | 8.76E+03 | 6.00E-01 | 2.00E-01 | 4.00E-01 | 2.00E-01 | 4.00E-01 | 1.00E+00 |
| | IRP02 | 8.76E+03 | 0.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 |
| Child | IRP(DBA) | 8.76E+03 | 0.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 |
| | IRP01 | 8.76E+03 | 6.00E-01 | 2.00E-01 | 4.00E-01 | 2.00E-01 | 4.00E-01 | 1.00E+00 |
| | IRP02 | 8.76E+03 | 0.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 |
| Adult | IRP(DBA) | 8.76E+03 | 0.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 |
| | IRP01 | 8.76E+03 | 6.00E-01 | 2.00E-01 | 4.00E-01 | 2.00E-01 | 4.00E-01 | 1.00E+00 |
| | IRP02 | 8.76E+03 | 0.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 |

**Table A7- 2:** Ingestion parameter values

| Ingestion, kg/y or L/y | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Infant** | **Receptor number:** | **IRP (DBA)** | **Child** | **Receptor number:** | **IRP (DBA)** | **Adult** | **Receptor number:** | **IRP (DBA)** |
| Food | Ingestion rate (kg/y) | food fraction produced locally | Food | Ingestion rate (kg/y) | food fraction produced locally | Food | Ingestion rate (kg/y) | food fraction produced locally |
| Cow meat | 4.00E+01 | 1.00E+00 | Cow meat | 6.50E+01 | 1.00E+00 | Cow meat | 1.00E+02 | 1.00E+00 |
| Cow milk | 5.20E+01 | 1.00E+00 | Cow milk | 5.20E+01 | 1.00E+00 | Cow milk | 8.80E+01 | 1.00E+00 |

| **Ingestion, kg/y or L/y** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Infant** | **Receptor number:** | **IRP (DBA)** | **Child** | **Receptor number:** | **IRP (DBA)** | **Adult** | **Receptor number:** | **IRP (DBA)** |
| Cow milk products | 5.20E+01 | 1.00E+00 | Cow milk products | 5.20E+01 | 1.00E+00 | Cow milk products | 8.80E+01 | 1.00E+00 |
| Cow liver | 3.86E+01 | 1.00E+00 | Cow liver | 4.66E+01 | 1.00E+00 | Cow liver | 5.87E+01 | 1.00E+00 |
| Sheep meat | 2.26E+01 | 1.00E+00 | Sheep meat | 4.19E+01 | 1.00E+00 | Sheep meat | 6.33E+01 | 1.00E+00 |
| Sheep liver | 5.00E-01 | 1.00E+00 | Sheep liver | 1.50E+00 | 1.00E+00 | Sheep liver | 2.75E+00 | 1.00E+00 |
| Green vegetables | 4.31E+01 | 1.00E+00 | Green vegetables | 4.78E+01 | 1.00E+00 | Green vegetables | 8.00E+01 | 1.00E+00 |
| Root vegetables | 4.50E+01 | 1.00E+00 | Root vegetables | 9.50E+01 | 1.00E+00 | Root vegetables | 1.30E+02 | 1.00E+00 |
| Grain | 1.25E+02 | 1.00E+00 | Grain | 2.13E+02 | 1.00E+00 | Grain | 2.50E+02 | 1.00E+00 |
| Fruit | 1.76E+01 | 7.50E-01 | Fruit | 2.40E+01 | 7.50E-01 | Fruit | 3.76E+01 | 7.50E-01 |
| Infant | Receptor number: | IRP01 | Child | Receptor number: | IRP01 | Adult | Receptor number: | IRP01 |
| Food | Ingestion rate (kg/y) | food fraction produced locally | Food | Ingestion rate (kg/y) | food fraction produced locally | Food | Ingestion rate (kg/y) | food fraction produced locally |
| Cow meat | 3.21E+01 | 5.00E-01 | Cow meat | 3.75E+01 | 5.00E-01 | Cow meat | 4.25E+01 | 5.00E-01 |
| Cow milk | 5.20E+01 | 1.00E+00 | Cow milk | 5.20E+01 | 1.00E+00 | Cow milk | 8.80E+01 | 1.00E+00 |
| Cow milk products | 1.39E+01 | 2.50E-01 | Cow milk products | 1.21E+01 | 2.50E-01 | Cow milk products | 1.64E+01 | 2.50E-01 |
| Cow liver | 1.02E+00 | 5.00E-01 | Cow liver | 1.72E+00 | 5.00E-01 | Cow liver | 2.70E+00 | 5.00E-01 |
| Sheep meat | 6.67E+00 | 1.00E+00 | Sheep meat | 1.45E+01 | 1.00E+00 | Sheep meat | 2.34E+01 | 1.00E+00 |
| Sheep liver | 1.50E-01 | 1.00E+00 | Sheep liver | 1.10E-01 | 1.00E+00 | Sheep liver | 4.00E-01 | 1.00E+00 |

