
# The Radioactively Contaminated Land Exposure Assessment Methodology – Technical Report

CLR-14

Version 1.2

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# The Radioactively Contaminated Land Exposure Assessment Methodology - RCLEA

The Radioactively Contaminated Land Exposure Assessment methodology (RCLEA) is Defra's recommended approach for the exposure assessment of a site under the extended Part 2A regime for managing contaminated land. It complements the Contaminated Land Exposure Assessment (CLEA) approach for non-radioactive contamination.

This report presents the conceptual models, mathematical models and data that form RCLEA. It also describes the scope and assumptions that underlie RCLEA, as well as the types of calculations that can be performed. It is complemented by a guide to the use of RCLEA (CLR-13) and a Microsoft Excel® software application (CLR-15) which incorporates the models and data.

The report is an update of Version 1.1, issued in December 2006. The revision has been made to take account of a change in the legal definition of "substance" that removes the exclusion for radon and its decay products. The updated methodology therefore includes a suitable method for assessing the significance of radon.

# List of Abbreviations

| | |
|---|---|
| CERRIE | Committee Examining Radiation Risks of Internal Emitters |
| CLEA | Contaminated Land Exposure Assessment |
| COMARE | Committee on Medical Aspects of Radiation in the Environment |
| Defra | Department for Environment, Food and Rural Affairs |
| GV | Guideline Value (site-specific and applicable to situations of contamination with multiple radionuclides) |
| HPA RPD | Radiation Protection Division of the Health Protection Agency |
| HTO | Tritiated water |
| ICRP | International Commission on Radiological Protection |
| NCRP | National Council on Radiation Protection and Measurements (US) |
| NRPB | National Radiological Protection Board |
| RCLEA | Radioactively Contaminated Land Exposure Assessment |
| RCLSG | Radioactively Contaminated Land Steering Group |
| RSGV | Radioactivity in Soil Guideline Value (for a single radionuclide present in isolation in contaminated land) |
| SGV | Soil Guideline Value (for non-radioactive contaminants) |
| UV | Ultra violet radiation |

# Contents

# 1 Introduction

1.1 The Part 2A regime[1] for managing contaminated land has been extended to include radioactive contamination. Statutory Guidance on the new arrangements has been published by Defra (2006). Since this was issued there has been a change in the legal definition of "substance" that removes the existing exclusion of radon and its decay products from the regime.

1.2 The Radioactively Contaminated Land Exposure Assessment methodology (RCLEA) is Defra's recommended approach for the exposure assessment of a site under the extended regime, with respect to radioactivity in soil and human health. It is based on the original Contaminated Land Exposure Assessment (CLEA) approach that was developed for the assessment of non-radioactive contamination (Defra and Environment Agency, 2002), although there are several important differences due to the nature of radioactive contaminants. The version of CLEA on which RCLEA is based is has now been superseded (Environment Agency, 2009), but RCLEA remains compatible with the revised approach.

1.3 This document, CLR-14, describes the recommended mathematical models and data. It is an update to the version issued in 2006 (Defra and Environment Agency, 2006), but the only change is the inclusion of a model for the assessment of the consequences of radon gas released from ground containing Ra-226. These models and data have been implemented in an updated software application based around a Microsoft Excel® workbook, which has been published as CLR-15 (Environment Agency, 2011a).

1.4 This Technical Report is primarily intended for those familiar with exposure assessment calculations, particularly in relation to radioactively contaminated soil. It should be read in conjunction with the Part 2A Statutory Guidance and procedures. Reference should also be made to CLR-13 (Environment Agency, 2011b), which describes the practical application of RCLEA and includes a user guide for the RCLEA software application together with a worked example of its use.

1.5 The document is structured as follows:

- ▲ The overall scope of RCLEA is presented in Section 2, together with key assumptions;

[1] Part 2A of the Environmental Protection Act 1990, as amended - "Contaminated Land"

- The basic conceptual models considered in RCLEA are based on those adopted in CLEA, and are described in Section 3 for convenience;
- The equations used to evaluate the models are presented in Section 4;
- Section 5 presents the reference data values used in the equations; and
- Section 6 describes the type of calculations that can be undertaken with RCLEA.

1.6 Some further information is presented in Appendices. Appendix A presents the radionuclides considered in RCLEA, whilst Appendix B lists differences between the RCLEA and the 2002 CLEA methodologies.

# 2 Scope and Assumptions

2.1 This section provides a context for RCLEA by defining its scope and the high-level assumptions adopted.

## Scope of RCLEA

2.2 The scope of RCLEA has been defined by Defra and subject to consultation. Key points are summarised in Box 1.

**Box 1: Scope of RCLEA**

S1. RCLEA can be used for screening radioactively contaminated land using generic exposure assessment, and enables the calculation of potential radiation doses for given concentrations of radionuclides in soil as well as Guideline Values, radionuclide concentrations that correspond to regulatory dose criteria.

S2. The methodology enables 'site-specific' calculations to be made. The user can undertake assessments for mixtures of radionuclides and define the exposure pathways and parameter values to represent site-specific conditions. However, more detailed assessments (e.g. considering groundwater migration and/or mixed radioactive and non-radioactive contamination) are beyond the scope of RCLEA.

S3. The methodology is for the assessment of existing (historic) radioactive contamination. RCLEA will only apply to long-term effects of accidents (several years after the accident); tools are already available to assess health effects in the immediate aftermath of an accident.

S4. Defra has taken advice from appropriate organisations in order to specify regulatory criteria for radioactively contaminated land. These criteria are given in the Statutory Guidance (Defra, 2006).

S5. A set of 47 radionuclides (and/or combinations thereof) are considered in RCLEA. These radionuclides represent those most likely to be found in radioactively contaminated land in the UK. RCLEA allows screening assessments of individual radionuclides as well as mixtures of radionuclides.

S6. RCLEA is consistent with the CLEA methodology, as far as appropriate.

S7. The methodology is aimed at 'practitioners' with some specialist knowledge of radioactively contaminated land and the assessment of associated human health risks.

# Key Assumptions

A number of assumptions underlie the RCLEA models and data that should be borne in mind when evaluating the results generated by the application. The key assumptions are shown in Box 2.

**Box 2: Key Assumptions that Underlie RCLEA**

| | |
|---|---|
| **Assumption 1:** Source Geometry | RCLEA considers uniform contamination to a depth of 1 m from the surface. This is the most cautious assumption and is consistent with CLEA. Patchy contamination can be represented using a simple scaling assumption. More detailed consideration of source geometry is beyond the scope of RCLEA and should be considered, if necessary, with site-specific calculations. |
| **Assumption 2:** Radionuclides | Radionuclides of interest have a half-life greater than 1 year and are not highly mobile in the environment. Shorter-lived radioactive daughters are assumed to be present in secular equilibrium with parents. RCLEA neglects radioactive decay in calculations, which is cautious. |
| **Assumption 3:** Land Uses | RCLEA considers the same land uses as CLEA for the basis of its exposure scenarios. The generic land uses include residential, allotment, and commercial/industrial. A user defined land use can be created in the case that the generic land uses poorly represent the actual or potential situation. |
| **Assumption 4:** Age Groups | RCLEA considers three reference age groups (1-year old, 10 year-old and adult), consistent with the usual approach for assessing human exposure to radionuclides. Age-dependent data has been obtained from CLEA where possible. |
| **Assumption 5:** Exposure Duration | RCLEA calculates radiation doses for a single year of exposure for any given age group. |
| **Assumption 6:** Building Types | The effect of building construction is considered in RCLEA, to account for the shielding effect of walls and floors. The building types are consistent with those considered in CLEA. |
| **Assumption 7:** CLEA Exposure Pathways | RCLEA considers the same exposure pathways as CLEA, with the exception of pathways associated with volatile contaminants (which are not considered as radioactive contamination is not encountered in a form for which this pathway is relevant) and skin absorption (the possibility of significant absorption is very low). |
| **Assumption 8:** External Irradiation | RCLEA takes account of whole body external irradiation when outdoors and indoors (making allowance for shielding) and external irradiation of the skin due to dermal contact. |

**Box 2 (continued): Key Assumptions that Underlie RCLEA**

| | |
|---|---|
| **Assumption 9:** Exposure Pathways Not Considered in RCLEA | The ingestion of animal products is not considered so as to maintain consistency with the land use assumptions of CLEA. Although groundwater migration might be an important pathway for specific radionuclides in specific situations, it is not included in RCLEA. |
| **Assumption 10:** Data for Existing Parameters | RCLEA uses data specified in the CLEA methodology for many parameters. However, where values are significantly different from established radiation protection assumptions the latter are adopted. Additional data have been selected to be consistent with CLEA as far as possible. |
| **Assumption 11:** Dose Coefficients | Reference dose coefficients for radionuclide intakes have been selected from international recommendations, whilst dose coefficients for external and skin exposure have been selected from a suitable internationally respected source. |
| **Assumption 12:** Approach to Uncertainty | RCLEA adopts a deterministic approach. Cautious but realistic parameter values have been selected for those parameters assigned distributions in CLEA. |
| **Assumption 13:** Computer Application | RCLEA is implemented in a Microsoft Excel® workbook application. The software seeks to have similar functionality to other CLEA applications. |
| **Assumption 14:** Regulatory Criteria | RCLEA adopts the regulatory criteria defined in Defra's Statutory Guidance. |
| **Assumption 15:** Range of Results | RCLEA enables Guideline Values and doses to be calculated for generic exposure scenario assumptions. It also allows the user to assess site-specific cases. |

# 3 Conceptual Models

3.1 This section presents the key features of the conceptual models.

3.2 As RCLEA complements CLEA, the same generic exposure situations are considered in the methodology. The exposure pathways are also the same as adopted in CLEA, with the exception of the external irradiation and radon exposure pathways that are specific to RCLEA, and the exclusion of two pathways of limited relevance to radioactive contamination. Differences between RCLEA and CLEA are described in Appendix B.

3.3 The detailed derivation of the CLEA models is presented in the main technical report, 'CLR 10' (Defra and Environment Agency, 2002), and subsequent briefing notes. Therefore, the basis of models is not discussed except in respect of the additional exposure pathways considered by RCLEA. The associated mathematical models and data are presented in Sections 4 and 5, and are also based on CLR 10 (Defra and Environment Agency, 2002). The CLEA models have since been updated (Environment Agency, 2009). These changes have not been carried through to RCLEA, but the model remains sufficiently consistent.

## Radionuclides and Contaminated Soil

3.4 The radionuclide(s) are cautiously assumed to be uniformly distributed in the whole area of land occupied by the exposed individual. Contamination is also cautiously assumed to extend to a depth of 1 m from the surface, with a lateral extent of several tens of metres or more.

3.5 Exposure to patchy contamination can be simply approximated by assuming that the dose is linearly related to the proportion of the area that is contaminated. More complex treatment of geometry, such as would be needed to assess potential exposures from discrete articles (e.g. luminised dials), is beyond the scope of RCLEA.

3.6 Buried contamination is not explicitly considered. More detailed external dose modelling would be required in order to properly assess the whole-body external irradiation pathway in such situations.

# Specification of a Land Use

3.7 Within RCLEA, land uses are represented through permitted combinations of exposure pathways and age groups, and with parameter value assumptions that describe the nature of human exposure to the contamination. This is the same approach as that adopted by CLEA.

## *Exposure Pathways*

3.8 The exposure pathways that can be considered include:

- **Whole body external irradiation** (occurring indoors and/or outdoors);
- Soil ingestion (occurring indoors and/or outdoors);
- Dust ingestion (occurring indoors and/or outdoors);
- **External irradiation of the skin** from dermal contact (occurring indoors and/or outdoors);
- Dust inhalation (occurring indoors and/or outdoors);
- **Inhalation of radon gas** generated by the decay of Ra-226 in soil (occurring indoors only);
- Consumption of home grown produce; and
- Consumption of soil associated with home grown produce.

3.9 Exposure pathways in bold are additional to CLEA. It should be noted that the following pathways are considered in CLEA, but are excluded from RCLEA:

- The inhalation of volatiles is not relevant to the contaminants and the nature of the contamination considered in RCLEA; and
- The absorption of radionuclides across the skin is also excluded, given that, with the possible exception of tritium, absorption through skin is extremely low.

## *Age Groups*

3.10 The RCLEA methodology considers the same range of ages considered by CLEA (infant through to adult). However, a smaller number of representative age groups are considered to ensure consistency with the recommendations of the ICRP and with established approaches for assessing exposure to radioactively contaminated land. The RCLEA age groups are therefore:

- 1 year old ('infant');
- 10 year old ('child'); and
- >17 year old ('adult').

3.11 Both males and females can be considered for any specified age.

3.12 Age and sex-dependent data include exposure durations, consumption rates and human characteristics such as body weight.

