LLW Repository Ltd

LLWR Environmental Safety Case

Assessment Calculations for C-14 Labelled Gas and Radon for the LLWR 2011 ESC (Extended Disposal Area)

A report prepared by Quintessa for and on behalf of the Low Level Waste Repository Site Licence Company.

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L M C Limer

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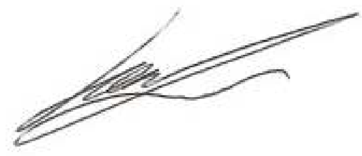

[2] A Paulley made a number of updates to the text. These were checked by L M C Limer.

Summary

The Low Level Waste Repository (LLWR) Site Licence Company is undertaking a programme of work that will result in the production of an Environmental Safety Case (ESC) for submission to the Environment Agency (EA) by May 2011. An important component of the arguments to be presented will be quantitative long-term calculations of system performance.

This report considers the potential radiological impacts of any C-14 or Rn-222 labelled gases released from wastes disposed in an extended LLWR facility comprising of an additional six vaults (15 to 20), termed the Extended Disposal Area (EDA). Previous reports have considered the potential impacts of C-14 and Rn-222 labelled gases from the reference disposal area (RDA), which comprises Trenches 1 to 7 and Vaults 8 to 14.

With respect to C-14, the calculated impacts associated with the EDA vaults specifically are notably lower than for the RDA calculation results, despite containing a significant C-14 inventory (18.9 TBq in the EDA vaults compared to 5.13 TBq in the RDA vaults). This shows that material distributions within the vaults, and the resulting evolution of biogeochemical conditions within the vaults, exert a strong control on the evolved fluxes and thus calculated doses.

For the Rn-222 the estimated effective inhalation doses for the EDA inventory are also lower than for the RDA assessment, primarily as the projected Ra-226 inventory in the EDA is lower than for the RDA.

Contents

1 Introduction

1.1 Background

The Low Level Waste Repository (LLWR) Site Licence Company is undertaking a programme of work that will result in the production of an Environmental Safety Case (ESC) for submission to the Environment Agency (EA) by May 2011. An important component of the arguments to be presented will be quantitative long-term calculations for system performance.

Consideration has previously been given to the potential impacts to humans of any C-14 labelled gas or gaseous Rn-222 that may be released from the wastes disposed to the Reference Disposal Area (RDA) of the LLWR (Limer et al., 2011; Limer and Thorne, 2011). Those calculations were based upon the following two assumptions:

- ▲ The final facility comprising of seven trenches (numbered 1 to 7) and seven vaults (numbered 8 to 14); and
- ▲ The inventory disposed of being that given in the PIER A2 inventory projections.

As part of the 2011 ESC, the LLWR is investigating the potential radiological implications associated with an extended facility, comprising of an additional six vaults (15 to 20), termed the Extended Disposal Area (EDA). Figure 1-1 shows a schematic of the LLWR including the EDA (after Tonks, 2011).

The purpose of this report is to consider the potential radiological impacts that might be associated with any C-14 or Rn-222 labelled gas releases from wastes that may be disposed to the EDA.

1.2 Structure of Report

Section 2 provides a summary of the key assumptions relevant to assessments of the releases of C-14 and Rn-222 labelled gases from the LLWR, based upon those presented in Limer et al. (2011) and Limer and Thorne (2011) for assessments of the Reference Disposal Area (RDA). These assumptions are directly relevant to the EDA assessment also. Updated or additional assumptions required for the EDA are described in Section 3, including discussion of the source term for these gases. The assumptions are then summarised in Section 4. The results of the assessment calculations are given in Section 5. The overall conclusions are brought together in Section 6.

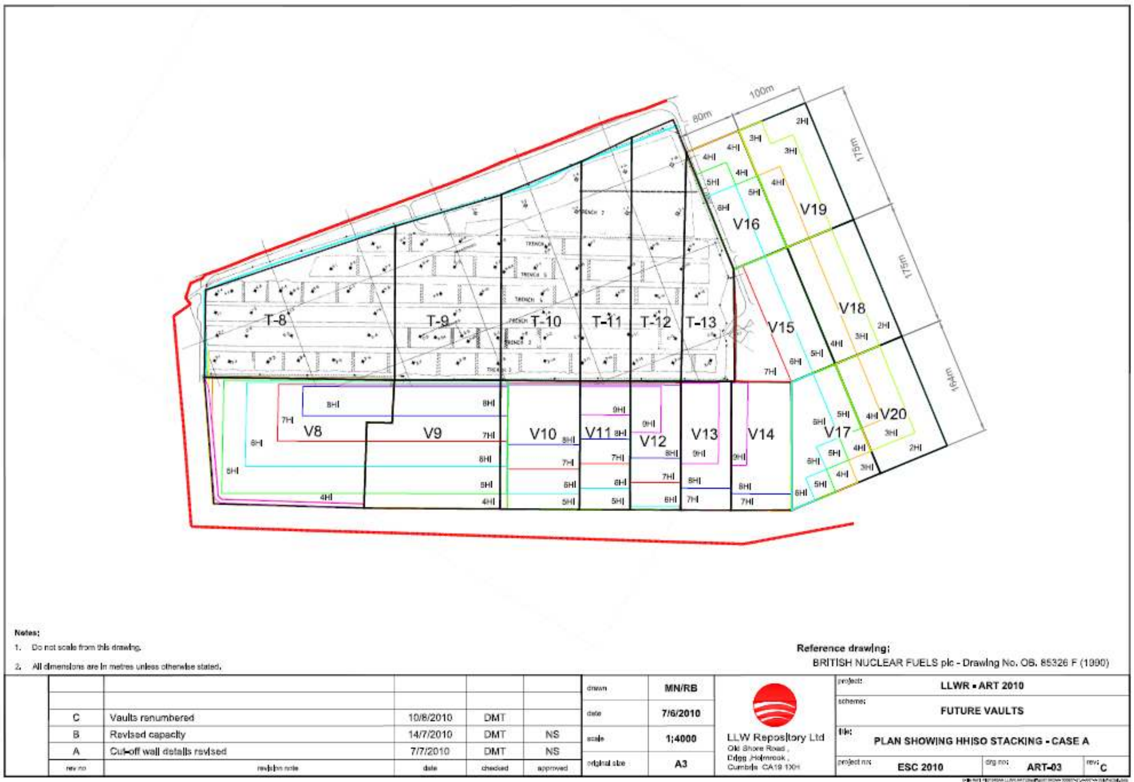

Figure 1-1: Schematic of the LLWR with Extended Disposal Area

2 Summary of Fundamental Assessment Assumptions and Models Used

In order to evaluate the potential impacts of C-14 and Rn-222 labelled gas released from wastes disposed of at the LLWR, it is necessary to consider how these gases might reach the soil zone and above-ground atmosphere for any impacts to occur. Thus, consideration needs to be given to the following aspects of the system:

- ▲ The source term of gas released from the wastes;
- ▲ Transport through the cap to the soil zone and above-ground atmosphere; and
- ▲ Impacts of that gas in the biosphere.

Full details of assumptions made for these aspects of the system were given in the equivalent RDA assessment reports (Limer et al., 2011; Limer and Thorne, 2011). The following subsections provide a summary of important aspects of the system identified in those RDA assessments.

2.1 Source Term

2.1.1 C-14

C-14 is present in the LLWR inventory in a variety of waste streams (Wareing, 2009), with the majority in the form of an activation product from the irradiation of materials. These materials include metals, concrete and graphite, and all are likely to offer some degree of retention of the C-14 during leaching by groundwater. Other LLW materials include cellulose and organic materials.

A key assumption made in the 2002 post-closure safety case (PCSC) was that the C-14 inventory was assumed to be released from all waste materials at the same rate and it was further assumed that the C-14 was present in the most reactive cellulose-type material (BNFL, 2002; Graham et al., 2003). The 2011 ESC uses updated assumptions about the dynamics of C-14 in the near-field (Baker et al., 2008; Small et al., 2008). Once released from the waste-forms in to the near-field, the C-14 is assumed to be fully available for and subject to the full range of biogeochemical processes that can affect the subsequent reactions of the C-14 and partitioning between mobile (aqueous and gas) and immobile (carbonate minerals and microbial biomass) phases.

In the near-field modelling, the C-14 labelled gas released is in the form of methane and carbon dioxide (Small et al., 2011a). In these calculations, it is assumed that the entire C-14 inventory arises at the time of closure, that is to say that any decay of C-14 already emplaced at the LLW repository is conservatively neglected. Any earlier degradation of organics and release of C-14 is also cautiously neglected. This means that the chemical evolution of all the trenches and vaults are assumed to commence at the same time, whereas in reality the disposals and chemical evolution of the system would be spread over a period of over 100 years (1959 to 2080 for the RDA assessment, 1959 to 2130 for the EDA assessment).

Near-field calculations of C-14 release have been carried out using the Generalised Repository Model (GRM) (Small et al., 2011a).

2.1.2 Rn-222

Radon gas may be released from the LLWR following radioactive decay of disposals of Ra-226 and (over longer timescales) in-growth through decay chains associated with longer-lived disposed radionuclides such as U-234.

In addition to data relating to inventory projections, engineering feature design and performance, the LLWR has previously commissioned monitoring surveys of current releases of radon from the wastes (Bechelli and Smith, 2005; Hornsby and Bechelli, 2007). These data provide an upper bound on fluxes of Rn-222 in the gas phase that might be observed at the surface. Specifically, these surveys indicate that the Rn-222 concentrations in the gas-filled pore space of the waste are likely to be around 10% of the volumetric Ra-226 concentrations in the waste (with a range of 7 to 15%[3]; Limer and Thorne, 2011). More specifically, excluding probe locations at which measured values were of doubtful quality in 2005, the mean measured Rn-222 concentration in 2005 in the gas-filled pore space was 9.4E+4 Bq m^{-3} and in 2010 was 4.4E+4 Bq m^{-3}. Given the different periods of measurement in the two surveys and the effects of local, time-dependent variability, these concentrations are in reasonable agreement.

For comparison, the average Ra-226 concentration in the trenches as measured in 2005 and expressed on a volumetric basis was $6.2\ 10^{5}$ Bq m^{-3}. Thus, the mean measured Rn-222 concentrations were about a factor of seven to fourteen lower than the concentration that would be expected by consideration of secular equilibrium with Ra-226. The most likely reason for this is decay of Rn-222 within the wastes prior to release to that part of the gas phase that is well connected to the probes. If this is the

[3] These numbers cautiously disregard the porosity of the wastes and as such represent upper bounds on the range of Rn-222 that might be released from the Ra-226 bearing wastes.

case, it implies a mean residence time for Rn-222 of about 10 to 14 days in the waste before reaching the portion of the gas phase that is well connected to the probes.

2.2 Bulk Gas Transport

Bulk gas transport through the cap is addressed in detail elsewhere (Limer et al., 2011), where it is argued that atmospheric pumping and buoyancy driven flow are advective transport processes that have the potential to be significant in permeable cap materials. Atmospheric pumping will only occur where permeable cap materials are in direct contact with the atmosphere, and are not isolated by low permeability materials. Diffusion is expected to dominate in the low permeability cap materials. Therefore, the significance of atmospheric pumping will depend on:

- The cap design/geometry and the path length through permeable materials to the cap surface;
- The permeability;
- The magnitude and frequency of atmospheric pressure changes.

Limer et al. (2011) conducted a variety of 1D and 2D modelling studies and reached the following conclusions relating to vented and unvented caps.

- If the gas vent is not connected to the atmosphere (or there is no vent), then release of methane (and, by implication, other gases) will be dominated by diffusion through the resistive layer, although there will be some preferential diffusion in the gravel gas collection layer towards the vent, in the area of the gravel layer closest to the vent.
- If the gas vent is connected to the atmosphere, then atmospheric pumping will dominate in the vent and in the gravel gas-collection layer adjacent to the vent. Within the gravel gas-collection layer, with increasing distance from the vent, the effects of atmospheric pumping will diminish and diffusion through the overlying resistive cap layer will become more important. The area of the gravel layer in which advective pumping dominates will depend on the permeability of the layer, and the magnitude and duration of atmospheric pressure falls.
- Considering the cap as a whole, if the vent is connected to the atmosphere, the gas flux could be dominated by diffusion through the resistive layer over the whole cap area, or atmospheric pumping via the vent, within the ranges of the anticipated properties of the different cap materials.

