CLESA Valley Development – PCRSA Addendum

Sellafield Ltd

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1. Introduction

The Calder Landfill Extension Segregated Area (CLESA) is an Environmental Permitting Regulations (EPR) authorised Low Activity - Low Level Waste (LA-LLW) containment landfill for the disposal of non-hazardous radioactive waste generated at Sellafield. The Permitted activity limit averaged over a consignment (a single vehicle load) is 12,000 Bq/g for H-3 and 200 Bq/g for all other radionuclides[1]. It is anticipated that the landfill will be full around 2030.

Sellafield Ltd (SL) are proposing to extend CLESA into an adjacent ‘valley area’ (Figure 1). This would increase CLESA’s volumetric capacity by around 23% and could extend the facility lifetime by around 5 to 6 years (based on typical historical disposal rates). In this document the terms ‘existing disposal area’ and ‘valley area’ are used to refer to the existing CLESA disposal facility and the area the CLESA disposal facility may be extended into, respectively.

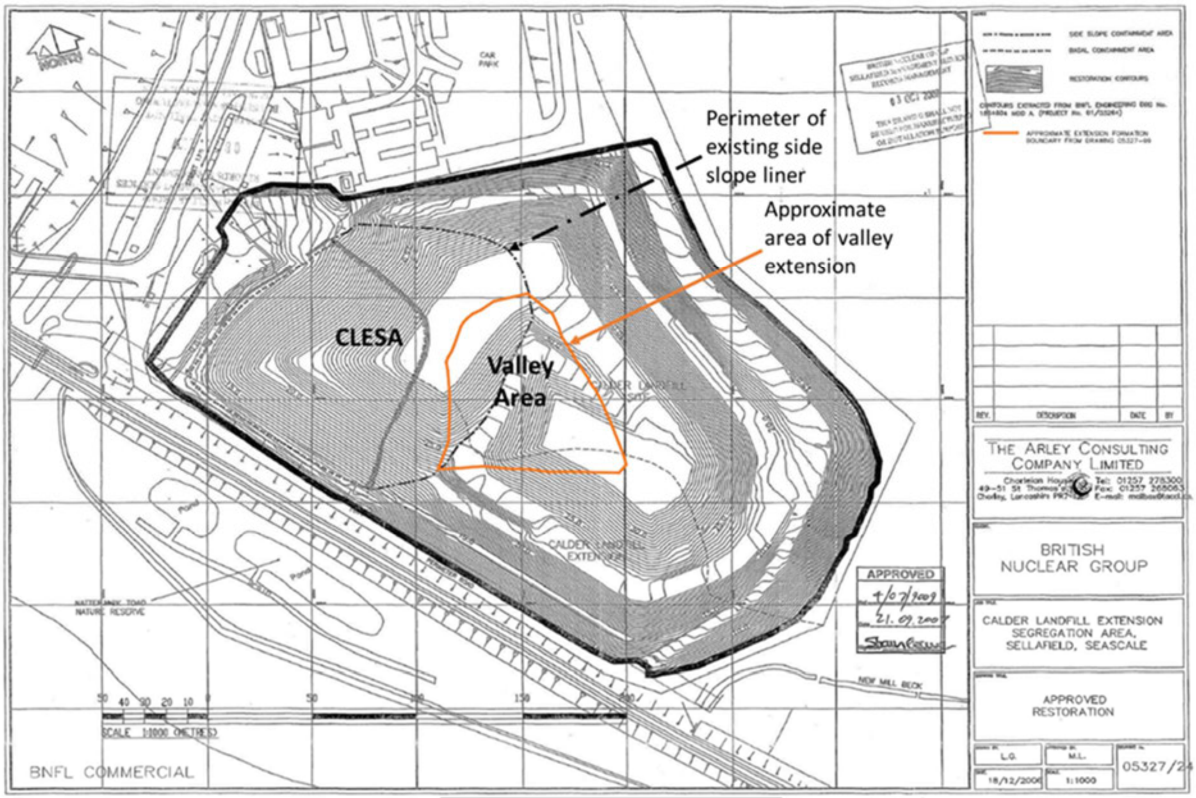

Figure 1. Perimeter of additional disposals to the valley area

This report is an addendum to the 2017 Post Closure Radiological Safety Assessment (PCRSA) for CLESA (AECOM, 2017a). The 2017 PCRSA was a periodic review and update, which also assessed the potential impacts of increased radionuclide activity limits after the end of the Period of Authorisation (PoA). It was used in support of a successful application for a Permit with higher activity limits.