### *Other Site Characteristics*

3.13 The RCLEA methodology considers a single generic soil type (a loamy soil is adopted).

3.14 RCLEA also allows the effect different types of building on radon concentrations and external irradiation to be considered. In respect of radon, the height of the building and its ventilation rate determine the extent to which radon accumulates in indoor air. In respect of external irradiation, the degree of shielding offered by a building is highly dependent on the radionuclides present and geometry of the contamination, building, and location of the exposed person. It is inappropriate to represent such a complex relationship in RCLEA, therefore two reference assumptions are made that are intended to be broadly representative of the likely conditions:

- Timber walls and floors – representing a situation in which there is limited shielding of the contaminated soil by the floor and/or walls of the building; and
- Concrete/brick walls and floors – representing a situation in which the floors and/ or walls of the building offer significant shielding of the contaminated soil.

## Reference Land Uses

3.15 Table 1 lists the reference land uses that are considered in RCLEA. These are the same as considered in CLEA and are suitable for generic assessments.

### *Residential Land Use*

3.16 The residential site is assumed to consist of a single property within a square-shaped area of 0.2 ha. The property is assumed to be two stories high and to have ready access to either a private garden or an adjacent public open space.

3.17 Infants up to schooling age are assumed to spend all of their time in or close to the home, whilst children of schooling age are taken to spend some time away from the home. Adults are assumed to spend all of their time in or close to the home (i.e. as a home maker or home worker).

**Table 1: Reference Land Uses Considered in RCLEA**

| Land Use | Permitted Age Groups | Permitted Exposure Pathways |
|---|---|---|
| Residential | ▲ Infant;<br>▲ Child; and<br>▲ Adult. | ▲ Whole body external irradiation (indoor and outdoor);<br>▲ Soil ingestion (indoor and outdoor);<br>▲ Dust ingestion (indoor and outdoor);<br>▲ External irradiation of the skin from dermal contact (indoor and outdoor);<br>▲ Dust inhalation (indoor and outdoor);<br>▲ Radon gas inhalation (indoor);<br>△ Consumption of home grown produce; and<br>△ Consumption of soil associated with home grown produce. |
| Allotments | ▲ Infant;<br>▲ Child; and<br>▲ Adult. | ▲ Whole body external irradiation (indoor and outdoor);<br>▲ Soil ingestion (indoor and outdoor);<br>▲ Dust ingestion (indoor and outdoor);<br>▲ External irradiation of the skin from dermal contact (indoor and outdoor);<br>▲ Dust inhalation (indoor and outdoor);<br>▲ Radon gas inhalation (indoor);<br>▲ Consumption of home grown produce; and<br>▲ Consumption of soil associated with home grown produce. |
| Commercial/ Industrial | ▲ Adult. | ▲ Whole body external irradiation (indoor and outdoor);<br>▲ Soil ingestion (indoor and outdoor);<br>▲ Dust ingestion (indoor and outdoor);<br>▲ External irradiation of the skin from dermal contact (indoor and outdoor); and<br>▲ Dust inhalation (indoor and outdoor);<br>▲ Radon gas inhalation (indoor). |

**Notes:** Both building types can be considered for all reference land uses. ▲ Included in the default assumptions; △ Permitted as optional.

3.18 As illustrated in Table 1, a key consideration for the Residential land use is whether the household grows its own vegetables in contaminated soil in the garden (allotments are considered to be a different reference land use). Two options can therefore be considered:

- Residential land use **with** home grown produce; and
- Residential land use **without** home grown produce.

3.19 If vegetables are grown in the garden, they are assumed to consist of brussels sprouts, cabbage, carrot, leafy salads, onions (including shallots and leeks) and potatoes.

3.20 It is assumed that the property receives drinking water via mains supply only (i.e. from an uncontaminated source).

### *Allotment Land Use*

3.21 The allotment is assumed to consist of an amalgamation of several individual plots into a square-shaped area of 0.8 ha. The allotment site is assumed to be largely open space with individual plots for growing fruits and vegetables that are subsequently consumed by the allotment gardener and his or her household. Vegetables assumed to be grown in the allotment are brussels sprouts, cabbage, carrot, leafy salads, onions (including shallots and leeks) and potatoes. The rearing of chickens and ducks or the grazing of goats on the allotment is not considered, consistent with the current assumptions of the CLEA methodology.

3.22 Adults are assumed to visit the allotment site four days a week for an average duration of four hours per visit. Infants are assumed to accompany the adults 75% of the time, whilst this reduces to 52% for older children. Consistent with CLEA, contaminated soil from the allotment is assumed to be tracked back to the home.

### *Commercial/Industrial Land Use*

3.23 The land use is intended to reflect individual shops or offices, or a small retail or light industrial park. The site is assumed to occupy a square shaped area of 2 ha, with an office or factory building occupying 0.1 ha of this space. It is assumed that workers spend the majority of their time indoors, with the exception of meal and rest breaks during three quarters of the year. The work is not assumed to involve any significant periods of heavy labour.

3.24 Individuals are assumed to spend 37.5 hours working during a five day week and an additional 1 hour per day for breaks, resulting in an average of about 8.5 hours on site per working day. Employees are also assumed to have up to six weeks leave.

### *Site-Specific Land Uses*

3.25 The RCLEA methodology can be used to assess site-specific land uses. In such circumstances, it is necessary to define and justify the age groups, exposure pathways and parameter value assumptions (such as occupancy and/or intake rates) that are relevant to the situation being assessed.

## Exposure Models

3.26 The following sub-sections provide brief descriptions of the conceptual model for each of the exposure pathways considered within the RCLEA methodology. The models are consistent with those used in CLEA but have been supplemented with models for external irradiation of the body and hands.

### *Whole Body External Irradiation*

3.27 Individuals are assumed to be subject to external irradiation for the whole time they are present at the contaminated site. A person is assumed to be standing on the contaminated soil at the centre of the area of contamination. Whilst outside, no 'shielding' of the person from the radiation is assumed. Whilst inside, some degree of shielding can be assumed, depending on the building type.

### *Soil Ingestion*

3.28 Whilst occupying radioactively contaminated land, individuals are assumed to inadvertently ingest some contaminated soil. Inadvertent soil ingestion may arise as a result of direct contact with the contaminated soil, for example:

- ▲ Whilst adults work in the garden or on an allotment, their hands may become dirty with contaminated soil, which is then inadvertently ingested either directly from the hand or by transferring the material onto an uncontaminated item of food; or
- ▲ Contaminated soil may adhere to objects that are picked up by infants. Infants have a tendency to use their mouths to explore objects, thereby providing a route for inadvertent ingestion of soil.

3.29 Inadvertent ingestion can occur both indoors as well as outdoors, as contaminated soil may be deliberately or inadvertently brought into a building. Age-dependent ingestion rates are combined with the duration spent in a particular location to determine the total intake of contaminated soil by this route by a given individual.

3.30 Consistent with the CLEA methodology, deliberate ingestion of soil is not considered. This type of 'pica' behaviour is considered to be too extreme for consideration in a generic screening assessment.

### *Dust Ingestion*

3.31 Dust deriving from the radioactively contaminated soil may also be inadvertently ingested following deposition onto surfaces that the individuals come into contact with, such as the surface of a table. This exposure may occur inside as well as outside since contaminated dust may be transported indoors.

### *Dermal Contact*

3.32 Dermal contact with contaminated soil can result in direct irradiation of the skin. Such dermal contact may occur whilst the individual is in direct contact with contaminated soil outdoors. Dermal contact may also occur indirectly, via contaminated material that has been inadvertently brought into a building.

3.33 Irradiation of the skin is assessed by considering the radiation dose rate from skin surface contamination at the depth at which sensitive cells are present. This is combined with the exposure duration and concentration of radionuclides on the skin to determine the annual dose to the skin. It is also necessary to determine the fraction of skin that is irradiated and apply a factor for the sensitivity of the skin to irradiation to determine the annual effective dose.

### *Dust Inhalation*

3.34 Dust deriving from contaminated soil can be suspended in the atmosphere and inhaled by individuals occupying a contaminated area both indoors as well as outdoors.

3.35 The assumed airborne dust concentration of particles of a respirable size is combined with the exposure duration and age dependent inhalation rate to determine the total annual intake of contaminated soil by this route.

### *Radon Gas Inhalation*

3.36 The radioactive decay of Ra-226 and Ra-224 leads to the generation of gaseous progeny, Rn-222 and Rn-220 respectively. These radionuclides can subsequently migrate through soil and into air.

3.37 The focus of the assessment model is Rn-222 rather than Rn-220. The Ra-226 parent is most likely to be found in significantly enhanced quantities in the environment. In addition, Rn-222 has a half-life of 3.82 days compared with less than a minute for Rn-220; as a consequence Rn-220 largely decays before it has migrated through soil.

3.38 Assessment modelling approaches are also focused on indoor exposure to radon. This is because in outside air the gas is rapidly dispersed, whereas concentrations can accumulate substantially indoors. Prospective calculation of indoor radon concentrations (whether through mathematical models or empirical relationships) is difficult as many parameters are highly dependent on the site-specific conditions. Therefore, where possible, radon concentrations should be measured by conventional and well-established methods.

3.39 In the event that such measurements are not available, a generic relationship of between Rn-222 concentration in indoor air and Rn-226 concentration in soil can be used. A suitable value has been derived from measurements and modelling studies (see Penfold, 2011). If particular characteristics such as building ventilation rate, dimensions, and soil porosity vary significantly from reference values, a standard model (UNSCEAR, 2000) can be used to determine Rn-222 concentration.

### *Consumption of Home Grown Produce*

3.40 Plants growing in radioactively contaminated soil will take up radionuclides through root systems, which will be incorporated into the plant tissues. If vegetables are grown on contaminated allotments or in contaminated gardens, then radionuclide uptake from the soil to the edible tissues provides an exposure pathway to individuals when the contaminated foodstuffs are ingested.

3.41 A range of plant types have been considered, in each case a radionuclide-dependent equilibrium soil-plant transfer factor being applied to determine the concentration of the radionuclide in the edible portions of the plant.

3.42 The annual intake of contaminants by this route is then determined with the application of an assumed ingestion rate (which is age-dependent).

### *Consumption of Soil Associated with Home Grown Produce*

3.43 In addition to radionuclides taken up by plant roots, vegetables can also retain external soil contamination, either from direct contamination, for root vegetables, or from soil-splash onto aerial plant parts. Although cleaning will remove some of the soil, some is considered to remain and can be ingested with the produce.

3.44 Plants are assumed to have a 'loading' of soil (a mass of contaminated soil per unit mass of edible plant). This is applied, with the age-dependent plant ingestion rate, to determine the individual's intake of contaminated soil by this route.

### *Calculation of Radiation Doses*

3.45 The exposure models described in paragraphs 3.27 to 3.44 describe the representation of the various exposure pathways in a manner that determines the duration of exposure in given conditions and/or quantity of contaminants that may be ingested or inhaled as a result.

3.46 However, the health protection criteria considered by RCLEA are expressed in terms of annual individual doses, with the contributions of individual radionuclides being aggregated over pathways. It is therefore necessary to convert intake or exposure to radiation dose.

3.47 For ingestion and inhalation pathways, the radiation dose is the product of the exposure rates (i.e. from Bq ingested or inhaled per year) and a radionuclide-dependent dose coefficient. RCLEA adopts dose coefficients recommended by ICRP (1996) for ingestion and the inhalation of particulates. The effective dose from exposure by the inhalation of Rn-222 in air is calculated using a standard model (UNSCEAR, 2000).

3.48 For whole body external irradiation and contact irradiation of the skin, doses are the product of the duration of exposure to a given concentration of radionuclides at a given distance, and a radionuclide and geometry-dependent dose factor. ICRP does not recommend external dose factors, therefore RCLEA adopts other well established dose factors (Eckerman and Ryman, 1993; Harvey et al., 1993).

# 4 Mathematical Models

4.1 Mathematical models are used in RCLEA to calculate the radiation dose from each exposure pathway. The equations are largely the same as those adopted in CLEA, with the exception of the external irradiation and radon inhalation model that are specific to RCLEA.

4.2 Different land uses are assessed by using some or all of the mathematical models (dependent on the exposure pathways of interest), with the relevant land use specific parameter values, presented in Section 5.

## Source Term

4.3 The radionuclides considered in RCLEA have been selected as being the most relevant to the situations the methodology is designed to assess. Because the focus of the RCLEA methodology is existing (historic) radioactively contaminated land, radionuclides with a half-life shorter than 1 year are not considered unless they are short-lived daughters of parent radionuclides considered in RCLEA (see Appendix A for further details).

4.4 Contaminated soil is represented in RCLEA with reference to the following fundamental physical and chemical properties:

- ▲ The unitless water filled porosity, $\theta_w$;
- ▲ The dry bulk density, $\rho_B$, kg $m^{-3}$;
- ▲ The density of soil water, $\rho_w$, kg $m^{-3}$;
- ▲ The soil solid-liquid distribution coefficient, $K_d$, $m^3$ $kg^{-1}$; and
- ▲ The unitless enrichment factor for contaminant concentrations in finer fractions of soil, *EF*.