- From a design perspective, it is intended that the LLWR cap will have a vent between the gas-collection layer and the surface during the period of site control. This will enhance release of gases through the cap and prevent any build up of gas. It is anticipated that gas generation will have reduced to low levels before the site is closed, since the most readily degradable material will have fully degraded. The vent will be engineered out before site release, i.e. before the period of institutional control ends, and after that gas movement will be diffusive only.

For C-14, although the cap will delay the release of C-14 labelled methane, the duration of the delay is limited, so that it is not possible to justify the assumption that the cap would significantly reduce the impact of C-14 in the biosphere. For this reason, the C-14 labelled gas assessment assumes that any C-14 labelled gas released from the waste is transported directly to the biosphere, i.e. without any radioactive decay occurring between any release of gas from the wastes and that gas entering the biosphere.

These conclusions have important implications for Rn-222 gas, because the gas travel through the cap may or may not be large relative to the half-life of Rn-222, and the dominant transport mechanism could change during the post-closure period, e.g. due to exposure of the cap vent at the ground surface through erosion, or drying out and cracking of the cap moisture retention barrier during summers. A slump or intrusion into the cap, that directly connects the gravel gas collection layer to the atmosphere, could behave like a vent. If the entire cap were assumed to be substantially damaged such that a building on top of the wastes had only 1 m of coarse material between the wastes and the base of the building, then Limer and Thorne (2011) showed that the characteristic travel time through the coarse material would be of the order of 3.9 days; the degree of attenuation associated with this is a factor of 5.0E-1. For an intact cap of 3 m thickness which comprised of some fine materials as well, the characteristic travel time would be longer, thereby reducing the potential impacts of any Rn-222 gas released.

2.3 Impact Assessments

2.3.1 C-14

For C-14 labelled gaseous carbon dioxide and methane, the principal exposure pathway identified in both UK and overseas studies involves uptake by plants in photosynthesis following the gas entering the soil zone and subsequent ingestion by humans. This is because, for a given flux of gaseous C-14 entering a specified area, the human dose from inhalation is many orders of magnitude lower than the dose arising from the ingestion of contaminated crops (Limer et al., 2010). These plants may be consumed directly, e.g. vegetables and fruit, or indirectly in the form of animal produce from livestock that have grazed on the contaminated area.

Although the exposure calculations consider exposure as a result of inhalation, for the reasons described above the focus is upon potential exposure groups (PEGs) who consume food grown on the cap. The exposure pathways are shown in Figure 2-1. The PEGs chosen are cautious but reasonably plausible estimates of human habits on the cap area; the descriptions of these PEGs are given in Thorne (2009) and are the same PEGs as were used in the RDA C-14 labelled gas assessment (Limer et al., 2011).

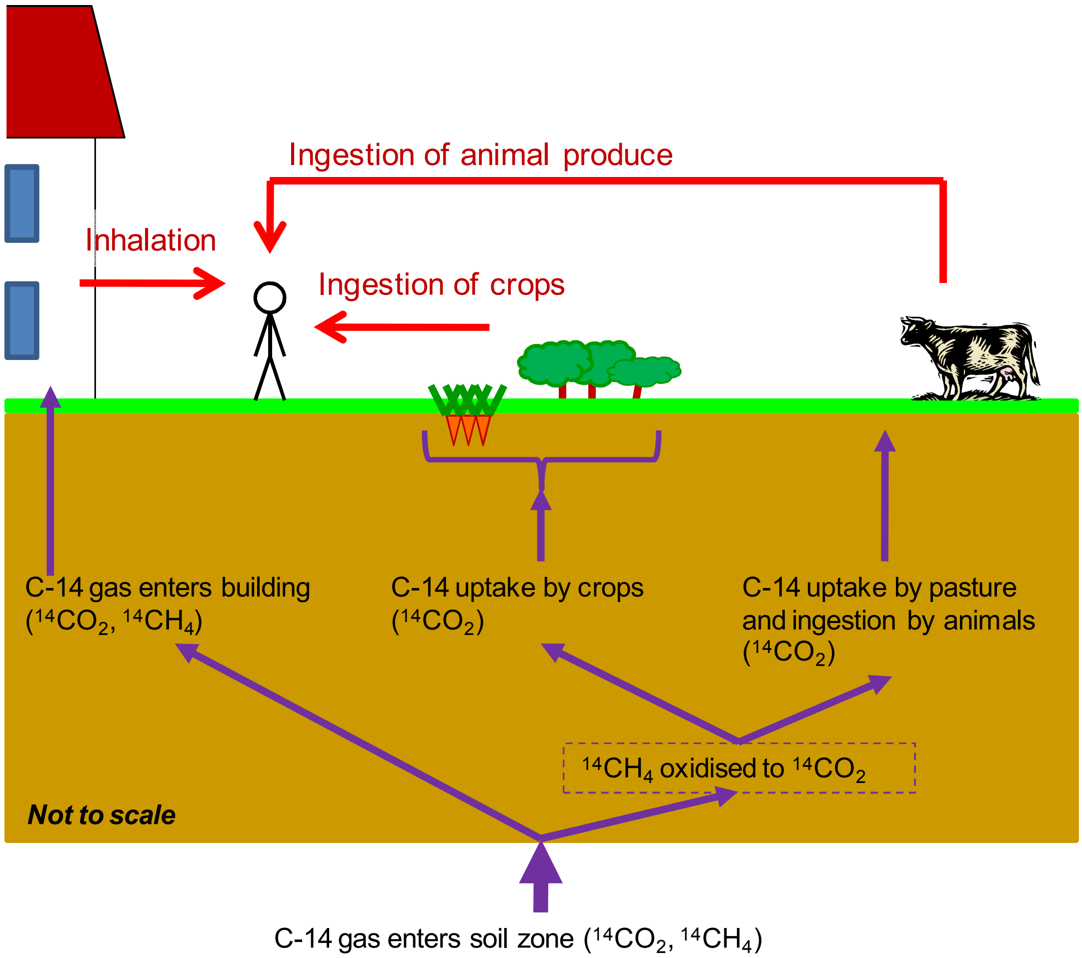

Figure 2-1: Schematic of Exposure Model for C-14 Labelled Gas Assessment (Limer et al., 2011)

For convenience the ingestion PEGs are summarised below.

- PEG A: The smallholder with 4 to 12 hectares of land who keeps several head of cattle and uses them to provide meat and milk products.

- PEG B: The smallholder with 1 to 3 hectares of land who keeps a single cow for milk production only.

▲ PEG C: The smallholder with 0.5 to 1 hectare of land who keeps two goats for milk production only.

▲ PEG D: The kitchen gardener who grows his own vegetables and fruit on 0.05 hectare.

Of these, we select PEG C as the reference (Limer et al., 2011), because the area occupied is sufficiently small to fit within the footprint of a single vault, and because the raising of goats allows intakes via milk and dairy products, as well as vegetables and fruit, which are common to all the PEGs. Nonetheless the PEG is considered to represent a cautiously realistic basis for assessment, based upon the habits assumed. PEGs A, B and D are retained as alternative exposed group assumptions.

In addition to the four ingestion PEGs listed above, consideration is also given to the impacts of inhaling C-14 labelled gas inside a building.

Consistent with the assessment of the implications of C-14 labelled gas released from the reference repository design (Limer et al., 2011), here it is assumed that all C-14 labelled gas produced in the near-field is transferred to the soil zone and that all C-14 labelled methane that enters the soil zone is converted to C-14 labelled carbon dioxide.[4] These two assumptions are cautious, but are considered to be realistic. It is unlikely that sufficient delays could occur to significantly attenuate C-14 fluxes through the cap by radioactive decay, meaning it is not possible to justify the assumption that the cap would significantly reduce the impact of C-14 in the biosphere. Furthermore, although it is possible that methane could pass through the soil zone without being oxidised to carbon dioxide, the expectation is that mass fluxes will be low. Agricultural soils have been demonstrated to have a high, if variable, potential for microbial metabolism of methane (Thorne and MacKenzie, 2005), so low mass fluxes would not be expected to overwhelm the capabilities of the microbial community to utilise methane.

Based upon the preceding arguments, the focus of the assessment of the implications of any C-14 labelled gas released from the wastes disposed of at the LLWR is upon the behaviour of the C-14 in the biosphere. For the 2011 ESC, a new biosphere model has been developed; the model considers two regions in the above-ground atmosphere and utilises concepts from the field of micrometeorology to describe the exchange of air between these regions and losses from the area of interest (a model schematic is given in Figure 2-2). The lower layer only experiences molecular diffusion processes in

[4] The C-14 labelled gas flux data from the near field calculations is processed using the same method as the main C-14 labelled gas assessment (equations 42 to 47 of Limer et al., 2011). As with the main assessment, a second order expansion is used to solve equation 45.

relation to the movement of molecules of carbon dioxide, whereas the upper layer experiences some degree of turbulent mixing as a result of winds that flow over the area of interest. The thickness of these layers, and the degree of plant uptake of carbon from these layers, is dependent upon the canopy density, which will affect the light intensity and thus the rate of photosynthetic uptake of carbon in the canopy profile. In this assessment the effect of assuming uniform C-14 uptake throughout the canopy profile, or that a higher proportion of uptake would occur in the upper canopy where there is more light, are both considered.

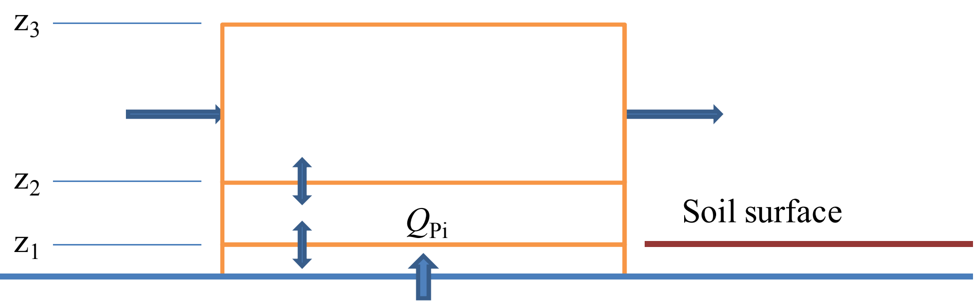

Figure 2-2: Vertical Structure of the Plant Canopy Atmosphere Model (Limer et al., 2011)

Within the biosphere aspect of the C-14 labelled gas assessment, two cases are considered:

1. There is equal probability of the smallholding or garden being placed anywhere over a given region of the cap. In this context a homogeneous flux of C-14 labelled gas over that region is regarded as being applicable, as this corresponds to the probability weighted flux and hence the probability weighted dose, as the dose scales proportionately with the flux. This is a reflection of the inherent uncertainty as to the behaviour of any future PEG, rather than the physical migration processes of gas within the cap.
2. Consideration is also given to a PEG residing entirely over a specific region of the facility (e.g. Vault 17). The areas of the specific regions are such that PEGs C and D could be supported (requiring 0.75 and 0.05 ha respectively).

2.3.2 Rn-222

The key exposure pathway associated with radon gas release is inhalation of the short-lived radon daughters. Consistent with the philosophy of following a ‘cautiously realistic’ assessment approach, calculations of potential impacts assume a single PEG with the following characteristics: the PEG inhabits a building constructed upon the cap, and that radon gas then migrates into that building. Impacts on the PEG are then calculated, primarily relating to the inhalation of radon gas inside the building exposure pathway.

In addition to the data outlined in the description of the source term, one other radon-specific information sets were considered in the RDA radon assessment (Limer and Thorne, 2011) in order to assess the potential impacts of radon release from the wastes disposed of at LLWR:

- ▲ an understanding of the physical processes involved in gas transport through the final cap as summarised in Section 2.2); and
- ▲ relationships between radon concentrations in soil and concentrations measured in indoor air (Appleton et al., 2010).