The Environment Agency (EA) has agreed that producing an addendum to the 2017 PCRSA is an appropriate approach to underpin an application for a Permit to extend disposals into the valley area. The impacts of valley development during the PoA have been assessed separately, in an addendum to the 2017 Operational Radiological Safety Assessment, ORSA (AECOM, 2022a).

In addition to assessing the potential impacts of valley development after the end of the PoA, this report also provides updates to the 2017 PCRSA using the latest information on waste disposals, closure engineering and long-term performance, coastal and riverine erosion. This report has been written assuming the reader is familiar with the 2017 PCRSA.

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[1] There is also a hotspot limit in the Permit where the activity of any hotspots within a consignment must meet the following requirement: (α / 1,700) + (β / 40,000) < 1. Where: α is the total surface alpha activity in Bq/g; and β is the total surface beta / gamma (excluding tritium) activity in Bq/g.

1.1. Background

The restoration profile described in the approved planning application is a mound structure that is formed from CLESA and the older Calder landfill and Calder landfill extension. Once disposals to CLESA are complete there will be a 'valley area' between the CLESA disposals and the older disposals to the Calder landfill and its extension (Figure 1). The valley area will need to be filled with clean materials (soil / spoil sourced from the Sellafield site or imported) to form the agreed restoration profile. Filling the valley area with waste rather than clean materials will extend CLESA's lifetime and delay the need for SL to develop a new facility or switch to using offsite commercial facilities, which might involve significant road transport. Filling the valley area with suitable radiological waste (that would be generated with or without valley development), makes beneficial use of this space and avoids sourcing and using clean materials.

The types of wastes that would be disposed to the valley area are the same as those disposed to the existing disposal area. There would be no increases to the radionuclide activity limits or changes to the working methods.

CLESA's side slope liner (the perimeter of which is shown with the black dot-dash line in Figure 1) would be extended across the valley area. The extended liner would provide the same functions as the existing side slope liner, i.e. to capture leachate and hydraulically separate CLESA from the underlying older wastes. The perimeter of the valley area liner extension is shown by the orange line in Figure 1. Some of the valley wastes would be disposed inside the footprint of the existing CLESA liner, while the remainder would be disposed inside the footprint of the extension. The impacts of loading the already-emplaced wastes with additional waste disposals will be negligibly different to loading the existing wastes with clean fill material, because the additional waste disposals and clean fill materials will have similar density (TACCL, 2023a).

An initial feasibility assessment has been made of the use of the valley area for radioactive waste disposals (AECOM, 2022b). The work included qualitative and semi-quantitative assessment of the radiological impacts of valley development. This identified the key pathways after the end of the PoA and concluded the additional post-PoA radiological impacts would be low. A similar assessment is being undertaken for the additional non-radiological impacts, via an updated Hydrogeological Risk Assessment (HRA) (TACCL, 2023b), and early indications are that these are also low.

1.2. Scope and Objectives

This document presents an updated assessment of the potential radiological impacts after the end of the PoA. Separate assessments are being undertaken for:

- the implications of valley development for landfill stability, landfill gases and impacts on groundwater;
- radiological impacts during the PoA (AECOM, 2022a); and
- optimisation of the valley area engineering design and operational approach.

The potential implications for the Environmental Setting and Installation Design (ESID) report and amenity risk assessment are also being considered.

The 2017 PCRSA included assessment calculations that were proportionate to the hazard, including the potential increase in hazard if disposal limits were raised, which they subsequently were. As noted above, initial feasibility work indicates that the increase in radiological hazard associated with valley development is low. Therefore, the assessment and calculation approaches used in the 2017 PCRSA have largely been retained for this addendum. Updates to assessments are made where valley development changes the characteristics of the facility, e.g. changes to the relevant inadvertent human intrusion events.

The scope of this addendum also includes updating the PCRSA to capture the latest information on the wastes, the closure engineering, and the potential long-term evolution of the Sellafield site, including the implications for potential receptors.

Subsequent to the 2017 PCRSA, SL were issued with a revised Permit that includes a total activity limit averaged over a consignment (a single vehicle load) of 200 Bq/g, with a higher combined alpha and beta / gamma limit for hotspots within the consignment. A further revision increased the activity limit for H-3 to 12,000 Bq/g. There have been around two years of disposals that include some consignments with activities within these new criteria but above the original Permitted activity limits. This provides updated information for assessing the potential average activities and fingerprints of future disposals. This new information can be used to improve the assessment calculations and provide more realistic assessments of potential future impacts.