4.5 Consistent with the CLEA methodology, the enrichment factor is used to correct the contaminant concentration in the bulk soil to that observed in finer particles, which are more likely to be inhaled or to be adhered to the skin. For CLEA, the enrichment factor is applied to most metal and lipophilic contaminants. For RCLEA it is cautiously applied to all radionuclides.

4.6 The radionuclide concentration(s) must be specified by the user and should be the total soil activity concentration of a given radionuclide (i.e. solid and liquid phase) per kg of dry soil, $C_T$, Bq kg$^{-1}$ dry weight soil. This is the value that is typically measured during site investigations.

4.7 Patchy contamination is represented with a simple unitless scaling factor, *P*, that represents the fraction of the total area considered for the land use that is contaminated. The average concentration in all soil that is assessed, per unit mass, $C_P$ (Bq kg$^{-1}$) is simply $C_T$ x *P*. The average volumetric concentration for dry soil is calculated with:

$$C_V = C_P \, \rho_B \tag{1}$$

where:

$C_V$ is the volumetric concentration, Bq m$^{-3}$.

4.8 The average wet weight soil concentration can be determined from:

$$C_W = \frac{C_V}{\rho_B + \theta_w \, \rho_w} \tag{2}$$

where:

$C_W$ is the wet weight concentration, Bq kg$^{-1}$.

## Whole Body External Irradiation

4.9 The annual effective individual dose due to whole body external irradiation, $D_{Ext}$, Sv y$^{-1}$, is calculated using the following expression:

$$D_{Ext} = C_V \, DC_{Ext} \left( O_{Out} + (1 - F_S) \, O_{In} \right) \tag{3}$$

where:

$DC_{Ext}$ is a dose coefficient for external whole body irradiation, Sv y$^{-1}$ per Bq m$^{-3}$;

$O_{Out}$ is the unitless fraction of time spent outside on the contaminated land;

$F_S$ is a unitless shielding factor applied whilst indoors; and

$O_{In}$ is the unitless fraction of time spent indoors on the contaminated land.

4.10 This pathway is not considered in CLEA. The expression presented above is consistent with that generally used in radiological assessments including those for contaminated land, such as Oatway and Mobbs (2003).

# Soil and Dust Ingestion

4.11 Consistent with the CLEA methodology, the calculation of doses from inadvertently ingested soil and dust is combined due to the difficulty in differentiating the two pathways. The annual effective committed individual dose due to the inadvertent ingestion of soil and dust, $D_{Soil}$, Sv y$^{-1}$, is calculated using the following expression:

$$D_{Soil} = I_{Soil} \, C_P \, DC_{Ing} \tag{4}$$

where:

$I_{Soil}$ is the annual ingestion rate of dry soil and dust, kg (dry soil) y$^{-1}$; and

$DC_{Ing}$ is the dose coefficient for ingestion, Sv Bq$^{-1}$.

# Direct Irradiation of the Skin from Dermal Contact

4.12 The approach for determining the annual individual equivalent dose due to direct irradiation of the skin caused by dermal contact, $H_{Skin}$, Sv y$^{-1}$, is based on that recommended by the Health Protection Agency Radiation Protection Division (HPA RPD; Oatway and Mobbs, 2003):

$$H_{Skin} = \frac{(O_{SCOut} \, \rho_{skinOut} + F_{Dust} \, O_{SCIn} \, \rho_{skinIn}) \, EF \, C_P \left(DF_\gamma + DF_\beta\right)}{10^6 \left(mg \; kg^{-1}\right)} \tag{5}$$

where:

$O_{SCIn}$ fractional duration of exposure for skin contact whilst indoors;

$O_{SCOut}$ fractional duration of exposure for skin contact whilst outdoors;

$\rho_{skinIn}$ is the dry weight soil loading on skin contaminated with soil whilst indoors, mg cm$^{-2}$;

$\rho_{skinOut}$ is the dry weight soil loading on skin contaminated with soil whilst outdoors, mg cm$^{-2}$;

$F_{dust}$ is the fraction of indoor dust comprising of locally derived contaminated soil;

$DF_\gamma$ is the skin equivalent dose rate to the basal layer of the skin epidermis for gamma irradiation (7 mg cm$^{-2}$), Sv y$^{-1}$ per Bq cm$^{-2}$; and

$DF_\beta$ is the skin equivalent dose rate to the basal layer of the skin epidermis for gamma irradiation (4 mg $cm^{-2}$), Sv $y^{-1}$ per Bq $cm^{-2}$.

4.13 The annual individual effective dose for the irradiation of the skin, $D_{Skin}$ (Sv $y^{-1}$) is calculated by applying a tissue weighting factor for the skin, and determining the average dose to the UV exposed skin by applying a factor that is the ratio of the area of skin contamination to the areas of skin exposed to UV (NPRB, 1997).

$$D_{Skin} = w_t \; F_{Skin} \; H_{Skin} \tag{6}$$

where:

$w_t$ is the unitless tissue weighting factor for ultra-violet (UV) exposed skin; and

$F_{Skin}$ is the ratio of the area of skin contaminated to the area of skin exposed to UV.

4.14 If the fraction of skin assumed to be contaminated is greater than the UV exposed area, the whole area of UV exposed skin is assumed to be contaminated and $F_{Skin}$ is 1. Although, strictly, the excess fraction (contamination on non-UV exposed skin) should also be taken into account in the calculation, this skin is less sensitive and NRPB recommends an additional weighting of 0.001 be applied due to the lower radiosensitivity of non-UV exposed skin. Neglecting this portion of exposed skin will only underestimate the effective dose less than 1%.

4.15 If the fraction of skin that is assumed to be contaminated is less than the UV exposed area, the ratio of the contaminated fraction to the UV exposed fraction is applied.

4.16 $F_{Skin}$ is therefore calculated as follows:

$$F_{Skin} = Min\left(1\,,\; \frac{\phi_{Out} O_{SCOut} + \phi_{In} O_{SCIn}}{O_{SCOut} + O_{SCIn}} \,/\, F_{UV}\right) \tag{7}$$

where:

$\phi_{\exp Out}$ is the fraction of exposed skin contaminated with soil whilst outdoors;

$\phi_{\exp In}$ is the fraction of exposed skin contaminated with soil whilst indoors; and

$F_{UV}$ is the fraction of all skin that is UV exposed.

## Dust Inhalation

4.17 The annual individual committed effective dose due to inhalation of contaminated dust, $D_{Inh}$, Sv y$^{-1}$, is calculated using the following expression:

$$D_{Inh} = EF\ C_{Dust}\ C_P\ DC_{Inh}\left(RV_{out} + F_{dust}\ RV_{In}\right) \tag{8}$$

where:

$C_{Dust}$ is the annual average air concentration of respirable particles (kg m$^{-3}$);

$DC_{Inh}$ is the dose coefficient for inhalation;

$RV_{Out}$ is the annual respired volume of air whilst outside (m$^3$ y$^{-1}$); and

$RV_{In}$ is the annual respired volume of air whilst indoors (m$^3$ y$^{-1}$).

4.18 The annual respired volumes ($RV_{Out}$ and $RV_{In}$) are determined for time spent outdoors and indoors from:

$$RV = \left(RR_{act}\ O_{act} + RR_{pas} O_{pas}\right)\ 8760\ \left(hours\ per\ year\right) \tag{9}$$

where:

$RR_{act}$ is the active respiration rate, m$^3$ h$^{-1}$;

$O_{act}$ is the unitless fractional active occupancy (outdoors or indoors);

$RR_{pas}$ is the passive respiration rate, m$^3$ h$^{-1}$; and

$O_{pas}$ is the unitless fractional passive occupancy (outdoors or indoors).

## Radon Gas Inhalation

4.19 The indoors concentration of radon $C_{Rn}$ (Bq m$^{-3}$) is calculated with:

$$C_{Rn} = f_{Rn}\ C_{P(Ra)} \tag{10}$$

where

$C_{P(Ra)}$ is the product of the concentration of Ra-226 in soil (Bq kg$^{-1}$), allowing for any "patchiness; and

$f_{Rn}$ is the equilibrium concentration of Rn-222 in indoor air (Bq $m^{-3}$) for a given concentration of Ra-226 in soil beneath the building (Bq $kg^{-1}$).

4.20 Either a default value for the factor fRn may be used, or a site-specific value, calculated with and expression derived from UNSCEAR (2000):

$$f_{Rn} = \frac{\lambda_{Rn}\ f\ \rho_B}{H\ (\lambda_H + \lambda_{Rn})}\sqrt{\frac{De}{\lambda_{Rn}}} \qquad (11)$$

where

$\lambda_{Rn}$ is the Rn-222 decay constant ($s^{-1}$);

$f$ is the emanation fraction (unitless);

$De$ is the effective diffusion coefficient ($m^2\ s^{-1}$);

$H$ is the height of building (m); and

$\lambda_H$ is the building ventilation rate ($s^{-1}$).

4.21 The annual effective individual dose from exposure to Rn-222 indoors is then calculated using the following expression:

$$D_{Rn} = C_{Rn}\ O_{In}\ DC_{Rn}\ f_{Eq} \qquad (12)$$

where

$O_{In}$ is the indoors occupancy (in h $y^{-1}$);

$DC_{Rn}$ is the radon dose factor (Sv $m^3$ $Bq^{-1}$ $h^{-1}$) for which a default value is recommended by UNSCEAR (2000); and

$f_{Eq}$ is the equilibrium factor (unitless) for which a default value is recommended by UNSCEAR (2000).

## Consumption of Home Grown Produce

4.22 The annual effective committed individual dose following consumption of vegetables grown in contaminated soil, $D_{Veg}$, Sv $y^{-1}$, is calculated using the following expression:

$$D_{Veg} = DC_{Ing}\ C_P \sum_{Veg}\left(365.25\left[days\ y^{-1}\right] CR_{Veg}\ BW\ HF_{Veg}\ CF_{Veg}\right) \qquad (13)$$

where:

$CR_{Veg}$ is the annual consumption rate of each vegetable per kg of body weight, kg (fresh weight) kg$^{-1}$ (body weight) d$^{-1}$;

$BW$ is the individual's body weight, kg;

$HF_{Veg}$ is the unitless fraction of the consumption rate for each vegetable that is assumed to be derived from home grown produce; and

$CF_{Veg}$ is the soil-to-plant concentration factor, Bq kg$^{-1}$ (fresh weight plant) per Bq kg$^{-1}$ (dry weight soil).

4.23 Note also that the derivation of consumption rates from body weights is adopted for consistency with the CLEA methodology.

## Consumption of Soil Associated with Home Grown Produce

4.24 The annual individual committed effective dose from the inadvertent consumption of soil associated with home grown produce, $D_{Vsoil}$, Sv y$^{-1}$, is calculated using the following expression:

$$D_{VSoil} = DC_{Ing}\, C_P \sum_{Veg} \left( 365.25\,[days\ y^{-1}]\, CR_{Veg}\ BW\ HF_{Veg}\ SL_{Veg} \right) \qquad (14)$$

where:

$SL_{Veg}$ is the amount of soil contamination on the edible portion of the home grown produce, kg (dry weight soil) kg$^{-1}$ (fresh weight plant).

## Total Dose

4.25 The total annual individual committed effective dose for a particular scenario and a particular radionuclide, $D_{Tot}$, Sv y$^{-1}$, is therefore calculated by summing the dose calculated for the contributing exposure pathways:

$$D_{Tot} = D_{Ext} + D_{Soil} + D_{Skin} + D_{Inh} + D_{Rn} + D_{Veg} + D_{VSoil} \qquad (15)$$

4.26 For cases where multiple contaminants are considered then the total annual individual committed effective dose from all contaminants, $D_{TotAll}$, Sv y$^{-1}$, is calculated by summing $D_{Tot}$ over the contributing radionuclides:

$$D_{TotAll} = \sum_{Radionuclides} D_{Tot} \tag{16}$$

4.27 The annual equivalent dose is only calculated for the irradiation of the skin (Equation 5) therefore no summation over pathways is required. However, the total equivalent dose is calculated from the summation over radionuclides.

## Derivation of Guideline Values

4.28 One of the endpoints for the RCLEA methodology is the calculated soil concentration for an individual radionuclide that corresponds to predefined dose criteria. These concentrations are referred to as "Guideline Values".

4.29 A Guideline Value (*GV*) is calculated on the basis that the dose is linearly related to the soil concentration using the following expression:

$$GV = C_{T,n} \min\left(\frac{D_C}{D_{Tot}}, \frac{H_C}{H_{Tot}}\right) \tag{17}$$

where:

$C_{T,n}$ is the initial concentration of radionuclide *n* in dry soil, Bq $kg^{-1}$;

$D_C$ is the annual individual committed effective dose criterion, Sv $y^{-1}$;

$H_C$ is the annual individual equivalent dose criterion, Sv $y^{-1}$; and

$H_{Tot}$ is the total annual equivalent dose, Sv $y^{-1}$.

4.30 For uniform contamination by a given radionuclide, the limiting combination of building type, receptor age and receptor sex is used to calculate Radioactivity in Soil Guideline Values (RSGVs). RSGVs are presented in CLR-13 [Environment Agency, 2011b].