These sets of information were used together in order to provide a radon assessment that is founded upon the best information as to the current behaviour of radon at the site and the anticipated behaviour of radon in the post-closure period.

Taking account of travel time through the cap, based upon an understanding of the physical processes that are expected to dominate bulk gas transport through the cap, enables a more realistic upper limit to be placed upon potential Rn-222 fluxes to the ground surface as a result of attenuation, as compared to the non-attenuated fluxes of Rn-222 based on release from the waste.

In the RDA Rn-222 assessment it was noted that the estimates of Rn-222 concentration in buildings obtained from the empirical regression relationship are typically a factor of six lower than those obtained using a method based on radon ingress and the ventilation rate. Limer and Thorne (2011) proposed that the calculational approach using ventilation rates may be regarded as being unduly cautious (possibly due to neglect of an emanation fraction of substantially less than 1.0 from the soil surface).[5] For this reason the Rn-222 dose assessment used the empirical approach to estimate the concentrations of Rn-222 concentrations in buildings.

With respect to inhalation exposure, the short lived progeny of Rn-222 will also contribute to the dose associated with Rn-222. As concentrations of these progeny tend to be depleted relative to Rn-222, it is conventional to express their concentration in terms of the Equilibrium Equivalent Concentration (EEC) of Rn-222 with which they would be in secular equilibrium. Based on a review of inhalation dose factors, Limer and Thorne (2011) adopted an effective dose factor of 9 nGy per Bq h m^{-3}, where the concentration is the EEC; this effective dose factor is used in this assessment also. This corresponds to a risk of dying of lung cancer due to lifetime exposure of 2.5%. This risk is appropriate to a mixed population of smokers and non-smokers. For smokers, the risk is estimated to be about a factor of 2.4 higher (6%) and for non-smokers it is estimated to be about a factor of 8.3 lower (0.3%).

[5] The calculational approach using ventilation rates assumes that the flux of Rn-222 reaching the soil zone over the area of the building enters the building and is lost only by air exchange or radioactive decay. However, the rate of entry of Rn-222 into buildings from the underlying soil is determined by a complex set of factors including time-dependent pressure differences between the interior of the building and its surroundings, variations in the gas permeability of the soil zone, and the degree to which the building envelope impedes the inward flow of gas (e.g. as a consequence of the presence of solid floor slabs). Thus, it is not surprising that there is a significant difference in results between the empirical regression relationship and the simple theoretical calculation.

3 EDA-specific Assumptions

The purpose of this section is to outline those assessment assumptions that are specific to the assessment of the EDA. A distinction is made between those assumptions made for each of the two gases of interest.

3.1 C-14

As noted in Limer et al. (2011), to assess the potential impacts associated with gaseous releases of C-14, it is important to account for factors that may affect the calculated impacts of any C-14 entering the soil zone, and also any factors that may determine the initial release of C-14 labelled gas from the wastes.

For the assessment of the EDA, the following uncertainties associated with the initial release of C-14 labelled gas from the wastes are considered in a range of near-field calculations which provide the source fluxes for the EDA assessment (Small et al., 2011b).

- ▲ Case 2 groundwater flow with PIER Inventory A, with instantaneous release of C-14 from all metal wastes and slower release from the graphite matrix, based on elicitations (**Case2_InvA**) (the reference case);
- ▲ A variant of Case2_InvA case examining the effect of instantaneous C-14 release from all C-14 wastes including the 9.3 TBq anticipated to be present in graphite (**Case2_InvA_C14rel**);
- ▲ A variant of Case2_InvA case examining the effect of increased flow resulting from considering higher cap infiltration rates (**Case2_var1_InvA**);
- ▲ A variant of Case2_InvA examining the effect of a slower release from the Stage 3 decommissioning metals (**Case2_InvA_S3M**); and
- ▲ Case 2 groundwater flow with PIER Inventory B (additional volume for new build), where the flow model takes account of the increased vault volume, and uses the same C-14 release assumptions as Case2_InvA (**Case2_InvB**).

The PIER A2 and B2 C-14 inventories are given in Table 3-1; the inventory data comes from Harper (2011). In the B2 inventory not only is the total anticipated C-14 inventory greater, more of it is anticipated to be emplaced in the first three EDA vaults (15 to 17).

Table 3-1: C-14 Information for the EDA

EDA Vault	C-14 Inventory (TBq)	
	PIER A2	PIER B2
15	5.41E+00	7.15E+00
16	4.35E+00	5.50E+00
17	5.16E+00	4.64E+00
18	2.09E+00	1.20E+00
19	1.06E+00	9.94E-01
20	8.36E-01	6.99E-01
Total	1.89E+01	2.02E+01

3.2 Rn-222

For the Rn-222 assessment associated with the extended facility, there are three pieces of information that are required:

- The Ra-226 inventory and its distribution in the extended disposal area;
- The volume of the extended disposal area; and
- The surface area associated with the extended disposal area.

This information, associated with two inventory assumptions, is given in Table 3-2; the data are based upon that presented for the EDA in Harper (2011). Inventory Cases A2 and B2 from the above reference are considered. In each case, 96-98% of the Ra-226 inventory is anticipated to be located within Vaults 15 and 16. The assessment calculations focus upon the cautious assumption of a PEG whose dwelling is built in the area associated these two vaults. In all calculations the raw waste volumes are used to estimate the Rn-222 concentration in soil.

Table 3-2: Rn-222 Inventory Information for the EDA

Inventory Assumption	Vault	Ra-226 Inventory (TBq)	Raw Waste Volume (m^3)	Total Air Volume Accounting for Grout and Containers (m^3)
PIER A2	15	3.31E-03	78,489	153,000
	16	1.88E-03	50,274	98,000
	17	2.02E-04	62,586	122,000
	18	2.72E-05	36,936	72,000
	19	2.29E-05	34,371	67,000
	20	3.33E-05	31,303	61,020
	Total	5.48E-03	293,959	573,020
PIER B2	15	3.96E-03	103,626	202,000
	16	1.48E-03	75,924	148,000
	17	4.98E-05	69,768	136,000
	18	2.68E-05	42,579	83,000
	19	2.29E-05	42,579	83,000
	20	2.86E-05	40,014	78,000
	Total	5.57E-03	374,490	730,000

4 Summary of C-14 and Rn-222 Assessment Assumptions

The assumptions made in the C-14 EDA gas pathway assessment are given in Table 4-1. These are consistent with those used for the RDA assessment.

Table 4-1: Summary of Assumptions Made in the LLWR 2011 ESC C-14 Labelled Gas Pathway Assessment

Aspect of the System	Assumption	Description
Inventory	Nature of projected C-14 inventory	The PIER A2 and B2 inventories are each considered
Gas release from the waste	Degradation of the waste, geochemical conditions	Two hydrological flows are considered
Gas transport through the cap	Importance of gas transport processes	Post-closure diffusion is the dominant gas transport process
Gas release to the biosphere	Quantity of C-14 labelled gas reaching the soil zone	It is assumed that all C-14 labelled gas reaches the soil zone and is consequently available for plant uptake.
	Nature of the C-14 labelled gas	Any methane is assumed to be fully oxidised to carbon dioxide in the soil zone, making it available for plant uptake. Inhalation doses are greater for carbon dioxide than methane.
Land use	Vegetation grown on the cap	Small vegetable gardens and small-scale livestock grazing
Plant uptake of carbon	Nature of plant uptake of carbon through the canopy profile as a result of photosynthesis	Both uniform uptake through the canopy, and an uptake rate that depends upon the light intensity in the canopy, have been considered.
Animal uptake of carbon	The quantity of livestock feed which can be obtained from the cap	Since the areas required for each PEG are less than that of the of the total cap area, it is assumed that the cap would provide more than sufficient area for PEGs raising livestock to use only the cap area.
	C-14 activity in the feed obtained from the cap	The pasture consumed by the livestock has the average C-14 concentration calculated across a given region of the cap at any given time.
Human habits	Quantity of carbon a PEG might obtain from the cap area	It is assumed that approximately 10-30% of the PEGs annual carbon intake could come from produce associated with the cap area.

Please see Table 5-1 of Limer et al, 2011 for further details on assumptions made for the C-14 labelled gas assessment.

The assumptions made in the EDA Rn-222 assessment, are given in Table 4-2. These are unchanged from the RDA assessment.

Table 4-2: Rn-222 Gas Assessment Assumptions

Aspect of the System	**Assumption**	**Description**
Source term: release of Rn-222 from the waste	Activity of Rn-222 released from the waste is lower than the rate of production from the Ra-226 inventory disposed of.	The monitoring data (e.g. Hornsby and Bechelli, 2007) support the hypothesis that there is a significant degree of decay of the Rn-222 before it is released from the waste.
Inventory of Rn-222 in soil zone	No attenuation in the cap	The analysis of bulk gas transport in the cap indicates that if direct channels (e.g. vents, cracks) between the waste and above-ground atmosphere were to occur, that gas transport would be dominated by advection (Limer et al., 2011). In such an instance, it is cautiously assumed that any Rn-222 released from the wastes is transported directly to the surface.
	Attenuation in the cap	The analysis of bulk gas transport demonstrates that in the absence of any direct channels to the surface that gas migration would occur via molecular diffusion (Limer et al., 2011). Travel times through the cap material indicate substantial attenuation factors as a result of prolonged travel times through the cap.
Indoor concentration of Rn-222	Empirical relationship between soil gas and indoor air Rn-222 concentrations	A scaling factor is applied to soil Rn-222 concentrations to determine indoor concentrations, based upon work carried out by the British Geological Survey and the Health Protection Agency to analyse UK data and to develop empirical relationships between uranium and radium in soil, radon in soil and radon in dwellings (Appleton et al., 2010).
Inhalation Dose Factor	UNSCEAR (2000)	This is an intermediate dose factor, between factors derived using epidemiological and dosimetric methods (ICRP, 1993; UNSCEAR, 2000)

5 Results

Results of the EDA assessments for C-14 and Rn-222 are presented in the following subsections.

5.1 C-14

In the near-field calculations that provide the source term for the assessment, it is assumed that the entire C-14 inventory arises at 2130. Therefore any decay of C-14 already emplaced at the LLW repository is conservatively neglected. C-14 is long-lived and so this assumption does not have a major impact on peak releases. However the biogeochemical evolution during emplacement is also therefore neglected; this is a more important assumption as it is predicted that the highest evolved fluxes of C-14 will occur during the first few hundred years following emplacement.

The gas flux calculations involve a series of complex biogeochemical operations. Once the remaining C-14 in the wastes has reduced by several orders of magnitude, the calculated gas fluxes, involving very small concentrations of C-14 in the gas by this stage, become numerically unstable, leading to a degree of biogeochemical calculation 'noise' being seen in the calculated gas fluxes. For this reason, the calculated gas flux data is truncated at 3000 (AD), and no potential impacts associated with fluxes that long after the completion of the cap are considered.

5.1.1 Reference Case

Decay Corrected Flux of C-14 Labelled Gas from the Wastes

The total decay-corrected[6] fluxes of C-14 labelled gas from the wastes from the trenches, the RDA vaults and the EDA vaults are shown in Figure 5-1. The initial calculated fluxes of C-14 labelled gas are approximately an order of magnitude greater for both the RDA and EDA vaults than for the Trenches.

The total decay-corrected C-14 labelled gas fluxes from individual EDA vaults are shown in Figure 5-2. From this it is clear that it is just a few of the EDA vaults

[6] The fluxes provided by GRM include post-release decay and thus need to be decay corrected to back-calculate fluxes.

contribute substantially to the total flux of C-14 labelled gas, specifically Vaults 17, 18 and 19.

Note that differences in GRM outputs between the RDA and EDA near-field assessments indicate initial fluxes of C-14 labelled gases for the RDA vaults differ at early times compared to the original RDA assessment. The differences are notable but not major e.g. peak fluxes differ by a factor less than two (Figure 5-3). This is thought to be related to updates to the GRM configuration and associated biogeochemical interactions.