| Ingestion, kg/y or L/y | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Infant** | **Receptor number:** | **IRP (DBA)** | **Child** | **Receptor number:** | **IRP (DBA)** | **Adult** | **Receptor number:** | **IRP (DBA)** |
| Green vegetables | 1.02E+01 | 7.50E-01 | Green vegetables | 2.03E+01 | 7.50E-01 | Green vegetables | 4.61E+01 | 7.50E-01 |
| Root vegetables | 1.07E+01 | 5.00E-01 | Root vegetables | 1.28E+01 | 5.00E-01 | Root vegetables | 2.54E+01 | 5.00E-01 |
| Grain | 2.36E+01 | 5.00E-01 | Grain | 2.19E+01 | 5.00E-01 | Grain | 5.87E+01 | 5.00E-01 |
| Fruit | 1.76E+01 | 2.00E-01 | Fruit | 2.40E+01 | 2.00E-01 | Fruit | 3.76E+01 | 2.00E-01 |
| Infant | Receptor number: | IRP02 | Child | Receptor number: | IRP02 | Adult | Receptor number: | IRP02 |
| Food | Ingestion rate (kg/y) | food fraction produced locally | Food | Ingestion rate (kg/y) | food fraction produced locally | Food | Ingestion rate (kg/y) | food fraction produced locally |
| Cow meat | 3.21E+01 | 1.00E+00 | Cow meat | 3.75E+01 | 1.00E+00 | Cow meat | 4.25E+01 | 1.00E+00 |
| Cow milk | 5.20E+01 | 1.00E+00 | Cow milk | 5.20E+01 | 1.00E+00 | Cow milk | 8.80E+01 | 1.00E+00 |
| Cow milk products | 1.39E+01 | 2.50E-01 | Cow milk products | 1.21E+01 | 2.50E-01 | Cow milk products | 1.64E+01 | 2.50E-01 |
| Cow liver | 1.02E+00 | 1.00E+00 | Cow liver | 1.72E+00 | 1.00E+00 | Cow liver | 2.70E+00 | 1.00E+00 |
| Sheep meat | 7.35E+00 | 1.00E+00 | Sheep meat | 1.60E+01 | 1.00E+00 | Sheep meat | 2.86E+01 | 1.00E+00 |
| Sheep liver | 1.50E-01 | 1.00E+00 | Sheep liver | 1.10E-01 | 1.00E+00 | Sheep liver | 4.00E-01 | 1.00E+00 |
| Green vegetables | 4.31E+01 | 1.00E+00 | Green vegetables | 4.78E+01 | 1.00E+00 | Green vegetables | 5.84E+01 | 1.00E+00 |
| Root vegetables | 3.57E+01 | 1.00E+00 | Root vegetables | 4.82E+01 | 1.00E+00 | Root vegetables | 7.57E+01 | 1.00E+00 |
| Grain | 3.78E+01 | 7.50E-01 | Grain | 1.05E+02 | 7.50E-01 | Grain | 7.22E+01 | 7.50E-01 |

| Ingestion, kg/y or L/y | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Infant | Receptor number: | IRP (DBA) | Child | Receptor number: | IRP (DBA) | Adult | Receptor number: | IRP (DBA) |
| Fruit | 1.24E+01 | 5.00E-01 | Fruit | 2.40E+01 | 5.00E-01 | Fruit | 3.76E+01 | 5.00E-01 |

**Table A7- 3:** Individual delays time from collection/harvest to ingestion

| Individual delays | |
|---|---|
| **Food Type** | **Individual delays (d)** |
| Green vegetables | 0 |
| Grain | 30 |
| Root vegetables | 0 |
| Sheep meat | 7 |
| Sheep liver | 0 |
| Cow meat | 3 |
| Cow liver | 0 |
| Cow milk | 0 |
| Cow milk products | 7 |
| Fruit | 0 |