# 5 Data

5.1 Parameter values for the RCLEA mathematical models are presented in this section for each reference land use.

5.2 The data have been based on values used in CLEA, so far as appropriate. Some additional data are necessary, however, relating to radionuclide-specific properties, for example. In such cases, the values have been obtained from well-established sources.

## Soil Properties

5.3 Soil properties are the same as those presented in CLR 10 for a loam soil and are shown in Table 2.

**Table 2: Soil Properties**

| Parameter | Description | Units | Value |
|---|---|---|---|
| $\rho_B$ | Soil dry bulk density | kg $m^{-3}$ | 1400 |
| $\theta_w$ | Soil water filled porosity | - | 0.25 |
| $\theta_t$ | Soil total porosity | - | 0.5 |
| *EF* | Enrichment factor | - | 3 |

Note: Based on loam soil in Table 5.2 of CLR 10.

5.4 In addition to the soil parameters presented in Table 2, RCLEA requires the density of soil water, $\rho s$, which is assumed to be 1000 kg $m^{-3}$. It is assumed that small deviations due to dissolved substances will have a negligible effect on the resulting soil concentration.

5.5 RCLEA also requires soil solid:liquid distribution coefficients, *Kd*, $m^3$ $kg^{-1}$. These are presented in Table 3 for the elements considered by RCLEA.

**Table 3: Soil Solid:Liquid Distribution Coefficients, m³ kg⁻¹**

| Element | Value | Table Footnote plus Additional Comments |
|---|---|---|
| H | 0 | (2) |
| C | 0.02 | Davis et al. (1993) |
| K | 0.2 | (1) & Rb assumed as an analogue |
| Fe | *0.5* | (2) |
| Co | *0.5* | (2) |
| Ni | 0.5 | (3) |
| Se | *0.05* | (2) |
| Sr | 0.02 | (1) |
| Nb | 0.5 | (1) |
| Mo | *0.05* | (2) |
| Tc | 0.0001 | (1) |
| Ag | 0.1 | (1) |
| Sn | 0.5 | (1) |
| Sb | *0.1* | (2) |
| I | 0.02 | (3) |
| Cs | *1* | (2) |
| Pm | 0.8 | (1) & Sm assumed as an analogue |
| Sm | 0.8 | (2) |
| Eu | 0.8 | (1) & Sm assumed as an analogue |
| Pb | *1* | (2) |
| Ra | *5* | (2) |
| Ac | *1* | (2) & Adjusted for similarity with Pu |
| Th | 3 | (2) & Increased distinction Sandy<Loam |
| Pa | *1* | (2) & Adjusted for similarity with Pu |
| U | 0.05 | (3) |
| Np | 0.03 | (1) |
| Pu | 1 | (1) |
| Am | *5* | (1) & Adjusted to maintain Clay>Loam |

Notes:
The quality of the data does not justify giving values to more than one significant figure.
(1) Values derived from the mean of the natural logarithm reported for loam soil in Sheppard and Thibault (1990), which forms the basis of the recommendations in IAEA (1994) and Thorne et al. (2005).
(2) Consistent with Thorne et al. (2005), values derived from Sheppard and Thibault (1990), whilst italic numbers have subsequently been modified to ensure that the loam $K_d$ is greater than or equal to the sand $K_d$ and less than or equal to the clay $K_d$ in that reference.
(3) Based on consideration of Table 3.3 of Thorne et al. (2005).

## Dose Coefficients and External Dose Factors

5.6 The dose coefficients and external dose factors used in RCLEA are presented in Table 4 and Table 5.

5.7 Values for intakes of radionuclides represent the annual committed effective dose from the intake of unit activity of the radionuclide, with short-lived daughters in secular equilibrium. ICRP dose coefficients are calculated for a 'Reference Person'. The physiology of the Reference Person may not be fully consistent with those assumed for certain other parameters in RCLEA (e.g. skin surface area). However, it is standard practice to adopt ICRP's reference dose coefficients despite such minor inconsistencies.

5.8 Values for whole body external irradiation represent the annual effective dose from irradiation by the radionuclide and its short-lived daughters, 1 m above a uniformly contaminated slab of 1 m depth and infinite area.

5.9 Dose factors for skin irradiation represent the equivalent dose resulting from uniform contamination of 1 cm$^2$ of skin with unit activity. Values are given for both gamma and beta radiation, taking account of attenuation of radiation by the radiation-insensitive skin epidermis.

**Table 4: RCLEA Dose Coefficients for Ingestion, Inhalation and External Irradiation**

| Radio-nuclide | Ingestion °, Sv Bq$^{-1}$, $DC_{Ing}$ | | | Inhalation #, Sv Bq$^{-1}$, $DC_{Inh}$ | | | External Irradiation ‡, Sv y$^{-1}$ per Bq m$^{-3}$, $DC_{Ext}$ |
|---|---|---|---|---|---|---|---|
| | Infant | Child | Adult | Infant | Child | Adult | |
| H-3 | 1.2E-10[n] | 5.7E-11[n] | 4.2E-11[n] | 2.7E-10 | 8.2E-11 | 4.5E-11 | 0.0E+0 |
| C-14 | 1.6E-9 | 8.0E-10 | 5.8E-10 | 6.6E-9 | 2.8E-9 | 2.0E-9 | 2.3E-15 |
| K-40 | 4.2E-8 | 1.3E-8 | 6.2E-9 | 1.7E-8 | 4.5E-9 | 2.1E-9 | 1.8E-10 |
| Fe-55 | 2.4E-9 | 1.1E-9 | 3.3E-10 | 1.4E-9 | 6.2E-10 | 3.8E-10 | 0.0E+0 |
| Co-60 | 2.7E-8 | 1.1E-8 | 3.4E-9 | 3.4E-8 | 1.5E-8 | 1.0E-8 | 2.7E-9 |
| Ni-63 | 8.4E-10 | 2.8E-10 | 1.5E-10 | 1.9E-9 | 7.0E-10 | 4.8E-10 | 0.0E+0 |
| Se-79 | 2.8E-8 | 1.4E-8 | 2.9E-9 | 1.3E-8 | 5.6E-9 | 1.1E-9 | 3.1E-15 |
| Sr-90* | 9.3E-8 | 6.6E-8 | 3.1E-8 | 1.2E-7 | 5.4E-8 | 3.8E-8 | 4.2E-12 |
| Nb-93m | 9.1E-10 | 2.7E-10 | 1.2E-10 | 2.4E-9 | 8.2E-10 | 5.1E-10 | 1.8E-14 |
| Nb-94 | 9.7E-9 | 3.4E-9 | 1.7E-9 | 3.7E-8 | 1.6E-8 | 1.1E-8 | 1.6E-9 |
| Mo-93 | 6.9E-9 | 4.0E-9 | 3.1E-9 | 1.8E-9 | 7.9E-10 | 5.9E-10 | 1.0E-13 |
| Tc-99 | 4.8E-9 | 1.3E-9 | 6.4E-10 | 1.3E-8 | 5.7E-9 | 4.0E-9 | 2.1E-14 |
| Ag-108m* | 1.1E-8 | 4.3E-9 | 2.3E-9 | 2.7E-8 | 1.1E-8 | 7.4E-9 | 1.6E-9 |
| Sn-121m* | 4.0E-9 | 1.2E-9 | 5.6E-10 | 1.6E-8 | 6.7E-9 | 4.7E-9 | 3.6E-13 |
| Sn-126 | 3.0E-8 | 9.8E-9 | 4.7E-9 | 1.0E-7 | 4.1E-8 | 2.8E-8 | 2.5E-11 |
| Sb-125 | 6.1E-9 | 2.1E-9 | 1.1E-9 | 1.6E-8 | 6.8E-9 | 4.8E-9 | 4.1E-10 |
| I-129 | 2.2E-7 | 1.9E-7 | 1.1E-7 | 8.6E-8 | 6.7E-8 | 3.6E-8 | 2.2E-12 |
| Cs-134 | 1.6E-8 | 1.4E-8 | 1.9E-8 | 7.3E-9 | 5.3E-9 | 6.6E-9 | 1.6E-9 |
| Cs-137* | 1.2E-8 | 1.0E-8 | 1.3E-8 | 5.4E-9 | 3.7E-9 | 4.6E-9 | 6.1E-10 |
| Pm-147 | 1.9E-9 | 5.7E-10 | 2.6E-10 | 1.8E-8 | 7.0E-9 | 5.0E-9 | 8.5E-15 |
| Sm-147 | 1.4E-7 | 6.4E-8 | 4.9E-8 | 2.3E-5 | 1.1E-5 | 9.6E-6 | 0.0E+0 |
| Sm-151 | 6.4E-10 | 2.0E-10 | 9.8E-11 | 1.0E-8 | 4.5E-9 | 4.0E-9 | 1.7E-16 |
| Eu-152 | 7.4E-9 | 2.6E-9 | 1.4E-9 | 1.0E-7 | 4.9E-8 | 4.2E-8 | 1.2E-9 |
| Eu-154 | 1.2E-8 | 4.1E-9 | 2.0E-9 | 1.5E-7 | 6.5E-8 | 5.3E-8 | 1.3E-9 |
| Eu-155 | 2.2E-9 | 6.8E-10 | 3.2E-10 | 2.3E-8 | 9.2E-9 | 6.9E-9 | 3.1E-11 |
| Pb-210* | 1.2E-5 | 4.5E-6 | 1.9E-6 | 1.5E-5 | 6.2E-6 | 4.5E-6 | 1.0E-12 |
| Ra-226* | 9.6E-7 | 8.0E-7 | 2.8E-7 | 1.1E-5 | 4.9E-6 | 3.5E-6 | 1.9E-9 |
| Ra-228* | 5.7E-6 | 3.9E-6 | 6.9E-7 | 1.0E-5 | 4.7E-6 | 2.6E-6 | 1.0E-9 |
| Ac-227* | 4.3E-6 | 2.0E-6 | 1.2E-6 | 1.7E-3 | 7.4E-4 | 5.7E-4 | 3.4E-10 |
| Th-228* | 1.1E-6 | 4.3E-7 | 1.4E-7 | 1.4E-4 | 5.9E-5 | 4.3E-5 | 1.7E-9 |
| Th-229* | 2.4E-6 | 1.2E-6 | 6.1E-7 | 2.3E-4 | 1.1E-4 | 8.6E-5 | 2.7E-10 |
| Th-230 | 4.1E-7 | 2.4E-7 | 2.1E-7 | 3.5E-5 | 1.6E-5 | 1.4E-5 | 2.0E-13 |
| Th-232 | 4.5E-7 | 2.9E-7 | 2.3E-7 | 5.0E-5 | 2.6E-5 | 2.5E-5 | 8.8E-14 |

| Radio-nuclide | Ingestion °, Sv Bq$^{-1}$, $DC_{Ing}$ | | | Inhalation #, Sv Bq$^{-1}$, $DC_{Inh}$ | | | External Irradiation ‡, Sv y$^{-1}$ per Bq m$^{-3}$, $DC_{Ext}$ |
|---|---|---|---|---|---|---|---|
| | Infant | Child | Adult | Infant | Child | Adult | |
| Natural Th~ | 2.6E-6 | 1.6E-6 | 4.3E-6 | 7.8E-5 | 3.5E-5 | 2.8E-5 | 9.1E-10 |
| Pa-231 | 1.3E-6 | 9.2E-7 | 7.1E-7 | 2.3E-4 | 1.5E-4 | 1.4E-4 | 3.2E-11 |
| U-233 | 1.4E-7 | 7.8E-8 | 5.1E-8 | 1.1E-5 | 4.9E-6 | 3.6E-6 | 2.4E-13 |
| U-234 | 1.3E-7 | 7.4E-8 | 4.9E-8 | 1.1E-5 | 4.8E-6 | 3.5E-6 | 6.8E-14 |
| U-235* | 1.3E-7 | 7.2E-8 | 4.7E-8 | 1.0E-5 | 4.3E-6 | 3.1E-6 | 1.3E-10 |
| U-236 | 1.3E-7 | 7.0E-8 | 4.7E-8 | 1.0E-5 | 4.5E-6 | 3.2E-6 | 3.6E-14 |
| U-238* | 1.5E-7 | 7.5E-8 | 4.8E-8 | 9.4E-6 | 4.0E-6 | 2.9E-6 | 2.3E-11 |
| Natural U+ | 1.4E-7 | 7.5E-8 | 4.9E-8 | 1.0E-5 | 4.4E-6 | 3.2E-6 | 1.4E-11 |
| Np-237* | 2.1E-7 | 1.1E-7 | 1.1E-7 | 4.0E-5 | 2.2E-5 | 2.3E-5 | 1.9E-10 |
| Pu-238 | 4.0E-7 | 2.4E-7 | 2.3E-7 | 7.4E-5 | 4.4E-5 | 4.6E-5 | 2.6E-14 |
| Pu-239 | 4.2E-7 | 2.7E-7 | 2.5E-7 | 7.7E-5 | 4.8E-5 | 5.0E-5 | 5.0E-14 |
| Pu-240 | 4.2E-7 | 2.7E-7 | 2.5E-7 | 7.7E-5 | 4.8E-5 | 5.0E-5 | 2.5E-14 |
| Pu-241* | 5.7E-9 | 5.1E-9 | 4.8E-9 | 9.7E-7 | 8.3E-7 | 9.0E-7 | 3.2E-15 |
| Am-241 | 3.7E-7 | 2.2E-7 | 2.0E-7 | 6.9E-5 | 4.0E-5 | 4.2E-5 | 7.4E-12 |

Notes:

* Includes contribution from short-lived daughters (see Appendix A).