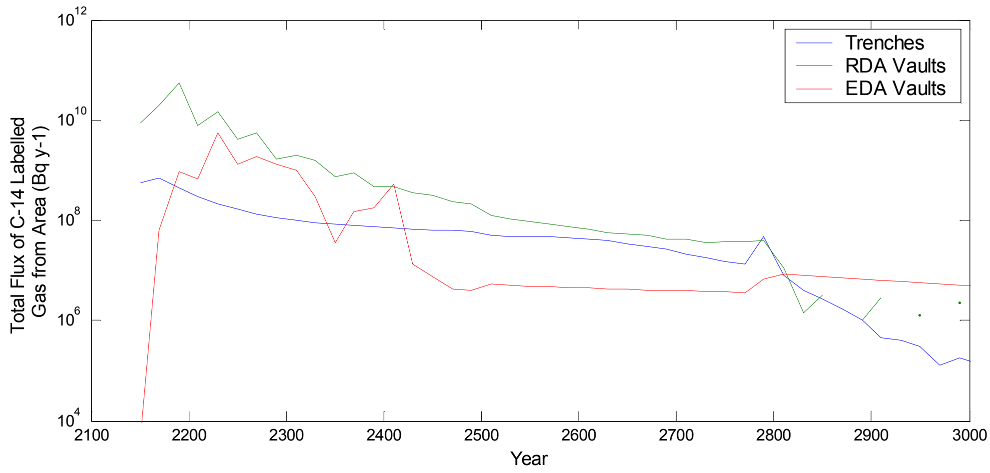

Figure 5-1: Total Decay Corrected Fluxes of C-14 Labelled Gas from the Wastes for the Reference Case, Case2_InvA (Bq y^{-1})

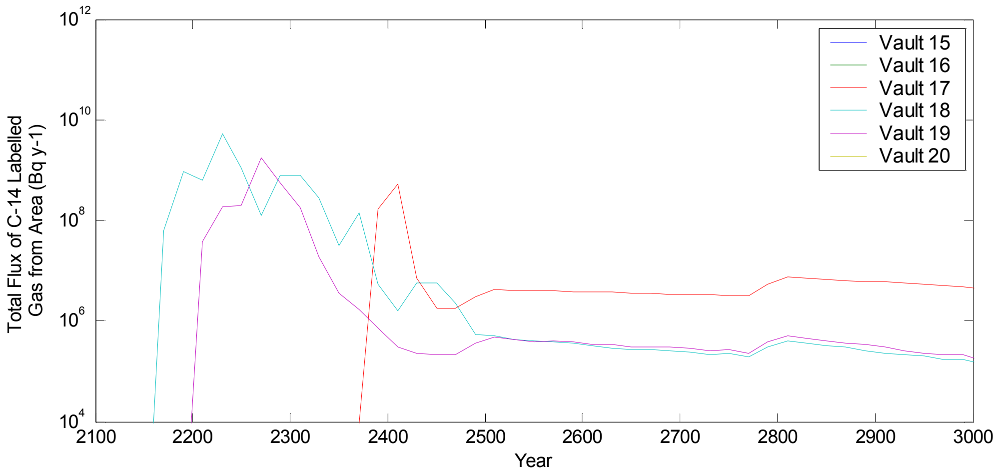

Figure 5-2: Total Decay Corrected Fluxes of C-14 Labelled Gas from the Wastes for the Reference Case over Specific EDA Vaults, Case2_InvA (Bq y^{-1}). Only Fluxes Greater than 1E+4 Bq y^{-1} are shown.

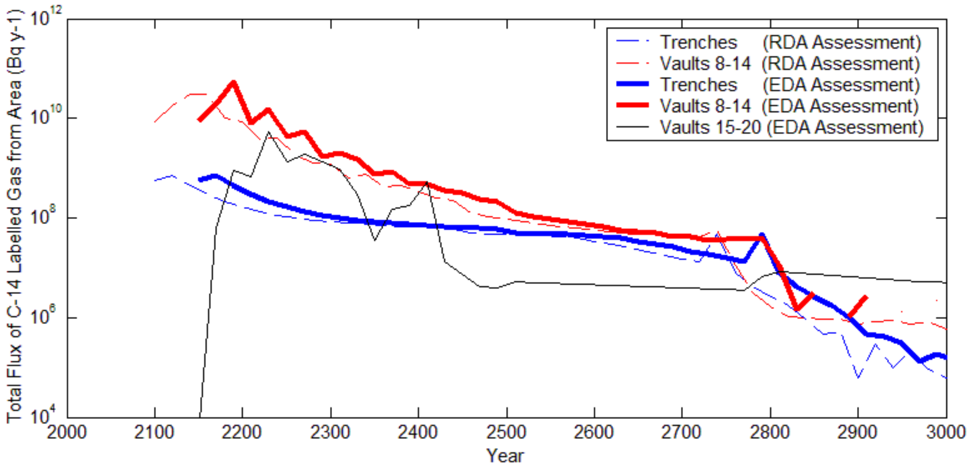

Figure 5-3: Total Decay Corrected Fluxes of C-14 Labelled Gas from the Wastes for the Reference Cases for the RDA (Case2r3_a2_v3) and EDA Assessments (Case2_InvA) (Bq y^{-1})

Data showing area averaged fluxes for the trenches and vaults are shown in Figure 5-4. This figure also contains a dashed black line which demonstrates the flux per unit area which, given the biosphere model employed, is associated with a calculated annual ingestion dose for the reference PEG (PEG C) of 20 μSv (i.e. a dose equivalent to the risk guidance level of 1E-6 y^{-1}; EA et al., 2009). Average fluxes from the two regions cross this line at around 100, 350 and 300 years post cap completion, for the Trenches, RDA vaults and EDA vaults respectively.

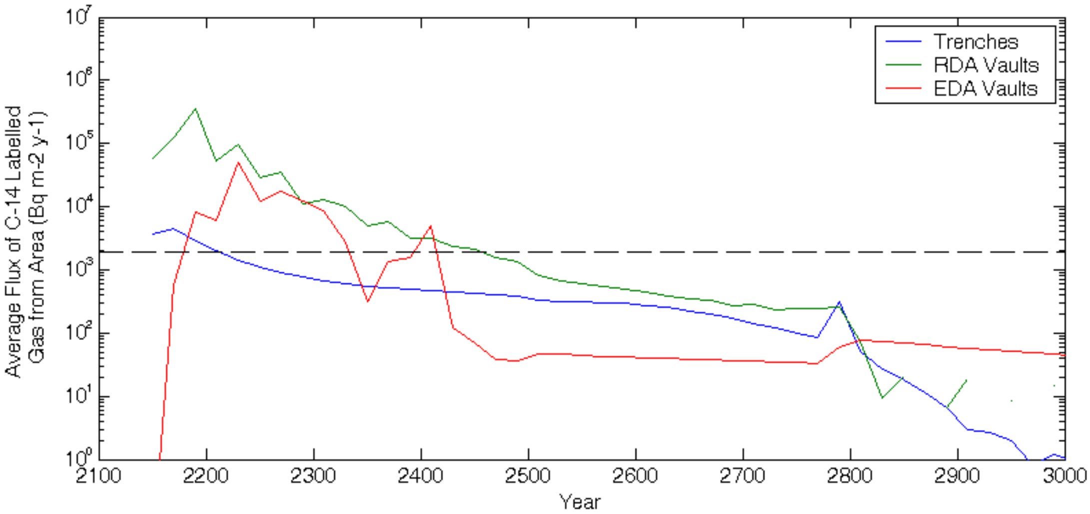

Figure 5-4: Average Fluxes of C-14 Labelled Gas in the Trenches and Vaults for the Reference Case, Case2_InvA (Bq m^{-2} y^{-1})

Calculated Effective Ingestion Doses

Potential impacts from ingestion are calculated for four different PEGs, as noted in Section 2.3. The PEGs may reside over any part of the trenches, RDA vaults or EDA vaults. It is considered there is an equal probability that they would establish their garden or smallholding in any part of that region. Thus, average fluxes associated with relevant regions of the cap are used to calculated potential impacts. Figure 5-5 presents calculated potential impacts at 100 year intervals following the completion of the final cap.

The effective annual ingestion dose target of 20 μSv is again indicated using a black line. Consistent with the average flux data (Figure 5-4), for the trenches, the potential exposures are lower than the guidance dose level within 100 years following the completion of the cap. However it is anticipated that it would take nearer 350 and 300 years for the dose associated with the RDA and EDA vaults, respectively, to drop to such a level. The calculated annual doses are also presented in Table 5-1**Error! Reference source not found.**; calculated doses which exceed 20 μSv are shown in red font.

Table 5-1: Calculated Annual Effective Ingestion Doses for Equal Likelihood of Placing Garden or Smallholding Anywhere on Cap for the Reference Case (mSv)

Location	Time (y)	Flux of C-14 Labelled Gas (Bq m^{-2} y^{-1})	Calculated Effective Ingestion Exposure (mSv)			
			PEG A	PEG B	PEG C	PEG D
Trenches	2230	1.41E+03	1.74E-02	1.47E-02	1.47E-02	9.50E-03
	2330	5.94E+02	7.29E-03	6.16E-03	6.16E-03	3.99E-03
	2430	4.45E+02	5.46E-03	4.62E-03	4.62E-03	2.99E-03
	2530	3.18E+02	3.91E-03	3.30E-03	3.30E-03	2.14E-03
	2630	2.57E+02	3.16E-03	2.67E-03	2.67E-03	1.73E-03
RDA Vaults	2230	9.83E+04	1.21E+00	1.02E+00	1.02E+00	6.60E-01
	2330	1.01E+04	1.24E-01	1.05E-01	1.05E-01	6.79E-02
	2430	2.32E+03	2.85E-02	2.41E-02	2.41E-02	1.56E-02
	2530	6.80E+02	8.35E-03	7.06E-03	7.06E-03	4.57E-03
	2630	3.80E+02	4.66E-03	3.94E-03	3.94E-03	2.55E-03
EDA Vaults	2230	5.01E+04	6.15E-01	5.20E-01	5.20E-01	3.37E-01
	2330	2.77E+03	3.40E-02	2.87E-02	2.87E-02	1.86E-02
	2430	1.19E+02	1.46E-03	1.23E-03	1.23E-03	7.97E-04
	2530	4.55E+01	5.59E-04	4.72E-04	4.72E-04	3.06E-04
	2630	3.94E+01	4.84E-04	4.09E-04	4.09E-04	2.65E-04