A conceptual closure engineering design that uses Best Available Techniques (BAT) is currently being developed (AECOM, 2022c). Progress to date informs this addendum, and the results of the updated PCRSA will feed back into the design. It is important the PCRSA is not overly cautious leading to unnecessarily complex and, or overengineered approaches. Therefore, an objective is to make cautiously realistic assumptions about the closure engineering performance, and more generally to use a cautiously realistic approach to assess the post-closure risks. In this addendum, improvements are made to some aspects of the assessment calculations to make them more realistic and less cautious. Once the conceptual closure engineering design is finalised, the implications for the PCRSA will be assessed and documented, ready to be fully incorporated into the PCRSA at the next scheduled update.

SL are also currently undertaking work to understand the potential long-term evolution of the Sellafield site including evolution of the rivers and coastal erosion. Although this work has not been finalised, the initial results have been fed into this addendum to update the assessment scenarios used in the 2017 PCRSA and ensure the PCRSA assesses the range of potential future evolutions, and includes an appropriate degree of caution.

Surface contaminated blocks are arguably the most hazardous radioactive wastes disposed to CLESA. The radiological hazard is associated with uncovering of the blocks as the facility erodes, and subsequent radiological exposure of people from blocks on the coastline. The timing of exposure is important because it affects the amount of radioactive decay of key radionuclides including Cs-137, and therefore the radioactivity remaining when the blocks are exposed. Therefore, this addendum reviews the implications of the latest evolution scenarios for the potential doses from blocks and confirms the current activity limits are still appropriate.

1.3. Structure

The 2017 PCRSA (AECOM, 2017a) was developed, and structured, using the International Atomic Energy Agency (IAEA) Improvement of Safety Assessments for Near Surface Disposal Facilities (ISAM) approach (IAEA, 2004), which is a best practice approach to undertaking post-closure safety assessments. This approach has been retained therefore this report is structured as follows:

- Section 2 describes the assessment context.
- Section 3 updates the system description.
- Section 4 presents updates to the assessment scenarios.
- Section 5 describes the assessment models and calculation cases.
- Section 6 presents the assessment results.
- Section 7 reviews the radiological capacities and disposal activity limits.
- Section 8 concludes.

2. Assessment Context

2.1. Regulatory Context

Environmental matters relating to the operation of the facility are regulated by the EA. The EA attaches limits and conditions to Permits under the Environmental Permitting (England and Wales) 2010 Regulations and subsequent amendments (EPR10) for the disposal of radioactive waste. These limits and conditions are binding on operators and provide the means by which the EA regulates the development and operation of a near-surface disposal facility for radioactive waste.

The developers and operators of near-surface facilities for solid radioactive waste disposal have to demonstrate that their facilities will properly protect people and the environment. They need to show that their approach to developing the facilities and the location, design, construction, operation and closure of the facilities will meet a series of principles and requirements. The Guidance on Requirements for Authorisation (GRA) (Environment Agency et al., 2009) sets out these principles and requirements to provide guidance to developers and operators of near surface repositories in compliance with their Permit authorisations. A key goal of the GRA is to apply proportionate regulation, and the complexity of submissions should be proportionate to the hazard posed by the radioactivity. The GRA also provides information about the associated framework of legislation, government policy and international obligations. There have been a number of legislative and policy updates subsequent to publication of the GRA in 2009, and supplementary guidance notes have been published.

The PCRSA evaluates the potential radiological impacts of the site once disposal operations have been completed and following surrender of the Permit at the end of any period of control for the purposes of radiological protection (i.e. period of institutional control). The results of the PCRSA need to be assessed against requirements R6, R7 and R9 (post-closure only) of the GRA:

- Requirement R6: Risk guidance level after the period of authorisation. After the period of authorisation, the assessed radiological risk from a disposal facility to a person representative of those at greatest risk should be consistent with a risk guidance level of 10^{-6} per year (i.e. 1 in a million per year). A risk of 10^{-6} per year equates to an annual effective dose of around 20 µSv assuming the exposure occurs, i.e. the probability of exposure is one. The risk guidance level of 10^{-6} per year includes a significant factor of safety (of around an order of magnitude) to account for uncertainty and variability in the characteristics of the system and the habits that lead to exposures.