~ Natural thorium is assumed to be refined thorium of sufficient age that the Th-232 decay chain has re-established equilibrium (20 years or so). Therefore, 1 Bq of natural thorium is assumed to contain 0.333 Bq of Th-232, 0.333 Bq of Th-230 and 0.333 Bq of Th-228 as well as 0.333 Bq of Ra-228 that has ingrown.

+ Natural uranium is taken to contain 99.2745% U-238, 0.72% U-235 and 0.0055% U-234 by mass, therefore 1 Bq of natural uranium is assumed to contain 0.483 Bq U-238, 0.022 Bq U-235 and 0.495 Bq U-234.

n Conservatively adopts the ingestion dose coefficient for organically bound tritium.

° Values from ICRP (1996).

# Values from ICRP (1996) adopting the recommended lung absorption type, or the worst value available in the absence of a recommendation.

‡ Values represent the effective dose rate (h_E) for external irradiation from soil contaminated to an infinite depth, based on Eckerman and Ryman (1993). Note that the source derives the effective dose rates from both beta and gamma components for an adult human, whereas the values have been used for all ages in the absence of more appropriate data for the Infant and Child age groups.

**Table 5: RCLEA Dose Factors for Skin Contact**

| Radionuclide | Contact°, Sv y$^{-1}$ per Bq cm$^{-2}$ | |
|---|---|---|
| | Beta, $DF_{\beta}$ | Gamma, $DF_{\gamma}$ |
| H-3 | 0.0E+0 | 0.0E+00 |
| C-14 | 7.9E-3 | 0.0E+00 |
| K-40 | 2.1E-2 | 7.0E-05 |
| Fe-55 | 0.0E+0 | 1.4E-04 |
| Co-60 | 1.6E-2 | 1.1E-03 |
| Ni-63 | 1.6E-4 | 0.0E+00 |
| Se-79 | 0.0E+0 | 0.0E+0 |
| Sr-90* | 4.5E-2 | 2.1E-8 |
| Nb-93m | 0.0E+0 | 1.0E-6 |
| Nb-94 | 1.9E-2 | 8.3E-4 |
| Mo-93 | 0.0E+0 | 5.5E-6 |
| Tc-99 | 1.4E-2 | 0.0E+0 |

| Radionuclide | Contact°, Sv y$^{-1}$ per Bq cm$^{-2}$ | |
|---|---|---|
| | **Beta, $DF_\beta$** | **Gamma, $DF_\gamma$** |
| Ag-108m* | 2.4E-3 | 8.8E-4 |
| Sn-121m* | 0.0E+0 | 0.0E+0 |
| Sn-126 | 0.0E+0 | 0.0E+0 |
| Sb-125 | 1.2E-2 | 2.7E-4 |
| I-129 | 5.7E-3 | 8.5E-5 |
| Cs-134 | 1.6E-2 | 7.7E-4 |
| Cs-137* | 2.2E-2 | 2.9E-4 |
| Pm-147 | 1.1E-2 | 4.3E-9 |
| Sm-147 | 0.0E+0 | 0.0E+0 |
| Sm-151 | 2.5E-4 | 7.0E-9 |
| Eu-152 | 1.4E-2 | 6.0E-4 |
| Eu-154 | 3.0E-2 | 6.5E-4 |
| Eu-155 | 7.6E-3 | 3.0E-5 |
| Pb-210* | 2.3E-2 | 7.3E-5 |
| Ra-226* | 5.2E-2 | 9.6E-4 |
| Ra-228* | 2.7E-2 | 5.1E-4 |
| Ac-227* | # | # |
| Th-228* | 5.6E-2 | 8.8E-4 |
| Th-229* | 5.5E-2 | 6.4E-4 |
| Th-230 | 9.1E-4 | 3.3E-5 |
| Th-232 | 8.3E-2 | 1.4E-3 |
| Natural Th~ | 5.5E-2 | 9.5E-4 |
| Pa-231 | 1.3E-3 | 2.5E-5 |
| U-233 | 4.6E-5 | 1.5E-5 |
| U-234 | 6.5E-5 | 2.4E-5 |
| U-235* | 2.2E-2 | 9.5E-5 |
| U-236 | 4.0E-5 | 8.3E-7 |
| U-238* | 3.3E-2 | 8.5E-5 |
| Natural U+ | 1.7E-2 | 5.5E-5 |
| Np-237* | 3.0E-2 | 4.8E-4 |
| Pu-238 | 9.3E-4 | 2.4E-5 |
| Pu-239 | 3.8E-6 | 8.8E-6 |
| Pu-240 | 0.0E+0 | 9.1E-7 |
| Pu-241* | 4.2E-7 | 1.6E-8 |
| Am-241 | 4.8E-4 | 1.5E-4 |

Note:

* * Includes contribution from short-lived daughters (see Appendix A).
* ~ Natural thorium is assumed to be refined thorium of sufficient age that the Th-232 decay chain has re-established equilibrium (20 years or so). Therefore, 1 Bq of natural thorium is assumed to contain 0.333 Bq of Th-232, 0.333 Bq of Th-230 and 0.333 Bq of Th-228 as well as 0.333 Bq of Ra-228 that has ingrown.
* \+ Natural uranium is taken to contain 99.2745% U-238, 0.72% U-235 and 0.0055% U-234 by mass, therefore 1 Bq of natural uranium is assumed to contain 0.483 Bq U-238, 0.022 Bq U-235 and 0.495 Bq U-234.
* ° The contact equivalent dose rates are derived from Harvey et al. (1993) and assume a skin thickness of 40 mg cm$^{-2}$.
* \# No values for Ac-227 in Harvey et al. (1993).

### Shielding Factor Applied whilst Indoors

5.10 Walls and floors provide a degree of shielding from external irradiation whilst an individual is indoors. The degree of shielding depends on the density and thickness of the building material as well as the type and energy of the radiation.

5.11 Simple assumptions have been adopted for RCLEA. A material dependent shielding factor is adopted that assumes the same degree of shielding irrespective of the emissions of a given radionuclide. Two alternatives are provided based on material type:

- ▲ A shielding factor of 0.9 is adopted for buildings with concrete/brick floors and walls; whilst
- ▲ A shielding factor of 0 is adopted for buildings with wooden floors and/or walls, representing a cautious assumption that the relatively thin and light wooden floors and walls provide no shielding.

5.12 This assumption is based observed reductions in radiation dose rate from contaminated soil due to the presence of building materials (see, for example, the review presented in Smith et al. (2004)).

### Tissue Weighting Factor for UV Exposed Skin

5.13 The calculation of the annual equivalent dose for direct irradiation of skin due to dermal contamination (see Equations 5 and 6) requires a tissue weighting factor for UV exposed skin, *wt*. The representation of this exposure pathway is based on the recommendations of the HPA RPD and the value recommended by ICRP (ICRP, 1991) is adopted:

- ▲ The recommended tissue weighting value for UV exposed skin is 0.01.

## Exposure Group Parameters

5.14 RCLEA adopts a deterministic approach to calculating exposure. For this reason, it is necessary to obtain deterministic values from the distributions adopted for some parameters in CLEA. The following approach is taken unless otherwise stated:

- ▲ For human anatomical and physiological characteristics, parameter values are generally chosen from CLEA data to be consistent with ICRP Reference Man assumptions (ICRP, 1975).

- ▲ Other values recommended for RCLEA represent the 95th percentile (mean plus 1.645 standard deviations) of the CLEA distributions as a cautious estimate.

### *Body Weight*

5.15 The body weight of an exposed individual, *BW*, kg, is used to determine a person's vegetable consumption rate (see Equations 10 and 11). The recommended values are shown in Table 6 and are based on those presented in Table 5.6 of CLR 10.

**Table 6: Age Group Body Weights**

| Age Group | Body Weight, kg | | Comment |
|---|---|---|---|
| | Male | Female | |
| Infant | 11 | 11 | Based on 1 to 2 year olds |
| Child | 37 | 37 | Based on 10 to 11 year olds |
| Adult | 81 | 68 | Based on 16 to 59 year olds |

Note that the values are rounded to two significant figures.

### *Fraction of Skin Area Exposed to Contaminated Soil or Dust*

5.16 Equation 7 requires the exposed skin area as a fraction of the total, $\varphi_{exp}$. This has been reviewed for the CLEA methodology and revised values presented in CLEA Briefing Note 1. These revised values are adopted as the basis for the RCLEA recommendations and are presented in Table 7.

**Table 7: Exposed Skin Area as a Fraction of the Total Skin Surface Area**

| Land Use | Age Group | Maximum Exposed Skin Area | | Comment |
|---|---|---|---|---|
| | | Outdoors | Indoors | |
| Residential or Allotment | Infant | 0.26 | 0.33 | Based on 1 to 2 year olds |
| | Child | 0.15 | 0.22 | Based on 10 to 11 year olds |
| | Adult | 0.26 | 0.33 | Based on 16 to 59 year olds |
| Commercial/ Industrial | Adult | 0.07 | | Based on 16 to 59 year olds |

Note values drawn from Table 2 of CLEA Briefing Note 1, note that Residential and Allotment values are only given for females.

### *Fraction of Skin Exposed to UV*

5.17 The calculation of the annual individual effective dose from skin irradiation requires the fraction of all skin area that is routinely exposed to UV light (i.e.

daylight), *FUV* (-), to be specified. The value recommended by NRPB (1997) for adults is 3 000 $cm^2$ out of a total skin surface area of 18 000 $cm^2$ (i.e. a fraction of 0.167). It is assumed that this portion is the same for all ages and sexes.

### *Soil Contamination of Skin*

5.18 The dry weight of soil on skin contaminated with soil, $\rho_{skin}$, mg (dry soil) $cm^{-2}$ (see Equation 5) was recently reviewed in CLEA Briefing Note 1, which forms the basis for the values recommended for RCLEA in Table 8.

**Table 8: Dry Weight Soil Loading for Skin Contaminated with Soil**

| Land Use | Location | Soil Loading by Age Group, mg (dry soil) $cm^{-2}$ | |
|---|---|---|---|
| | | **Infants and Children** | **Adults** |
| Residential | Indoors<br>Outdoors | 0.06<br>1 | 0.06<br>0.3 |
| Allotments | Indoors<br>Outdoors | 0.06<br>1 | 0.06<br>0.3 |
| Commercial/ Industrial | Indoors and Outdoors | - | 0.14 |

Note that these values are derived from Table 3 of CLEA Briefing Note 1, assuming that the soil-to-skin adherence factor for Residential indoors applies for the Allotment indoors and noting that the Commercial/Industrial value applies indoors and outdoors.

### *Consumption Rate of Home grown Vegetables*

5.19 Calculation of the annual committed effective individual dose from consumption of home grown vegetables and the inadvertent ingestion of soil associated with home grown vegetables requires a vegetable consumption rate expressed in relation to body weight, $CR_{Veg}$, kg (fresh weight plant) $kg^{-1}$ (body weight) $d^{-1}$ (see Equations 10 and 11).

5.20 The consumption rates adopted for RCLEA are shown in Table 9. Note that for the RCLEA 1 year old Infant, the value for the Toddler (1 to 4 years old) presented in CLR 10 is adopted as a cautious assumption. The resulting annual consumption rates that are calculated with the default body weights (Table 6) are shown in Table 10 for information. Consistent with other exposure group parameters, these rates represent a cautious assumption.

**Table 9: Consumption Rate of Vegetables Relative to Body Weight**

| Age Group | Consumption Rate $CR_{Veg}$, kg (fresh weight plant) kg$^{-1}$ (body weight) d$^{-1}$ | | | | | |
|---|---|---|---|---|---|---|
| | **Brussels sprouts** | **Cabbage** | **Carrot** | **Leafy Salads** | **Onion (shallots and leeks)** | **Potato** |
| Infant | 1.3E-3 | 1.5E-3 | 1.8E-3 | 1.1E-3 | 9.2E-4 | 7.5E-3 |
| Child | 6.8E-4 | 6.3E-4 | 1.0E-3 | 5.3E-4 | 6.3E-4 | 5.7E-3 |
| Adult | 7.0E-4 | 6.7E-4 | 6.5E-4 | 4.9E-4 | 4.4E-4 | 3.4E-3 |

Note that these values represent the 95$^{th}$ percentile of the CLEA distributions and are derived from Table 6.3 of CLR 10 and rounded to 2 significant figures.