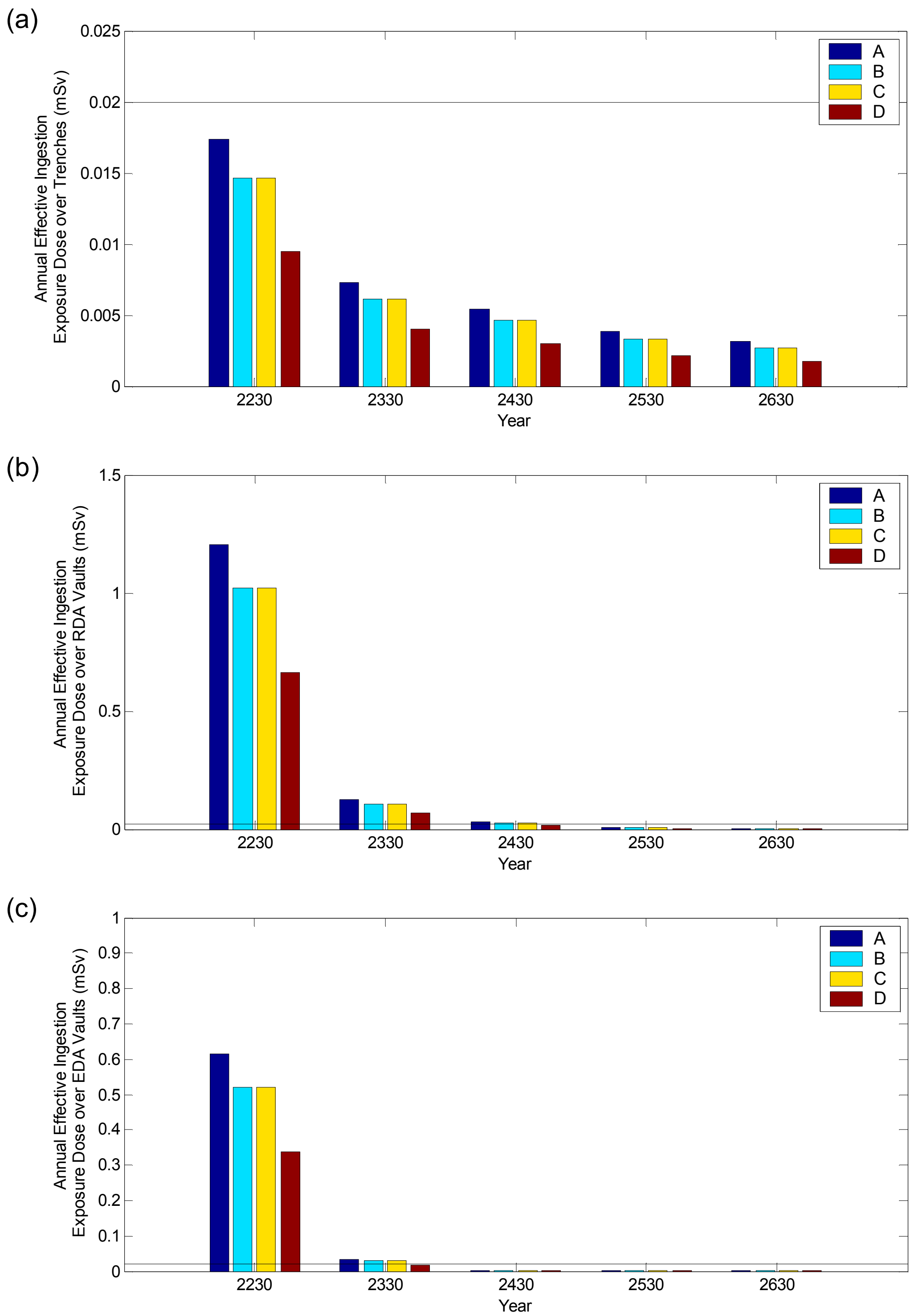

Figure 5-5: Calculated Annual Effective Ingestion Dose to the PEGs for the Reference Case (mSv). (a) Trenches; (b) RDA Vaults; and (c) EDA Vaults.

Calculated Effective Inhalation Doses

The inhalation exposures calculated for the reference case are given in Table 5-2. For trenches the peak inhalation dose is associated with C-14 labelled CO_2, whilst for the vaults it is associated with C-14 labelled CH_4. For either gas, the peak calculated effective annual inhalation doses are less than 5.0E-5 mSv. This peak inhalation dose is greater than that determined in the RDA assessment (3.3E-5 mSv; Limer et al., 2011), and consistent with the changes in C-14 flux noted above, arises as a result of the differences in the assumptions in the near-field modelling in the RDA and EDA assessments (see Small et al., 2011a, and Small et al., 2011b, for the RDA and EDA assessments respectively).

Table 5-2: Calculated Effective Inhalation Doses for the Reference Case (mSv)

Location	Time (y)	Flux of C-14 Labelled Gas (Bq m^{-2} y^{-1})		Calculated Effective Inhalation Exposure (mSv)	
		CO_2	CH_4	CO_2	CH_4
Trenches	2230	4.84E+02	9.30E+02	5.24E-07	4.72E-07
	2330	1.98E+02	3.96E+02	2.14E-07	2.01E-07
	2430	1.44E+02	3.01E+02	1.57E-07	1.53E-07
	2530	8.75E+01	2.31E+02	9.49E-08	1.17E-07
	2630	6.78E+01	1.89E+02	7.35E-08	9.60E-08
RDA Vaults	2230	7.45E+00	9.83E+04	8.08E-09	4.99E-05
	2330	2.04E-01	1.01E+04	2.21E-10	5.12E-06
	2430	1.36E-01	2.32E+03	1.48E-10	1.18E-06
	2530	1.30E-01	6.80E+02	1.41E-10	3.45E-07
	2630	1.23E-01	3.79E+02	1.34E-10	1.92E-07
EDA Vaults	2230	5.27E-02	5.01E+04	5.72E-11	2.54E-05
	2330	7.87E-02	2.77E+03	8.54E-11	1.40E-06
	2430	5.16E-02	1.19E+02	5.60E-11	6.01E-08
	2530	8.81E-02	4.54E+01	9.55E-11	2.30E-08
	2630	2.61E-02	3.94E+01	2.83E-11	2.00E-08

5.1.2 Variant Cases

Decay Corrected Flux of C-14 Labelled Gas from the Wastes for the Variant Cases

Total decay corrected fluxes for the variant cases are presented in Figure 5-6, and area averaged fluxes are presented in Figure 5-7. As with the reference case, the average flux figure (Figure 5-7) also contains a dashed black line which demonstrates the flux per unit area which, given the biosphere model employed, is associated with a calculated annual ingestion dose for the reference PEG (C) of 20 μSv (i.e. a dose equivalent to the risk guidance level of 1E-6 y^{-1}; EA et al., 2009).

The time periods following cap completion that it takes the average fluxes to drop below that level are given in Table 5-3. These times are similar to those for the RDA assessment (relevant values from the RDA reference case are provided for comparison).

Table 5-3: Time period following completion of final cap before average flux drops below that associated with an effective ingestion dose of 2.0E-2 mSv for the reference PEG (C)

Case	**Time period following completion of final cap before average flux drops below that associated with a risk of 1E-6 y^{-1} for PEG A**		
	Trenches	**RDA Vaults**	**EDA Vaults**
Reference Case (Case2_InvA)	~ 100 y	~ 350 y	~ 300 y
Case2_InvA_C14rel	~ 100 y	~ 300 y	~ 300 y
Case2_var1_InvA	~ 100 y	~ 300 y	~ 150 y
Case2_InvA_S3M	~ 100 y	~ 350 y	~ 350 y
Case_InvB	~ 100 y	~350 y	~ 400 y
Reference Case for RDA assessment	*~ 100 y*	*~340 y*	*N/A*

The timescales upon which calculated annual effective ingestion doses for the reference PEG drop below the target are broadly similar in each case.

For Case2_var1_InvA, where the flow through the wastes are assumed to be higher due to increased infiltration rates, the time for the C-14 fluxes to drop below the target is substantially shorter for the EDA vaults (see also Figure 5-7b). When the Stage 3 decommissioning metals are assumed to be subject to a slower release rate of C-14 than other metals, the tail of the C-14 flux from the wastes takes longer to decline, leading to it taking about 400 years for the flux to drop below that associated with the target.

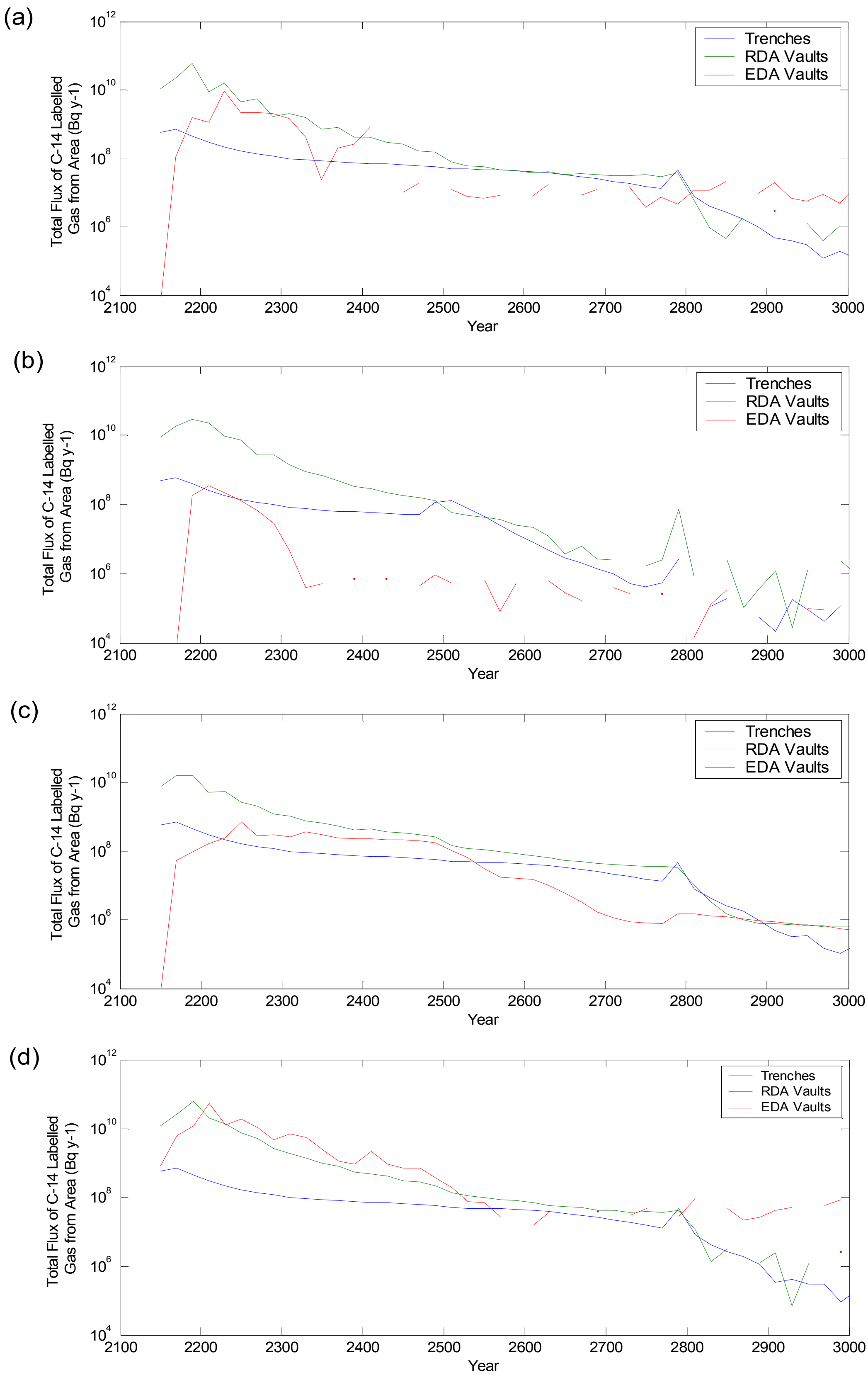

Figure 5-6: Total Decay Corrected Fluxes of C-14 Labelled Gas from the Wastes for the Variant Cases (Bq y-1). (a) Case2_InvAC14rel; (b) Case2_var1_InvA; (c) Case2_InvA_S3M; and (d) Case2_InvB.