- Requirement R7: Human intrusion after the period of authorisation. The developer/operator of a near-surface disposal facility should assess the potential consequences of human intrusion into the facility after the period of authorisation on the basis that it is likely to occur. The developer/operator should, however, consider and implement any practical measures that might reduce the chance of this happening. The assessed effective dose to any person during and after the assumed intrusion should not exceed a dose guidance level in the range of around 3 mSv y^{-1} to around 20 mSv y^{-1}. Values towards the lower end of this range are applicable to assessed exposures continuing over a period of years (prolonged exposures), while values towards the upper end of the range are applicable to assessed exposures that are only short term (transitory exposures).

- Requirement R9: Environmental radioactivity. The developer/operator should carry out an assessment to investigate the radiological effects of a disposal facility on the accessible environment, both during the period of authorisation and afterwards with a view to showing that all aspects of the accessible environment are adequately protected.

The scope of Requirement R9 includes potential doses to non-human biota. The GRA does not specify a dose guidance level for non-human biota, however a habitat assessment study undertaken at the same time the GRA was published (Environment Agency, 2009) refers to a threshold of 40 µGy/h below which it was agreed there would be no adverse effect on the integrity of designated conservation sites (then referred to as ‘Natura 2000’ sites). Subsequent to the 2017 PCRSA, guidance has been provided on release of nuclear sites from radioactive substances regulation (the ‘GRR’, SEPA et al., 2018). Although the GRR does not directly apply to CLESA, it is useful to note its position on doses to non-human biota as the guidance parallels many aspects of the GRA, and has been issued more recently:

“At the time of publication there are no statutory criteria for determining radiological protection of the environment, though some criteria have been recommended by IAEA (1992, 1998) and ICRP (2008, 2014). A number of research studies and regulatory guidance documents have proposed criteria and assessment approaches (for example Copplestone et al., 2001; Andersson et al., 2008; Brown et al., 2016). We currently use ‘Environmental Risk from Ionising Contaminants: Assessment and Management’ (ERICA) (Brown et al., 2016) for our own assessments of radiological impacts of discharges upon non-human organisms. When making an initial assessment of the dose rates from a single premises we use simplified assumptions and a dose rate screening criterion of 10 µGy/h for populations of non-human organisms in designated conservation sites[2] *(for example Sites of Special Scientific Interest, Special Areas of Conservation and Special Protected Areas). We consider this value sufficiently cautious that, if it is not exceeded, we would not expect populations of non-human organisms and their habitats to be adversely affected by the discharge. Should this screening criterion be exceeded, we would then use more site-specific data and the ERICA model to generate more realistic assessments.”*

The EA has issued supplementary guidance (EA, 2012) to the GRA about meeting the requirements of the Groundwater Directive (Directive 2006/118/EC). It identifies the requirements of the GRA that if met, would enable the EA to permit the disposal of solid radioactive waste as compliant with the groundwater activity provisions of EPR10. Of the requirements identified by EA (2012), only R6 is within the scope of this addendum.

A key goal of the GRA is to encourage proportionate regulation, such that the complexity of submissions should be proportionate to the hazard. The 2017 PCRSA was developed to be proportionate to a proposed activity limit of 200 Bq/g, assuming the results of the 2017 PCRSA and other assessments supported this. Initial feasibility

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[2] N.B. CLESA is not a designated conservation site.

assessment (AECOM, 2022a) showed that valley development is only expected to result in a small increase to the radiological hazard of the facility. Therefore, the breadth and depth of assessment, and assessment approaches used in the 2017 PCRSA should be broadly appropriate. Nevertheless, where there are opportunities to make simple improvements to the assessments it is appropriate to do so, even if they are not directly impacted by valley development.

The 2017 PCRSA used inputs from a wide range of sources including assessments undertaken for the Sellafield site, the LLWR 2011 ESC, assessments undertaken for commercial landfills receiving LA-LLW, and data from international bodies. The LLWR 2011 ESC was particularly relevant as the LLWR is located close to CLESA, in a similar environmental setting, and the 2017 PCRSA was able to learn from the outputs of detailed assessments already undertaken for a significantly more hazardous facility. The same approach is used in this addendum.