**Table 10: Annual Vegetable Consumption Rates Derived from Table 9 and the Default Body Weights**

| Sex | Age Group | Annual Consumption Rate $CR_{Veg}$, kg (fresh weight plant) y$^{-1}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Brussels sprouts** | **Cabbage** | **Carrot** | **Leafy Salads** | **Onion (shallots and leeks)** | **Potato** |
| Male | Infant | 5 | 6 | 7 | 4 | 4 | 30 |
| | Child | 9 | 9 | 14 | 7 | 9 | 77 |
| | Adult | 21 | 20 | 19 | 14 | 13 | 101 |
| Female | Infant | 5 | 6 | 7 | 4 | 4 | 30 |
| | Child | 9 | 9 | 14 | 7 | 9 | 77 |
| | Adult | 17 | 17 | 16 | 12 | 11 | 84 |

Note: Derived from default body weights (Table 6) and relative consumption rates (Table 9) and rounded to the nearest integer.

### *Fraction of Consumption Derived from Home Grown Produce*

5.21 In addition to the consumption rate of vegetables, Equations 10 and 11 also require a fraction of each crop type that is derived from home grown produce, $HF_{Veg}$. Consistent with the CLEA methodology, the same values are adopted for both the Residential (with plant uptake) and Allotment land uses and are shown in Table 11.

**Table 11: Fraction of Consumption Derived from Home grown Produce**

| Vegetable | Home grown Fraction |
|---|---|
| Brussels Sprouts | 0.87 |
| Cabbage | 0.92 |
| Carrot | 0.70 |
| Leafy Salads | 0.51 |
| Onion (including shallots and leeks) | 0.91 |
| Potato | 0.66 |

Note that these values are based on Table 6.4 of CLR 10.

## *Inadvertent Ingestion Rate of Soil and Dust*

5.22 The inadvertent ingestion rates for soil and dust, $I_{Soil}$, kg (dry soil) $y^{-1}$ (see Equation 4), are dependent on the land use and on the age group. The values are shown in Table 12 and are selected to be consistent with the recommendations in CLR 10.

**Table 12: Inadvertent Ingestion Rate of Soil and Dust, kg (dry dust) $y^{-1}$**

| Age Group | Land Use | | |
|---|---|---|---|
| | Residential | Allotments | Commercial/Industrial |
| Infant | 5.5E-2 | 5.5E-2 | - |
| Child | 3.7E-2 | 3.7E-2 | - |
| Adult | 2.2E-2 | 2.6E-2 | 9.2E-3 |

Note that these values take account of the rate and exposure frequency reported in Table 6.1 of CLR 10.

## *Occupancies*

**Exposure Group Occupancy Assumptions**

5.23 Various exposure pathways require information on fraction of time spent indoors or outdoors on contaminated land (the ‘occupancy’). This information is drawn from CLR 10 and is presented in Table 13, Table 14 and Table 15. Note that in some instances the number of ‘hours per day’ does not sum to 24 h $d^{-1}$ for a particular combination of land use and age. This is because ‘hours per day’ is the average duration during the specified number of ‘days per year’ that time is spent indoors or outdoors, active or passive. In practice, the fractional occupancy is used in the calculations, which is calculated from the product of ‘hours per day’ and ‘days per year’, all divided by 8760 hours per year.

**Table 13: Occupancy Assumptions for the Residential Land Use**

| Exposure Pathway | Units | Location/Activity | Infant | Child | Adult |
|---|---|---|---|---|---|
| Soil/dust ingestion | days per year | | 365 | 365 | 365 |
| Dermal | days per year | Indoors<br>Outdoors | 365<br>130 | 365<br>130 | 365<br>365 |
| External | days per year | Indoors<br>Outdoors | 365<br>365 | 365<br>365 | 365<br>365 |
| | hours per day | Indoors<br>Outdoors | 21<br>3 | 18<br>2 | 20<br>2.5 |
| Inhalation | days per year | Indoors<br>Outdoors | 365<br>365 | 365<br>365 | 365<br>365 |
| | hours per day | Indoors active<br>Indoors passive<br>Outdoors active<br>Outdoors passive | 3<br>18<br>2<br>1 | 2<br>16<br>2<br>0 | 3<br>17<br>1.5<br>1 |

Note that Infants adopt 1 to 2 year old characteristics from CLEA, Children adopt the 10 to 11 year old characteristics and Adults adopt the 59 to 70 year old characteristics to maximise the exposure duration. Values based on CLR 10 Tables 4.3 and 4.4.

**Table 14: Occupancy Assumptions for the Allotment Land Use**

| Exposure Pathway | Units | Location/Activity | Infant* | Child | Adult |
|---|---|---|---|---|---|
| Soil/dust ingestion | days per year | | 365 | 365 | 365 |
| Dermal | days per year | Indoors<br>Outdoors | 365<br>28 | 365<br>19 | 365<br>208 |
| External | days per year | Indoors<br>Outdoors | 365<br>78 | 365<br>52 | 365<br>208 |
| | hours per day | Indoors<br>Outdoors | 21<br>4 | 18<br>4 | 20<br>4 |
| Inhalation | days per year | Indoors<br>Outdoors | 365<br>78 | 365<br>52 | 365<br>208 |
| | hours per day | Indoors active<br>Indoors passive<br>Outdoors active<br>Outdoors passive | 3<br>18<br>2<br>2 | 2<br>16<br>2<br>2 | 3<br>17<br>2<br>2 |

Note that Infants adopt 1 to 2 year old characteristics from CLEA, Children adopt the 10 to 11 year old characteristics and Adults adopt the 59 to 70 year old characteristics to maximise the exposure duration. Values based on CLR 10 Tables 4.8, 4.9 and 4.10.

**Table 15: Occupancy Assumptions for the Commercial/Industrial Land Use**

| Exposure Pathway | Units | Location/Activity | Adult |
|---|---|---|---|
| Soil/dust ingestion | days per year | | 230 |
| Dermal | days per year | Indoors<br>Outdoors | 230<br>170 |
| External | days per year | Indoors<br>Outdoors | 230<br>170 |
| | hours per day | Indoors<br>Outdoors | 7.5<br>0.99 |
| Inhalation | days per year | Indoors<br>Outdoors | 230<br>170 |
| | hours per day | Indoors active<br>Indoors passive<br>Outdoors active<br>Outdoors passive | 2<br>5.5<br>0.66<br>0.33 |

Values based on CLR 10 Table 4.13, which are presented for female workers aged 16 to 59.

**Fractional Occupancies for External Irradiation**

5.24 The calculation of the annual effective dose from external irradiation requires fractional indoor and outdoor occupancies on contaminated land, $O_{In}$ and $O_{Out}$ (see Equation 3). These values are based on the assumptions presented in Table 13, Table 14 and Table 15 and are shown in Table 16.

**Table 16: Fractional Occupancies for External Irradiation**

| Age Group | Land Use Fractional Occupancies for External Irradiation | | | | | |
|---|---|---|---|---|---|---|
| | Residential | | Allotment | | Commercial/Industrial | |
| | Outdoor | Indoor | Outdoor | Indoor | Outdoor | Indoor |
| Infant | 0.125 | 0.875 | 0.036 | 0.875 | - | - |
| Child | 0.083 | 0.750 | 0.024 | 0.750 | - | - |
| Adult | 0.104 | 0.833 | 0.095 | 0.833 | 0.019 | 0.197 |

**Fractional Occupancy for Dermal Contact**

5.25 The calculation of annual effective and equivalent doses arising from dermal contact with contaminated soil requires a fractional duration of skin contact with contaminated soil, $O_{SC}$ (see Equations 5 and 7). Paragraph 6.67 of the CLR 10 report assumes a single skin contact event per day with a duration of 12 hours. Table 13, Table 14 and Table 15 provide the number of days per year individuals are subject to indoor and outdoor dermal contact. The resulting fractional occupancies are presented in Table 17.

**Table 17: Fractional Occupancies for Dermal Contact**

| Age Group | Land Use Fractional Occupancies for Dermal Contact | | | | | |
|---|---|---|---|---|---|---|
| | Residential | | Allotment | | Commercial/Industrial | |
| | Outdoor | Indoor | Outdoor | Indoor | Outdoor | Indoor |
| Infant | 0.178 | 0.5 | 0.038 | 0.5 | - | - |
| Child | 0.178 | 0.5 | 0.026 | 0.5 | - | - |
| Adult | 0.5 | 0.5 | 0.285 | 0.5 | 0.233 | 0.315 |

**Fractional Occupancies for Inhalation**

5.26 The calculation of the annual volume of air containing contaminated dust breathed by an exposed individual requires fractional occupancies for active and passive respiration, $O_{act}$ and $O_{pas}$ (see Equation 9). Values are derived from the occupancy assumptions presented in Table 13, Table 16 and Table 15 and are shown in Table 18.

**Table 18: Fractional Occupancies for Inhalation**

| Land Use | Location | Respiration | Infant | Child | Adult |
|---|---|---|---|---|---|
| Residential | Indoors | Active | 0.125 | 0.083 | 0.125 |
| | | Passive | 0.750 | 0.667 | 0.708 |
| | Outdoors | Active | 0.083 | 0.083 | 0.063 |
| | | Passive | 0.042 | 0 | 0.042 |
| Allotment | Indoors | Active | 0.125 | 0.083 | 0.125 |
| | | Passive | 0.750 | 0.667 | 0.708 |
| | Outdoors | Active | 0.018 | 0.012 | 0.047 |
| | | Passive | 0.018 | 0.012 | 0.047 |
| Commercial/ Industrial | Indoors | Active | - | - | 0.052 |
| | | Passive | - | - | 0.144 |
| | Outdoors | Active | - | - | 0.013 |
| | | Passive | - | - | 0.006 |

### *Breathing Rates*

5.27 The calculation of the annual volume of air containing contaminated dust breathed by an exposed individual also requires active and passive breathing rates, $RR_{act}$ and $RR_{pas}$ (see Equation 9). These values are drawn from Table 5.9 of CLR 10 and are presented in Table 19.

**Table 19: Age Dependent Breathing Rates**

| Age Group | Breathing Rate, $m^3 h^{-1}$ | | | | Comment |
|---|---|---|---|---|---|
| | Male | | Female | | |
| | Active | Passive | Active | Passive | |
| Infant | 0.339 | 0.124 | 0.320 | 0.117 | Based on 1 to 2 year olds |
| Child | 1.103 | 0.404 | 1.100 | 0.403 | Based on 10 to 11 year olds |
| Adult | 1.456 | 0.485 | 1.234 | 0.411 | Based on 16 to 59 year olds |

Note that consistent with the CLEA methodology and with the body weight assumptions (Table 6).

## Transfer Parameters

5.28 This sub-section presents parameters associated with the transfer of radionuclides in the environment.

### *Fraction of Indoor Dust Comprising of Locally Derived Soil*

5.29 The fraction of indoor dust comprising of locally derived soil, $F_{dust}$, is required to calculate the dermal contact exposure (Equation 5) as well as exposure from the inhalation of indoor dust (Equation 8). The recommended values for RCLEA are based on those adopted for the CLEA methodology (CLR 10):

**Table 20: Fraction of Indoor Dust Comprising of Locally Derived Soil**

| Land Use | Fraction of Indoor Dust Comprising of Locally Derived Soil |
|---|---|
| Residential | 0.75 |
| Allotment | 0.375 |
| Commercial/Industrial | 0.75 |

Note values adopted from Table 5.3 of CLR 10.

### *Soil-to-Plant Concentration Factors*

5.30 Potential exposure due to contaminant uptake by home grown vegetables requires a soil-to-plant concentration factor for each of the RCLEA elements, $CF_{Veg}$ (see Equation 10).

5.31 Thorne et al. (2005) derive soil-to-plant concentration factors from soil $K_d$ and an element dependent 'uptake affinity', $\delta$, reflecting the differing degree to which plants can take up different elements from the soil solution. The same approach is adopted for RCLEA, with the soil-to-plant concentration factors being derived with the following expression:

$$CF_{Veg} = \frac{\delta}{(\theta_t + \rho_B \; K_d)} \tag{15}$$

5.32 The recommended values for $CF_{Veg}$ are derived using the soil properties given in Table 2 and Table 3 to ensure consistency. The resulting values are rounded to one significant figure and documented in Table 21, along with the values for the uptake affinity, $\delta$.