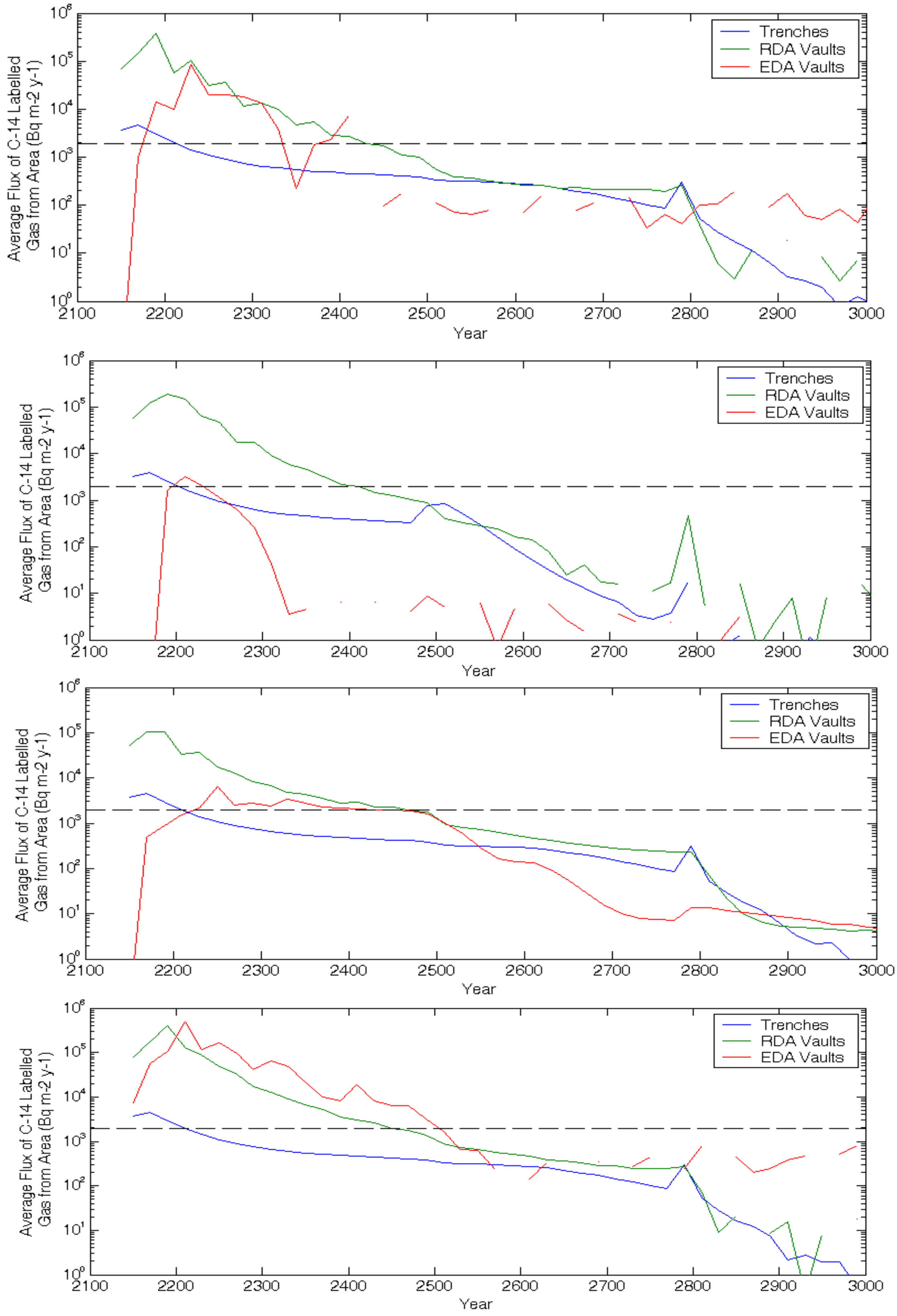

Figure 5-7: Average Decay Corrected Fluxes of C-14 Labelled Gas from the Wastes for the Variant Cases (Bq m^{-2} y^{-1}). (a) Case2_InvAC14rel; (b) Case2_var1_InvA; (c) Case2_InvA_S3M; and (d) Case2_InvB.

Calculated Effective Ingestion Doses

The calculated annual effective ingestion dose for each of the four variant cases, at 100 year intervals following the completion of the cap, are given in Table 5-4, Table 5-5, Table 5-6 and Table 5-7 for Case2_InvA_C14rel, Case2_var1_InvA, Case2_InvA_S3M and Case2_InvB respectively.

In order to explore how varying assumptions associated with the variant near-field cases influence calculated effective ingestion doses, Figure 5-8, Figure 5-9 and Figure 5-10 show the calculated annual effective ingestion doses for the reference PEG (C) for each of the cases (including the reference case).

Of particular interest is the impact of the alternative near-field assumptions on calculated impacts associated with the EDA vaults. For the case in which the PIER B2 inventory, which has a higher total inventory of C-14, particularly in Vaults 15 to 17, is considered (Case2_InvB) considerably higher ingestion doses for the PEGs are calculated than for any of the other cases. The other variant cases tend to have lower calculated impacts than for the reference EDA case.

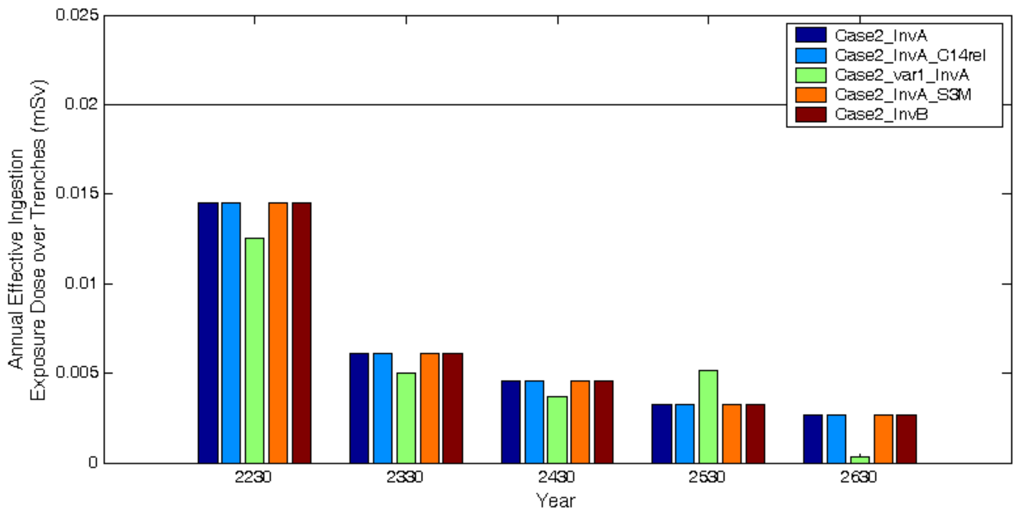

Figure 5-8: Calculated Effective Annual Ingestion Dose for the Reference PEG (C) Associated with Residing over the Trenches for all EDA Cases (mSv)

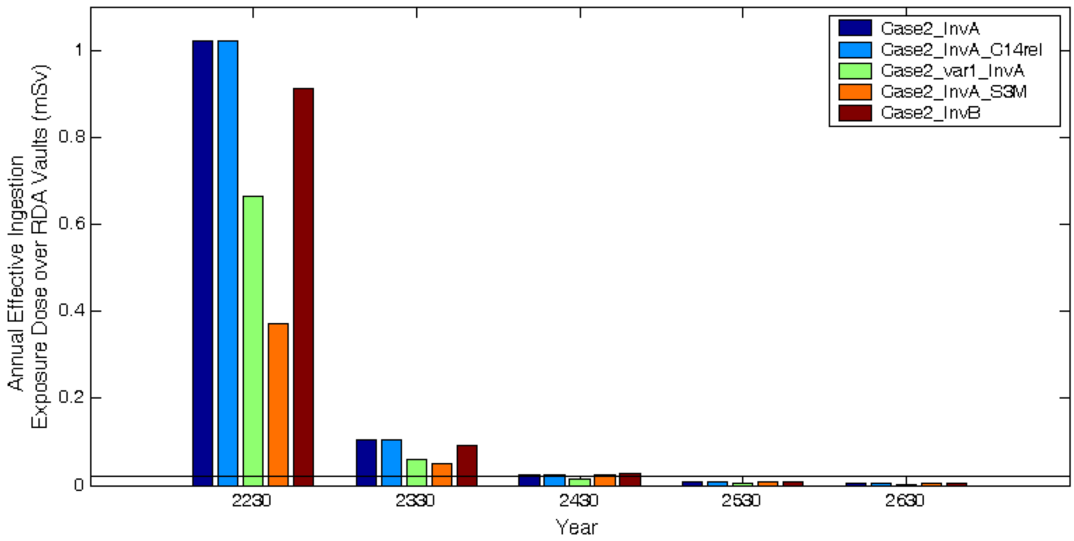

Figure 5-9: Calculated Effective Annual Ingestion Dose for the Reference PEG (C) Associated with Residing over the RDA Vaults for all EDA Cases (mSv)

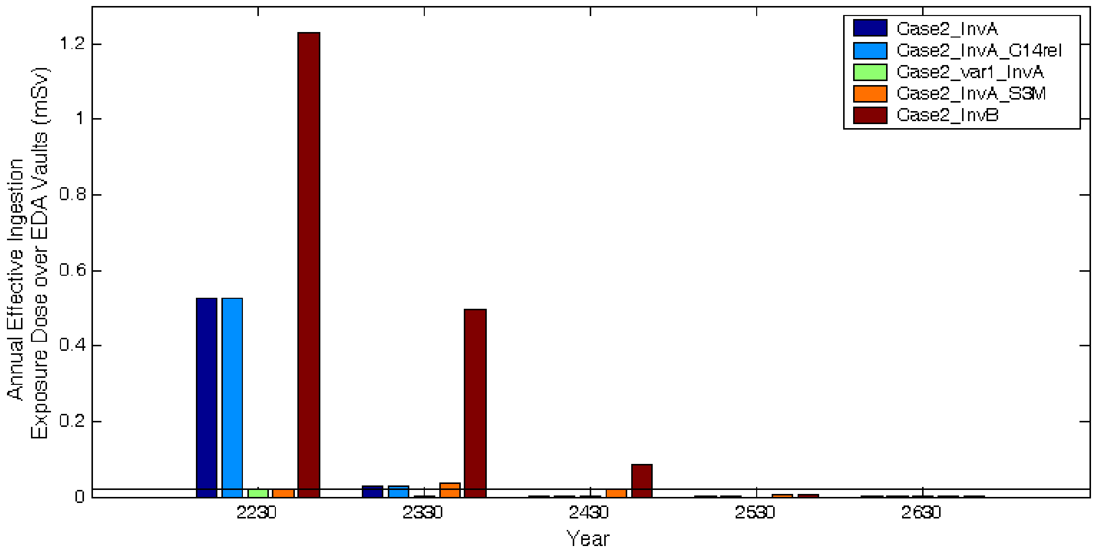

Figure 5-10: Calculated Effective Annual Ingestion Dose for the Reference PEG (C) Associated with Residing over the EDA Vaults for all EDA Cases (mSv)

Table 5-4: Calculated Annual Effective Ingestion Doses for Equal Likelihood of Placing Garden or Smallholding Anywhere on Cap for Case2_InvA_C14rel (mSv)

Location	Time (y)	Flux of C-14 Labelled Gas (Bq m^{-2} y^{-1})	Calculated Effective Ingestion Exposure (mSv)			
			PEG A	PEG B	PEG C	PEG D
Trenches	2230	1.41E+03	1.74E-02	1.47E-02	1.47E-02	9.50E-03
	2330	5.94E+02	7.29E-03	6.16E-03	6.16E-03	3.99E-03
	2430	4.45E+02	5.46E-03	4.62E-03	4.62E-03	2.99E-03
	2530	3.19E+02	3.91E-03	3.30E-03	3.30E-03	2.14E-03
	2630	2.58E+02	3.16E-03	2.67E-03	2.67E-03	1.73E-03
RDA Vaults	2230	1.04E+05	1.27E+00	1.08E+00	1.08E+00	6.97E-01
	2330	1.01E+04	1.24E-01	1.05E-01	1.05E-01	6.80E-02
	2430	1.92E+03	2.36E-02	1.99E-02	1.99E-02	1.29E-02
	2530	3.94E+02	4.83E-03	4.08E-03	4.08E-03	2.64E-03
	2630	2.62E+02	3.22E-03	2.72E-03	2.72E-03	1.76E-03
EDA Vaults	2230	8.62E+04	1.06E+00	8.94E-01	8.94E-01	5.79E-01
	2330	3.78E+03	4.64E-02	3.92E-02	3.92E-02	2.54E-02
	2430	-4.26E+01	-	-	-	-
	2530	7.24E+01	8.88E-04	7.50E-04	7.50E-04	4.86E-04
	2630	1.61E+02	1.98E-03	1.67E-03	1.67E-03	1.08E-03

Table 5-5: Calculated Annual Effective Ingestion Doses for Equal Likelihood of Placing Garden or Smallholding Anywhere on Cap for Case2_var1_InvA (mSv)