5.33 H-3 has a $K_d$ value of zero, therefore, the soil-to-plant concentration factor for tritium is not derived using Equation 15. Given that most fresh-weight plant material is about 90% water (IAEA, 1994), which is predominantly derived from root uptake, it can reasonably be assumed that the fresh weight concentration of H-3 in plants is the same as that for soil water, in which case, $CF_{Veg}$ for tritium can be determined from:

$$CF_{Veg,H-3} = \frac{\rho_B}{\theta_W \; \rho_W} \tag{16}$$

**Table 21: Derivation of Soil to Plant Concentration Factors for the RCLEA Reference Soil, Bq kg$^{-1}$ (fresh weight plant) per Bq kg$^{-1}$ (dry weight soil)**

| Element | Soil-to-Plant Concentration Factor | δ | Table Footnote |
|---|---|---|---|
| H | 6.E+0 | - | (1) |
| C | 2.E-1 | 5 | (2) |
| K | 2.E-1 | 50 | (3) |
| Fe | 7.E-3 | 5 | (4) |
| Co | 7.E-3 | 5 | (5) |
| Ni | 7.E-3 | 5 | (5) |
| Se | 7.E-1 | 50 | (5) |
| Sr | 2.E-1 | 5 | (5) |
| Nb | 4.E-4 | 0.5 | (5) |
| Mo | 7.E-2 | 5 | (6) |
| Tc | 8.E+0 | 5 | (5) |
| Ag | 4.E-2 | 5 | (7) |
| Sn | 7.E-3 | 5 | (8) |
| Sb | 4.E-2 | 5 | (5) |
| I | 4.E-3 | 0.1 | (5) |
| Cs | 4.E-3 | 5 | (5) |
| Pm | 4.E-4 | 0.5 | (9) |
| Sm | 4.E-4 | 0.5 | (9) |
| Eu | 4.E-4 | 0.5 | (9) |
| Pb | 4.E-3 | 5 | (5) |
| Ra | 7.E-4 | 5 | (10) |
| Ac | 4.E-4 | 0.5 | (11) |
| Th | 1.E-4 | 0.5 | (11) |
| Pa | 4.E-4 | 0.5 | (11) |
| U | 7.E-3 | 0.5 | (5) |
| Np | 1.E-2 | 0.5 | (5) |

| Element | Soil-to-Plant Concentration Factor | δ | Table Footnote |
|---|---|---|---|
| Pu | 4.E-4 | 0.5 | (5) |
| Am | 7.E-5 | 0.5 | (5) |

Notes:
(1) Derived using Equation 16.
(2) Plants obtain most C via the atmosphere from photosynthesis, Greger (2004) notes that some carbohydrates and dissolved $CO_2$ can be absorbed via roots, therefore moderate uptake affinity is cautiously assumed.
(3) Greger (2004) notes that K is an essential macronutrient, therefore a high uptake affinity is assumed.
(4) Greger (2004) notes that Fe is required by plants but it is not readily translocated, therefore a moderate uptake affinity is assumed.
(5) Uptake affinity from Thorne et al. (2005).
(6) Greger (2004) notes that Mo is moderately mobile in plants, therefore a moderate uptake affinity is assumed.
(7) Greger (2004) notes that Ag is taken up by plants, so a moderate uptake affinity is assumed.
(8) Greger (2004) notes that Sn is easily taken up from solution, therefore a moderate uptake affinity is assumed.
(9) Greger (2004) notes that lanthanides are strongly excluded by plants, therefore a low uptake affinity is recommended.
(10) Chemical and physiological similarity (Greger, 2004) with Ca means Ra assumed to have a moderate uptake affinity.
(11) Low uptake affinity assumed for these actinides.

### *Soil Contamination of Home Grown Vegetables*

5.34 The inadvertent ingestion of contaminated soil due to its presence on the surface of home grown produce (see Equation 11), requires the degree of assumed soil loading for the vegetables, $SL_{Veg}$, kg (dry weight soil) kg$^{-1}$ (fresh weight plant), to be specified. The recommended values are presented in Table 22.

**Table 22: Soil Contamination of Home grown vegetables**

| Vegetable | Soil Loading, kg (dry weight soil) kg$^{-1}$ (fresh weight plant) |
|---|---|
| Brussels sprouts | 0.001 |
| Cabbage | 0.001 |
| Carrot | 0.0001 |
| Leafy Salads | 0.001 |
| Leeks | 0.001 |
| Potatoes | 0.0002 |

Note that the values are adopted from Table 6.2 of CLR 10, where the value for leeks is cautiously adopted for onions and shallots.

### *Atmospheric Dust Parameters*

5.35 The CLEA methodology adopts an algorithm for determining the concentration of respirable particulates (used in Equation 8), which is based on the wind-driven resuspension of particles less than 10 µm in diameter (see paragraph 6.75 of CLR 10). It has been noted that the resulting concentration of 8E-10 kg $m^{-3}$ is low in comparison with values typically adopted in radiological assessments for respirable dust concentrations. Therefore a value of 5E-8 kg $m^{-3}$ is adopted for $C_{Dust}$. This is the ambient value used by Oatway and Mobbs (2003) for a housing scenario.

## Radon Model Parameters

5.36 The default value for the factor $f_{Rn}$ is 3 Bq $m^{-3}$ Rn-222 in indoor air per Bq $kg^{-1}$ of Rn-226 in soil. This factor is based primarily on measured relationships, but is also consistent with mathematical models of radon release. The basis for selecting this value is described by Penfold (2011).

5.37 Parameters used in the site-specific calculation of $f_{Rn}$ are given in Table 23. Of these parameters, only the building height and ventilation rate should be treated as variables in RCLEA. The reference values of all are based on UNSCEAR (2000) recommendations, as discussed by Penfold (2011).

**Table 23: Parameters for the Site-specific Calculation of Indoors Radon Concentration**

| Parameter | Reference Value |
|---|---|
| Rn-222 decay constant ($s^{-1}$) | $2.1\ 10^{-6}$ |
| Emanation fraction (-) | 0.2 |
| Effective diffusion coefficient ($m^2\ s^{-1}$) | $2.0\ 10^{-6}$ |
| Height of building (m) | 3 |
| Building ventilation rate ($s^{-1}$) | $8.33\ 10^{-5}$ * |

~ The diffusion coefficient depends on the soil porosity and saturation.

* Corresponds to 0.3 $h^{-1}$.

5.38 The recommended value for the dose factor $DC_{Rn}$ is 9 $10^{-9}$ Sv $m^3$ $Bq^{-1}$ $h^{-1}$ (UNCEAR, 2000). The equilibrium factor $f_{Eq}$ for indoors exposure takes a recommended value of 0.4 (UNSCEAR, 2000).

# 6 Calculations with RCLEA

6.1 The RCLEA methodology can be used as part the recommended approach to managing radioactively contaminated land, described in the Model Procedures (Environment Agency, 2004). This section describes how calculations can be undertaken. The use of RCLEA in making decisions in the context of the Part 2A regime is not discussed here, but is addressed an accompanying report, CLR-13.

6.2 Broadly, RCLEA can be used to undertake:

- A '**generic assessments**', when there is no reliable information about the site other than the suspected radionuclides present and general observations about the type of land use, etc.; and
- A '**site-specific assessments**' when more information is available about the site and the inhabitants or users of the contaminated land.

6.3 In the former case, the default data described in Section 6 are used for all parameters. In the latter, site-specific values can be adopted where justified; although the methodology contains a range of default parameter assumptions, it is acceptable to modify many of these assumptions if suitable information is available.

6.4 The application of the methodology in each situation is discussed in this section. In each case, RCLEA can be used to calculate Guideline Values (soil concentrations that correspond exactly to regulatory dose criteria) or radiation doses. The former are calculated concentrations that can be compared with measurements. Radiation doses can be calculated only if the contaminant concentrations in soil are already known.

6.5 It is noted that the RCLEA mathematical models and data have been implemented in a software application, based around Microsoft Excel® and published as CLR-15. It is generally recommended that, for convenience and consistency, this software application be used to apply the methodology. However, the models and data can be implemented in other ways if required.

## Generic Assessments

6.6 A generic calculation involves the application of RCLEA with only very limited information being required to be specified by the user:

- The reference land use most closely resembling the existing use of the contaminated site (selected from residential with or without home grown vegetables, allotments or commercial/industrial use);

- The building types most closely resembling those present (either timber or concrete/brick construction); and

- The receptor age and sex most closely resembling the exposed individual(s) (infant, child or adult, being male or female).

6.7 The general sequence with which the assessment should be defined is illustrated in Figure 1.

6.8 If it is not possible to determine any one of these aspects of the site (e.g. the building type is unknown), or several of the alternatives are present (e.g. adults, children or infants are all present), all should be considered and the combination that results in the highest exposure be identified.

6.9 It is also necessary to specify the radionuclide(s) expected or known to be present. Concentrations can be specified if estimates or measured values are available. Concentration values should be the excess over and above the typical background value at the site.

6.10 For all other parameters, the default parameter assumptions described in Section 5 are used for generic assessments.

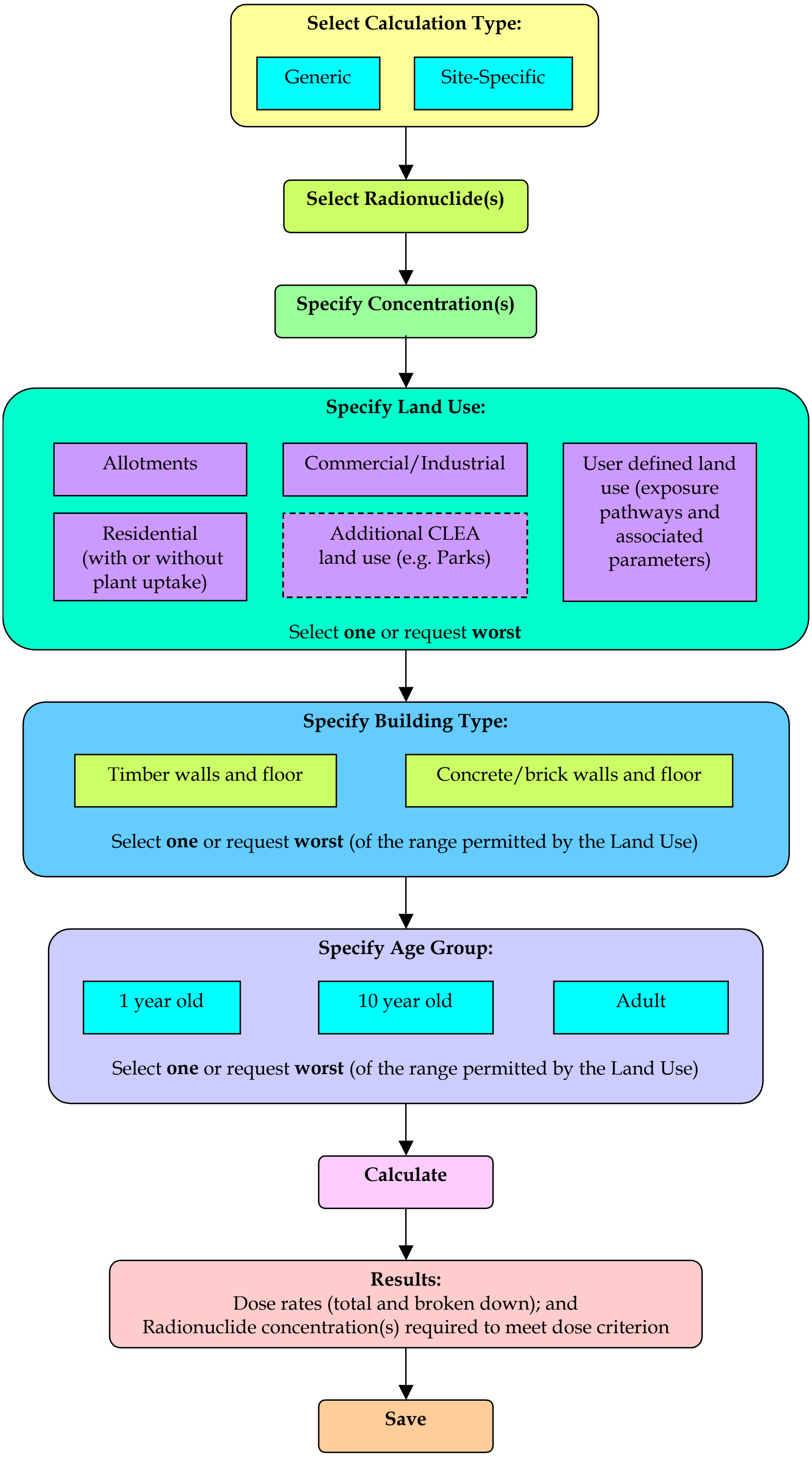
### *Calculation of Doses*

6.11 If the concentration of one or more radionuclides in soil is known, or has been estimated with sufficient confidence, the RCLEA models and data can be used to estimate the annual effective dose and annual equivalent dose to the skin of the exposed individual.

### *Calculation of Guideline Values*

6.12 In cases where only a single radionuclide is expected, it can be assigned a nominal activity (e.g. 1 Bq $kg^{-1}$) in order to calculate a Guideline Value. In cases where contamination with multiple radionuclides are anticipated then the expected ratios can be specified and Guideline Values for the specified mixture can be calculated. It is emphasised that the impact of multiple radionuclides is additive, therefore Guideline Values calculated for single radionuclides are **not applicable** in cases of contamination with multiple radionuclides.

**Figure 1: Application of the RCLEA Approach for a Generic Assessment**



### *Radioactivity in Soil Guideline Values*

6.13 The Radioactivity in Soil Guideline Values (RSGVs) represent a special type of single-radionuclide Guideline Value which relates to the most cautious combination of land use, building type, age and sex. RSGVs have been published in CLR-13.