Location	Time (y)	Flux of C-14 Labelled Gas (Bq m^{-2} y^{-1})	Calculated Effective Ingestion Exposure (mSv)			
			PEG A	PEG B	PEG C	PEG D
Trenches	2230	1.22E+03	1.50E-02	1.27E-02	1.27E-02	8.20E-03
	2330	4.89E+02	6.00E-03	5.07E-03	5.07E-03	3.28E-03
	2430	3.60E+02	4.42E-03	3.74E-03	3.74E-03	2.42E-03
	2530	5.02E+02	6.17E-03	5.21E-03	5.21E-03	3.37E-03
	2630	3.10E+01	3.81E-04	3.22E-04	3.22E-04	2.08E-04
RDA Vaults	2230	6.39E+04	7.85E-01	6.63E-01	6.63E-01	4.29E-01
	2330	5.78E+03	7.09E-02	5.99E-02	5.99E-02	3.88E-02
	2430	1.44E+03	1.77E-02	1.50E-02	1.50E-02	9.70E-03
	2530	3.24E+02	3.98E-03	3.36E-03	3.36E-03	2.18E-03
	2630	7.79E+01	9.56E-04	8.08E-04	8.08E-04	5.23E-04
EDA Vaults	2230	2.04E+03	2.51E-02	2.12E-02	2.12E-02	1.37E-02
	2330	3.63E+00	4.46E-05	3.76E-05	3.76E-05	2.44E-05
	2430	6.39E+00	7.85E-05	6.63E-05	6.63E-05	4.29E-05
	2530	-8.64E+00	-	-	-	-
	2630	5.81E+00	7.14E-05	6.03E-05	6.03E-05	3.90E-05

Table 5-6: Calculated Annual Effective Ingestion Doses for Equal Likelihood of Placing Garden or Smallholding Anywhere on Cap for Case2_InvA_S3M (mSv)

Location	Time (y)	Flux of C-14 Labelled Gas (Bq m^{-2} y^{-1})	Calculated Effective Ingestion Exposure (mSv)			
			PEG A	PEG B	PEG C	PEG D
Trenches	2230	1.41E+03	1.73E-02	1.46E-02	1.46E-02	9.49E-03
	2330	5.93E+02	7.28E-03	6.15E-03	6.15E-03	3.98E-03
	2430	4.43E+02	5.44E-03	4.60E-03	4.60E-03	2.98E-03
	2530	3.18E+02	3.91E-03	3.30E-03	3.30E-03	2.14E-03
	2630	2.57E+02	3.16E-03	2.67E-03	2.67E-03	1.73E-03
RDA Vaults	2230	3.59E+04	4.41E-01	3.73E-01	3.73E-01	2.41E-01
	2330	4.80E+03	5.89E-02	4.97E-02	4.97E-02	3.22E-02
	2430	2.31E+03	2.84E-02	2.40E-02	2.40E-02	1.55E-02
	2530	7.82E+02	9.60E-03	8.11E-03	8.11E-03	5.25E-03
	2630	4.15E+02	5.09E-03	4.30E-03	4.30E-03	2.79E-03
EDA Vaults	2230	2.15E+03	2.64E-02	2.23E-02	2.23E-02	1.45E-02
	2330	3.34E+03	4.10E-02	3.46E-02	3.46E-02	2.24E-02
	2430	2.00E+03	2.46E-02	2.08E-02	2.08E-02	1.35E-02
	2530	6.04E+02	7.41E-03	6.26E-03	6.26E-03	4.06E-03
	2630	9.54E+01	1.17E-03	9.89E-04	9.89E-04	6.41E-04

Table 5-7: Calculated Annual Effective Ingestion Doses for Equal Likelihood of Placing Garden or Smallholding Anywhere on Cap for Case2_InvB (mSv)

Location	Time (y)	Flux of C-14 Labelled Gas (Bq m^{-2} y^{-1})	Calculated Effective Ingestion Exposure (mSv)			
			PEG A	PEG B	PEG C	PEG D
Trenches	2230	1.41E+03	1.73E-02	1.47E-02	1.47E-02	9.49E-03
	2330	5.93E+02	7.27E-03	6.14E-03	6.14E-03	3.98E-03
	2430	4.45E+02	5.46E-03	4.61E-03	4.61E-03	2.99E-03
	2530	3.17E+02	3.89E-03	3.28E-03	3.28E-03	2.13E-03
	2630	2.56E+02	3.15E-03	2.66E-03	2.66E-03	1.72E-03
RDA Vaults	2230	8.80E+04	1.08E+00	9.12E-01	9.12E-01	5.91E-01
	2330	8.81E+03	1.08E-01	9.13E-02	9.13E-02	5.91E-02
	2430	2.64E+03	3.24E-02	2.74E-02	2.74E-02	1.77E-02
	2530	7.27E+02	8.93E-03	7.54E-03	7.54E-03	4.89E-03
	2630	3.88E+02	4.76E-03	4.02E-03	4.02E-03	2.60E-03
EDA Vaults	2230	1.17E+05	1.44E+00	1.21E+00	1.21E+00	7.85E-01
	2330	4.74E+04	5.81E-01	4.91E-01	4.91E-01	3.18E-01
	2430	8.08E+03	9.92E-02	8.38E-02	8.38E-02	5.43E-02
	2530	6.57E+02	8.07E-03	6.82E-03	6.82E-03	4.42E-03
	2630	3.27E+02	4.02E-03	3.39E-03	3.39E-03	2.20E-03

Calculated Effective Inhalation Doses

The calculated effective inhalation doses for the four variant cases are given in Table 5-8, Table 5-9, Table 5-10 and Table 5-11 for Case2_InvA_C14rel, Case2_var1_InvA, Case2_InvA_S3M and Case2_InvB respectively.

Table 5-8: Calculated Effective Inhalation Doses for Case2_InvA_C14rel (mSv)

Location	Time (y)	Flux of C-14 Labelled Gas ($Bq\ m^{-2}\ y^{-1}$)		Calculated Effective Inhalation Exposure (mSv)	
		CO_2	CH_4	CO_2	CH_4
Trenches	2230	4.84E+02	9.30E+02	5.24E-07	4.72E-07
	2330	1.98E+02	3.96E+02	2.14E-07	2.01E-07
	2430	1.44E+02	3.01E+02	1.57E-07	1.53E-07
	2530	8.80E+01	2.31E+02	9.54E-08	1.17E-07
	2630	6.83E+01	1.89E+02	7.41E-08	9.60E-08
RDA Vaults	2230	7.87E+00	1.04E+05	8.53E-09	5.26E-05
	2330	2.03E-01	1.01E+04	2.20E-10	5.13E-06
	2430	1.66E-01	1.92E+03	1.80E-10	9.75E-07
	2530	1.28E-01	3.93E+02	1.39E-10	2.00E-07
	2630	1.13E-01	2.62E+02	1.23E-10	1.33E-07
EDA Vaults	2230	5.30E-02	8.62E+04	5.75E-11	4.37E-05
	2330	1.72E-01	3.78E+03	1.86E-10	1.92E-06
	2430	1.15E-01	-	1.24E-10	-
	2530	1.65E-01	7.22E+01	1.79E-10	3.66E-08
	2630	2.04E-02	1.61E+02	2.21E-11	8.17E-08

Table 5-9: Calculated Effective Inhalation Doses for Case2_var1_InvA (mSv)

Location	Time (y)	Flux of C-14 Labelled Gas (Bq m^{-2} y^{-1})		Calculated Effective Inhalation Exposure (mSv)	
		CO_2	CH_4	CO_2	CH_4
Trenches	2230	3.70E+02	8.50E+02	4.02E-07	4.31E-07
	2330	1.38E+02	3.51E+02	1.49E-07	1.78E-07
	2430	9.66E+01	2.64E+02	1.05E-07	1.34E-07
	2530	9.53E+01	4.07E+02	1.03E-07	2.06E-07
	2630	6.53E+00	2.45E+01	7.08E-09	1.24E-08
RDA Vaults	2230	1.78E+01	6.39E+04	1.93E-08	3.24E-05
	2330	2.93E+00	5.78E+03	3.18E-09	2.93E-06
	2430	4.95E-01	1.44E+03	5.37E-10	7.32E-07
	2530	2.94E-02	3.24E+02	3.19E-11	1.64E-07
	2630	-	-	-	-
EDA Vaults	2230	1.29E-01	2.04E+03	1.40E-10	1.04E-06
	2330	7.78E-02	3.55E+00	8.44E-11	1.80E-09
	2430	2.57E-02	6.37E+00	2.78E-11	3.23E-09
	2530	-	-	-	-
	2630	-	-	-	-

Table 5-10: Calculated Effective Inhalation Doses for Case2_InvA_S3M (mSv)

Location	Time (y)	Flux of C-14 Labelled Gas ($Bq\ m^{-2}\ y^{-1}$)		Calculated Effective Inhalation Exposure (mSv)	
		CO_2	CH_4	CO_2	CH_4
Trenches	2230	4.83E+02	9.30E+02	5.24E-07	4.71E-07
	2330	1.97E+02	3.96E+02	2.14E-07	2.01E-07
	2430	1.43E+02	3.00E+02	1.56E-07	1.52E-07
	2530	8.72E+01	2.31E+02	9.45E-08	1.17E-07
	2630	6.71E+01	1.90E+02	7.28E-08	9.64E-08
RDA Vaults	2230	3.52E+00	3.59E+04	3.81E-09	1.82E-05
	2330	1.55E-01	4.80E+03	1.68E-10	2.43E-06
	2430	6.03E-02	2.31E+03	6.54E-11	1.17E-06
	2530	1.02E-01	7.82E+02	1.10E-10	3.97E-07
	2630	8.75E-02	4.15E+02	9.49E-11	2.10E-07
EDA Vaults	2230	5.23E-02	2.15E+03	5.67E-11	1.09E-06
	2330	2.80E-02	3.34E+03	3.04E-11	1.69E-06
	2430	1.67E-02	2.00E+03	1.81E-11	1.02E-06
	2530	3.78E-02	6.04E+02	4.10E-11	3.06E-07
	2630	1.85E-02	9.54E+01	2.01E-11	4.84E-08

Table 5-11: Calculated Effective Inhalation Doses for Case2_InvB (mSv)

Location	Time (y)	Flux of C-14 Labelled Gas ($Bq\ m^{-2}\ y^{-1}$)		Calculated Effective Inhalation Exposure (mSv)	
		CO_2	CH_4	CO_2	CH_4
Trenches	2230	4.83E+02	9.30E+02	5.24E-07	4.72E-07
	2330	1.97E+02	3.95E+02	2.14E-07	2.00E-07
	2430	1.45E+02	3.00E+02	1.57E-07	1.52E-07
	2530	8.71E+01	2.30E+02	9.44E-08	1.16E-07
	2630	6.64E+01	1.90E+02	7.20E-08	9.63E-08
RDA Vaults	2230	8.35E+00	8.80E+04	9.05E-09	4.46E-05
	2330	2.36E-01	8.81E+03	2.56E-10	4.47E-06
	2430	1.61E-01	2.64E+03	1.74E-10	1.34E-06
	2530	1.54E-01	7.27E+02	1.68E-10	3.69E-07
	2630	1.25E-01	3.88E+02	1.35E-10	1.97E-07
EDA Vaults	2230	4.06E-02	1.17E+05	4.41E-11	5.93E-05
	2330	3.19E-02	4.74E+04	3.46E-11	2.40E-05
	2430	1.28E-02	8.08E+03	1.39E-11	4.10E-06
	2530	1.48E-02	6.57E+02	1.60E-11	3.33E-07
	2630	9.74E-03	3.27E+02	1.06E-11	1.66E-07

5.2 Rn-222

The assessment of the potential impacts of Rn-222 gas released from the wastes disposed of at the LLW repository relies upon the following key aspects:

▲ Known activities and concentrations of Ra-226 to be disposed of at the LLWR (Table 3-2);

▲ Rn-222 concentrations in the wastes will be around 10% of the Ra-226 concentrations (with a range of 7 to 15%; see Section 2.1.2);

▲ Any Rn-222 attenuation in the cap will greatly reduce the concentration of Rn-222 in soil gas and the overlying atmosphere (Section 2.2); and

▲ Rn-222 concentrations in indoor air can be calculated based on either empirical relationships between soil gas and indoor air concentrations of Rn-222, or on ventilation rates of buildings (Section 2.3.2).

The cases summarised in Table 5-12 have been derived to explore the implications of assumptions associated with attenuation in the cap, and the implications of the method used for deriving the Rn-222 concentration in indoor air for calculated inhalation doses.

Table 5-12: Calculation Cases for Assessing Potential Impacts of Rn-222 Release from the Cap

Region of the LLWR	Case Name	Assumption About Cap
All EDA Vaults (15-20)	EDAVaults_1mCoarse	1 m coarse material
	EDAVaults_1.5mCoarse	1.5 m coarse material
	EDAVaults_2mCoarse	2 m coarse material
	EDAVaults_AsDesign	2.1 m coarse, 0.9 m fine
Vaults 15 to 16	Vaults1516_1mCoarse	1 m coarse material
	Vaults1516_1.5mCoarse	1.5 m coarse material
	Vaults1516_2mCoarse	2 m coarse material
	Vaults1516_AsDesign	2.1 m coarse, 0.9 m fine

From these cases, consistent with the RDA assessment, a reference case for exposure may be selected as follows.

The possibility that the low permeability layer could be disturbed through the creation of a domestic dwelling or light building with a cellar that could extend to a depth sufficient to penetrate the low permeability layer and make connection with the underlying coarse layers requires consideration. The reference case is therefore defined, cautiously, on the following basis.

- ▲ The impermeable layer is disturbed as a result of the creation of a building on the cap, with a cellar extending to sufficient depth.
- ▲ Average thicknesses of coarse material of 1.5 m above the vaults provide attenuation.
- ▲ An emanation fraction of 7% for the vaults is assumed (as the wastes are containerised and grouted, and the range is based upon trench monitoring; see Limer and Thorne, 2011).

For all the cases defined, the calculated annual effective doses are summarised in Table 5-13 and Table 5-14 for the PIER A2 and B2 inventories respectively. An indoor occupancy of 0.8 (7,013 h) and an indoor equilibrium factor of 0.4 are assumed throughout. The reference case is highlighted in bold. The maximum annual effective adult inhalation doses, greater than 1E-7, are shown in Figure 5-11.

Table 5-13: Potential Effective Adult Inhalation Doses (mSv) – PIER A2 Inventory

Case	Rn-222 Concentration in Soil (Bq m^{-3})		Potential Rn-222 Concentration in Buildings (Bq m^{-3})		Annual Effective Adult Inhalation Dose (mSv)	
	Min.	Max.	Min.	Max.	Min.	Max.
EDAVaults_1mCoarse	6.5E+02	1.4E+03	9.7E-01	2.1E+00	2.5E-02	5.3E-02
EDAVaults_1.5mCoarse	2.7E+02	5.8E+02	**4.1E-01**	8.7E-01	**1.0E-02**	2.2E-02
EDAVaults_2mCoarse	8.0E+01	1.7E+02	1.2E-01	2.6E-01	3.0E-03	6.5E-03
EDAVaults_AsDesign	n/s	n/s	n/s	n/s	n/s	n/s
Vaults1516_1mCoarse	1.4E+03	3.0E+03	2.1E+00	4.5E+00	5.3E-02	1.1E-01
Vaults1516_1.5mCoarse	5.9E+02	1.3E+03	8.8E-01	1.9E+00	2.2E-02	4.8E-02
Vaults1516_2mCoarse	1.7E+02	3.7E+02	2.6E-01	5.5E-01	6.5E-03	1.4E-02
Vaults1516_AsDesign	n/s	n/s	n/s	n/s	n/s	n/s

n/s is used for values less than 1E-100.

Table 5-14: Potential Effective Adult Inhalation Doses (mSv) – PIER B2 Inventory

Case	Rn-222 Concentration in Soil (Bq m^{-3})		Potential Rn-222 Concentration in Buildings (Bq m^{-3})		Annual Effective Adult Inhalation Dose (mSv)	
	Min.	Max.	Min.	Max.	Min.	Max.
EDAVaults_1mCoarse	5.2E+02	1.1E+03	7.8E-01	1.7E+00	2.0E-02	4.2E-02
EDAVaults_1.5mCoarse	2.2E+02	4.6E+02	**3.2E-01**	6.9E-01	**8.2E-03**	1.8E-02
EDAVaults_2mCoarse	6.3E+01	1.4E+02	9.5E-02	2.0E-01	2.4E-03	5.1E-03
EDAVaults_AsDesign	n/s	n/s	n/s	n/s	n/s	n/s
Vaults1516_1mCoarse	1.1E+03	2.3E+03	1.6E+00	3.4E+00	4.0E-02	8.6E-02
Vaults1516_1.5mCoarse	4.4E+02	9.4E+02	6.6E-01	1.4E+00	1.7E-02	3.6E-02
Vaults1516_2mCoarse	1.3E+02	2.8E+02	1.9E-01	4.2E-01	4.9E-03	1.0E-02
Vaults1516_AsDesign	n/s	n/s	n/s	n/s	n/s	n/s

n/s is used for values less than 1E-100.

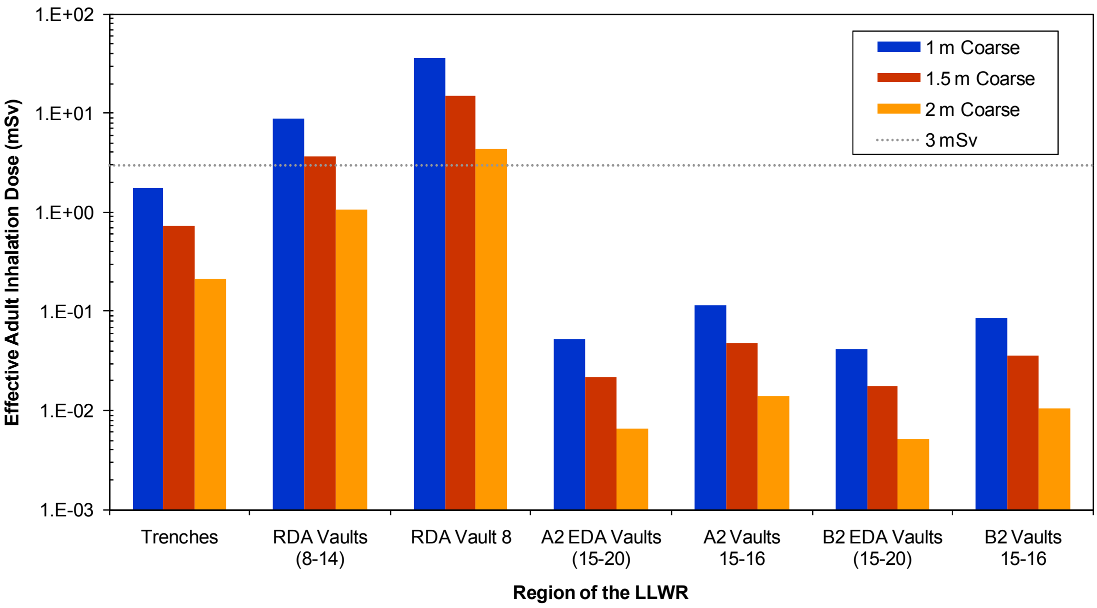

Figure 5-11: Effect of Attenuation Assumptions and Method Used to Estimate Potential Rn-222 Concentrations in Buildings on Annual Effective Adult Inhalation Dose (mSv)

The results show that for an intact, undegraded cap, the annual effective doses from Rn-222 inhalation will be negligible. However, were there to exist areas over which the infiltration barrier was substantially degraded (either as a result of ongoing degradation processes or as a result of intrusive human activities) and were a building to be constructed on those areas, then annual effective doses of > 0.1 mSv might be incurred by the occupants. This EDA assessment conclusion is consistent with the RDA assessment outcomes. Note that the results associated with the EDA vaults are lower than for the RDA vaults, and in particular Vault 8, and also the trenches. Therefore, the EDA assessment results show that the peak impacts essentially do not differ from the main RDA assessment.

It should be noted that the LLWR has proposed an emplacement strategy for high Ra-226 wastes that these should not be placed in the upper two half height ISO (HHISO) stack positions within the vaults; this is to reduce the likelihood of their excavation by humans (see Hicks and Baldwin, 2011). In the RDA assessment it was shown that consideration of this emplacement strategy would reduce the potential impacts associated with inhalation of Rn-222 from those wastes by three orders of magnitude.

In the RDA assessment (Limer and Thorne, 2011), a set of "what-if" calculations were performed for each of the three regions of the cap considered above for the situation of the facility surviving for 10,000 years and there no longer being any cap present. The same calculations have therefore been performed for the EDA assessment; the cases are

EDAVaults_NoCap@10000y and Vaults1516_NoCap@10000y for the two regions considered. The results are presented in Table 5-15. As was observed in the RDA assessment, the potential impacts associated with these variant cases are of little radiological significance.

Table 5-15: Potential Annual Effective Adult Inhalation Doses for the 'What if' Cases (mSv)

Inventory	Case	Rn-222 Concentration in Soil ($Bq\ m^{-3}$)		Potential Rn-222 Concentration in Buildings ($Bq\ m^{-3}$)		Annual Effective Adult Inhalation Dose (mSv)	
		Min.	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
PIER A2	EDAVaults_ NoCap@10000y	3.4E+01	7.4E+01	5.1E-02	1.1E-01	1.3E-03	2.8E-03
	Vaults1516_ NoCap@10000y	1.1E+02	2.4E+02	1.7E-01	3.6E-01	4.2E-03	9.0E-03
PIER B2	EDAVaults_ NoCap@10000y	5.5E+01	1.2E+02	8.2E-02	1.8E-01	2.1E-03	4.4E-03
	Vaults1516_ NoCap@10000y	1.4E+02	3.0E+02	2.1E-01	4.5E-01	5.3E-03	1.1E-02

6 Discussion

The assessment described herein is based on a variety of alternative source term calculations. For C-14 the estimated peak effective ingestion and inhalation doses are slightly higher than for the reference facility design for the RDA area (Limer et al., 2011). These arise from changes in the biogeochemical evolution predicted for the RDA vaults in the EDA GRM near-field calculations, compared to the predictions for the RDA alone.

Results for the EDA vaults specifically are notably lower than for the RDA calculation results, despite containing a significant C-14 inventory (18.9 TBq in the EDA vaults compared to 5.13 TBq in the RDA vaults). This shows that material distributions within the vaults, and the resulting evolution of biogeochemical conditions within the vaults, exert a strong control on the evolved fluxes and thus calculated doses.

The calculated peak annual committed effective adult ingestion doses associated with the EDA vaults for the reference PEG (PEG C) are about 0.6 mSv for the PIER A2 inventory and about 1.2 mSv for the PIER B2 inventory. Committed effective adult inhalation doses, associated with inhalation inside a building, are four orders of magnitude lower than those caused by ingestion. The calculated effective doses presented in this report demonstrate substantial decreases over 100 year time periods[7].

For the Rn-222 the estimated effective inhalation doses for the EDA inventory are also lower than for the RDA assessment, primarily as the projected Ra-226 inventory in the EDA is lower than for the RDA.

For Rn-222 gas, the results show that for an intact, undegraded cap, the annual effective doses from Rn-222 inhalation inside a dwelling constructed over Vaults 15 and 16 would be negligible. However, in the unlikely event that there to exist areas over which the infiltration barrier was substantially degraded (either as a result of ongoing degradation processes or as a result of intrusive human activities) and were a building to be constructed on those areas, then annual effective doses of > 0.1 mSv might be incurred by the occupants. This potential effective inhalation dose is a few orders of magnitude lower than the effective inhalation dose that might arise should an

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[7] The calculated effective ingestion doses associated trenches decrease by 60% between 2230 and 2330 and those associated with the RDA vaults decrease by at least 85%. For the EDA vaults, in the majority of cases the calculated effective ingestion doses associated with the EDA vaults decrease by at least 94% between 2230 and 2330, although for Case2_InvA_S3M the calculated exposures over that period increase by 50%.

area of the cap over vault 8 were to become substantially degraded (Limer and Thorne, 2011). This relates to the substantial inventory of Ra-226 ascribed to Vault 8.

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