6.14 If only a single radionuclide is present, and its concentration in soil has been established, these values can be used as a simple initial assessment requiring minimal information about a site. Should the measured value be less than the RSGV, no further action is needed.

6.15 If several radionuclides are present, it is necessary to apply a simple formula to determine whether the relevant combination of radionuclides might exceed the regulatory dose criteria on the basis of a generic assessment:

$$\sum_n \frac{C_{T,n}}{RSGV_n} \leq 1 \qquad (17)$$

where $C_{T,n}$ is the concentration of radionuclide $n$ per unit of dry soil (Bq kg$^{-1}$) and $RSGV_n$ is the RSGV for radionuclide $n$ (also in Bq kg$^{-1}$).

## Site-specific Assessments

6.16 RCLEA can also be used to take account of site-specific information if a more detailed assessment is required (Environment Agency, 2004). However, the breadth with which the RCLEA methodology can be adapted to represent a particular site is constrained by:

- ▲ The assumptions about the contaminated soil characteristics (e.g. contamination is present with uniform concentrations in the first 1 m of soil);
- ▲ The assumed exposure pathways (e.g. exposure to contaminated groundwater is not considered); and
- ▲ The modelling approach applied (e.g. a deterministic approach is adopted).

6.17 It is nevertheless possible to make many modifications that permit site-specific conditions to be assessed by modifying the default parameter values presented in Section 5. For example, intake rates can be adapted to represent the specific characteristics of individuals present on a site. Soil and plant characteristics can also be modified to better represent the conditions at the site.

6.18 However, caution must be exercised when modifying any of the default data because parameter values adopted within CLEA and RCLEA have been based on considerable research – they should not be changed without good reason. If alternative parameter values are used:

- Changes to parameter values should be clearly recorded, and the reasoning explained; and
- Any modifications should be checked to determine whether they have implications for other parameters (e.g. if the time spent indoors is increased, the time spent outdoors should be reduced).

## *Specification of a New Land Use*

6.19 The reference land uses in RCLEA are intended to represent broadly the circumstances in which contaminated land can be found. However, it is recognised that a given site is likely to differ significantly in some respects from the reference assumptions and parameter values. Therefore, site-specific land uses can be defined.

6.20 Consistent with the CLEA approach, the land use is defined in terms of the following parameters:

- Age groups that are (or may be) present;
- Exposure pathways that are (or may be) present;
- Basic characteristics of the site (e.g. the concentration of respirable dust in air and fraction of indoor dust arising from contaminated soil);
- The occupancy of the contaminated site by exposed individuals and fraction of time spent indoors or outdoors; and
- The inadvertent soil ingestion rate and contamination present on the skin.

6.21 An additional land use can therefore be defined by specifying this information. In many cases, it will be reasonable to start with the assumptions for an existing land use, and modify only those aspects necessary, as this will require less description and reasoning to be documented.

## *Modifications to Other Parameters*

6.22 Other than the radionuclides present and their concentrations, the only parameter describing the contaminated land itself that can be modified is the fraction of the area considered to be occupied that is contaminated. This is intended to allow the representation of patchy contamination. It should be noted that different areas are considered to be used for different land uses (0.2 ha for the residential scenario, 0.8 ha for allotments and 2 ha for commercial/industrial use).

6.23 Default soil and plant properties are intended to be generally representative, but site-specific variation can be expected in, for example, soil porosity and saturation. The generic soil type is based on a loam, so alternative site-specific assumptions may be appropriate if the soil characteristics are known to be more representative of sand or clay soils. However, site-specific information is unlikely to be available for soil:liquid distribution coefficients and soil-to-plant concentration factors. Furthermore, these values are often found to exhibit considerable variability. Therefore, it is recommended that the default values are retained unless well established alternative values are available. The radon emanation factor and diffusion coefficient are also categorised as soil parameters that may be modified where a site-specific calculation of radon concentrations is undertaken.

6.24 The only parameters related to building properties that can be modified are the shielding factor, height and ventilation rate. Th shielding factor represents fractional attenuation of the external dose rate by the building materials. In practice, this is a complicated function of radiation type and energy, the distribution of radionuclides in soil, and the geometry of the building. Whilst modifications to the simple, radionuclide-independent factor can be made, it is recommended that if external irradiation dominates the dose, and dose criteria are exceeded with an RCLEA calculation, a more detailed external irradiation model should be used. The height and ventilation rate are parameters that are used in site-specific calculations of radon concentration.

6.25 Human anatomical and physiological data are based on national and international surveys and should only be modified if the assumptions are clearly a poor representation of the exposed individual. The default values adopted in RCLEA are the mean of the distribution adopted in CLEA, and are consistent with reference values recommended by ICRP (1975).

6.26 Other human exposure parameters, such as the ingestion rate of vegetables can be changed if required. Caution should nevertheless be exercised, as the data has been based on extensive national studies. Furthermore, the reference values adopted in RCLEA are deliberately cautious.

6.27 Finally, it should be noted that the only parameters that may not be modified are dose coefficients and external dose factors, as these have been adopted by Defra based on national and international guidance.

### *Modifications to Mathematical Models*

6.28 The mathematical models adopted by RCLEA have been selected as being appropriate to the use of the methodology. If equations are modified, or supplemented (e.g. to represent an additional pathway such as ingestion of animal products) for a specific assessment, the results should not imply that RCLEA was used in their calculation.

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# Appendix A: Radionuclides Considered in RCLEA

**Table 24: Parent Radionuclides Considered in RCLEA**

| Radionuclide | Half-Life (y) | Radionuclide | Half-Life (y) |
|---|---|---|---|
| H-3† | 12.4 | Eu-155 | 4.96 |
| C-14 | 5730 | Pb-210+ | 22.3 |
| K-40* | $1.28 \times 10^{9}$ | Ra-226+ | 1600 |
| Fe-55 | 2.7 | Ra-228+ | 5.75 |
| Co-60 | 5.27 | Ac-227+ | 21.8 |
| Ni-63 | 96 | Th-228+ | 1.91 |
| Se-79 | $6.5 \times 10^{4}$ | Th-229+ | 7340 |
| Sr-90+ | 29.1 | Th-230 | $7.70 \times 10^{4}$ |
| Nb-93m | 13.6 | Th-232 | $1.41 \times 10^{10}$ |
| Nb-94 | $2.03 \times 10^{4}$ | Pa-231 | $3.28 \times 10^{4}$ |
| Mo-93 | 3500 | U-233 | $1.59 \times 10^{5}$ |
| Tc-99 | $2.13 \times 10^{5}$ | U-234 | $2.45 \times 10^{5}$ |
| Ag-108m+ | 127 | U-235+ | $7.04 \times 10^{8}$ |
| Sn-121m+ | 55 | U-236 | $2.34 \times 10^{7}$ |
| Sb-125 | 2.77 | U-238+ | $4.47 \times 10^{9}$ |
| Sn-126 | $1.0 \times 10^{5}$ | Np-237+ | $2.14 \times 10^{6}$ |
| I-129 | $1.57 \times 10^{7}$ | Pu-238 | 87.7 |
| Cs-134 | 2.06 | Pu-239 | $2.41 \times 10^{4}$ |
| Cs-137+ | 30 | Pu-240 | 6560 |
| Pm-147 | 2.62 | Pu-241+ | 14.4 |
| Sm-147 | $1.06 \times 10^{11}$ | Am-241 | 433 |
| Sm-151 | 90 | | |
| Eu-152 | 13.3 | Natural Th# | $1.41 \times 10^{10}$ |
| Eu-154 | 8.8 | Natural Uranium~ | $4.47 \times 10^{9}$ |

Notes:

† Modelled as tritiated water (HTO).

* Included for validation purposes.

+ Indicates that the short-lived daughters of the radionuclide in question will be assumed to be present with the same activity as the parent.

# Natural thorium is assumed to be refined thorium of sufficient age that the Th-232 decay chain has re-established equilibrium (20 years or so). Th-230 is also assumed to be present with the same activity as other thorium isotopes.

~ Natural uranium is taken to contain 99.2745% U-238, 0.720% U-235 and 0.0055% U-234 by mass.

**Table 25: Short-lived Radionuclides Assumed to be Present in Secular Equilibrium with Parents**

| Parent Radionuclide | Short-lived Daughters in Secular Equilibrium |
|---|---|
| Sr-90 | → Y-90 |
| Ag-108m | 0.089 → Ag-108 |
| Sn-121m | 0.776 → Sn-121 |
| Cs-137 | → Ba-137m |
| Pb-210 | → Bi-210 → Po-210 |
| Ra-226 | → Rn-222 → Po-218 0.9998 → Pb-214 → Bi-214 → Po-214<br>0.0002 → At-218 → Bi-214 → Po-214 |
| Ra-228 | → Ac-228 |
| Ac-227 | 0.9862 → Th-227 → Ra-223 → Rn-219 → Po-215 → Pb-211 → Bi-211 0.9972 → Tl-207<br>0.0028 → Po-211<br>0.0138 → Fr-223 → Ra-223 → Rn-219 → Po-215 → Pb-211 → Bi-211 0.9972 → Tl-207<br>0.0028 → Po-211 |
| Th-228 | → Ra-224 → Rn-220 → Po-216 → Pb-212 → Bi-212 0.6407 → Po-212<br>0.3593 → Tl-208 |
| Th-229 | → Ra-225 → Ac-225 → Fr-221 → At-217 → Bi-213 0.9784 → Po-213 → Pb-209<br>0.0216 → Tl-209 → Pb-209 |
| U235 | → Th-231 |
| U-238 | → Th-234 0.998 → Pa-234m→ Pa-234<br>0.002 → Pa-234 |
| Np-237 | Pa-233 |
| Pu-241 | 0.0000245 → U-237 |

# Appendix B: Differences Between RCLEA and CLEA

B.1 For information, this appendix lists the key differences between the RCLEA and CLEA methodologies.

- ▲ CLEA SGVs are contaminant specific and not additive, whilst the radiation doses from multiple radionuclides are additive and compared with a single exposure criteria. Therefore, RSGVs for individual radionuclides are only applicable to contamination with individual radionuclides. Where contamination with multiple radionuclides exists, the RSGVs are **not applicable** and site-specific calculations must be undertaken reflecting the contamination ratios, in which case, the guideline values of each radionuclide will be lower than the individual RSGVs.

- ▲ The RCLEA methodology is deterministic in nature in comparison to CLEA's probabilistic approach. The deterministic approach has been adopted because:

- CLEA only samples exposure group characteristics. The coefficients that convert ingestion and inhalation exposures to radiation doses are based on internationally accepted cautiously deterministic recommendations. Sampling of the CLEA probabilistic parameters within RCLEA risks the adoption of inconsistent assumptions between exposure group characteristics and dose coefficients. Therefore, cautiously deterministic (95th percentile) assumptions are adopted for sampled CLEA parameters in RCLEA.

- The assessment methodology includes various sources of scenario, model and parameter uncertainty. Indeed, several input parameters (e.g. soil solid:liquid distribution coefficients, soil-to-plant concentration factors, atmospheric dust concentrations) can vary over several orders of magnitude. The probabilistic representation of a single set of less variable and relatively well characterised parameters can result in a false impression of accuracy. The interpretation and communication of the results of such a semi-probabilistic assessment approach therefore proves difficult.

- ▲ The CLEA methodology includes data for 18 different age groups, whilst RCLEA includes only three (Infant, Child and Adult). The number of age groups has been reduced in the RCLEA methodology to reflect the dose coefficient recommendations of the ICRP.

- ▲ RCLEA includes two additional exposure pathways due to the potential of radionuclides to impact on human health whilst external to the body:

  - whole body external irradiation from contamination at a distance; and

  - irradiation of the skin from direct contact with contaminated material.

- ▲ Absorption through skin is excluded from the RCLEA methodology as it is considered not to be an appropriate pathway for radioactive contamination. The possibility of such transfer is considered very low, with the possible exception of tritiated water. Absorption through the skin for tritium should be considered separately.

- ▲ The RCLEA methodology adopts a single soil type given that the key soil type characteristic (the soil solid:liquid distribution coefficient, $K_d$) is considerably uncertain, even if the soil type is known. Other soil characteristics, such as bulk density and porosity, can be defined more reliably for different soil types, but vary to a much lesser extent. Therefore, the distinction between soil types has been excluded from RCLEA to avoid a false impression of precision. Should site-specific soil type information be available, then this can be adopted for more detailed assessment.

- ▲ Volatilisation is excluded from RCLEA on the basis that it is considered as an insignificant pathway for the historic contamination considered by the methodology.

- ▲ A higher concentration of atmospheric respirable particulates is adopted for RCLEA in comparison with the CLEA methodology. The CLEA value (equivalent to 8E-10 kg $m^{-3}$) is based solely on wind resuspension and is considerably lower than values adopted for radiological assessments. Therefore a value of 5E-8 kg $m^{-3}$ has been adopted for RCLEA, in line with typical radiological assessments (e.g. Oatway and Mobbs, 2003).

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