The results of this PCRSA addendum are intended to be fed into the Environmental Safety Case (ESC) for CLESA and a Permit application to dispose wastes to the valley area. Therefore, it is important that this PCRSA addendum is consistent with the requirements of the GRA and provides the information needed to underpin updates to the ESC, and an application for a revised Permit.

The results of the PCRSA can be used to calculate the safe radiological capacity[3] of the site and can be used to inform safe disposal limits and other Waste Acceptance Criteria (WAC). This report updates the radiological capacities presented in the 2017 PCRSA (AECOM, 2017) and reviews the activity limits, focussing on activity limits for disposal to the valley area.

2.2. Assessment Timeframes

The main timeframes for CLESA are:

- The operational phase.
- The subsequent period of (institutional) control for the purposes of radiological protection, during which the site will continue to be managed and access controlled.
- The post-authorisation phase, when controls have been removed, lasting until the potential impacts of the site are no longer significant.

This report covers the third period. The first two periods are addressed by an addendum to the ORSA (AECOM, 2022a).

Once the volumetric capacity of the site has been used the wastes will be capped to minimise infiltration of rainwater and generation of leachate, reduce the risk of inadvertent human intrusion and bio-intrusion, and prevent dispersion of the wastes through physical processes such as transport of particulates (dust) by wind. Other engineering measures may also be emplaced to ensure the long-term safe passive evolution of the site, for example this might include a passive drainage system to manage the small amounts of water that may infiltrate the cap (AECOM, 2022c). As noted previously, work is currently being undertaken to develop an optimised conceptual closure engineering design that uses Best Available Techniques (BAT) to minimise the long-term environmental impacts of the facility (AECOM, 2022c). Development of the closure engineering design is being undertaken as part of developing a Closure and Aftercare Management Plan (CAMP) for CLESA. (The study is considering how the optimal closure engineering could change with and without valley development).

Following capping there will be a period of (institutional) control for the purposes of radiological and non-radiological protection, during which the disposal facility and its environment will be monitored, and access to the facility will be controlled. Bio-intrusion will be minimised, and inadvertent human intrusion will be prevented during this period. The approaches to be employed will be described in the CAMP (which is currently under development) but will likely include approaches such as fencing and maintenance to remove unwanted vegetation. Monitoring will be undertaken to build confidence that the site and engineering are performing as anticipated. During the period of institutional control, the shorter-lived radionuclides will decay significantly so the radiological hazard will decrease. At the end of the PoA, management and monitoring of the facility will cease, control will be withdrawn, and uncontrolled access is assumed to be possible. This is the start of the post-PoA phase.

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[3] The radiological capacity describes the activity that gives rise to calculated risks equal to the GRA risk guidance level. The radiological capacity depends on the radiological fingerprint of the facility when it is closed. This is not known. Therefore, in practice radionuclide capacities are calculated for individual radionuclides. Use of the radiological capacity is then calculated using a Sum of Fractions (SoF) approach, i.e. summing the fractions of radionuclide inventory / radionuclide capacity for all the radionuclides present.

The 2017 PCRSA and this addendum assume that at this time the CLESA site will be released for unrestricted use, albeit controlled by the planning regulations of the time. Planning covenants and societal memory may initially limit the range of activities that occur at the site, and the resultant potential impacts, but the 2017 PCRSA and this addendum cautiously assume the only factors that influence use of the site are its characteristics and setting.

Based on the historic rate of disposals, with valley development it is estimated that the volumetric capacity of the facility will be used by around 2036. Consistent with the CLESA ESC (Sellafield Ltd, 2021a), the 2017 ORSA and PCRSA (AECOM, 2017a,b), and the ORSA addendum (AECOM, 2022a) the PoA is assumed to end at 2120 AD. Plans for Permit surrender will be linked to the Site End State and plans for surrendering the Permit for the Sellafield site, which could be in whole or at different times for different areas of the Sellafield site. Therefore, the exact date will be refined in the future as the Sellafield Site End State is progressively developed, but also in response to the evolution and performance of the facility during the period of institutional control, which will give confidence that the facility would be passively safe in the long-term. The performance and safety of the facility needs to be evaluated both in isolation, and in the wider context of the Site Wide Environmental Safety Case (SWESC) for all radioactive substances (whether disposed waste or contaminated ground or groundwater) remaining on and adjacent to the site.

During the period of institutional control, the radioactive inventory in the site will decrease due to radioactive decay. However, the inventory remaining at the end of the period of institutional control could still be a potential hazard. This hazard will generally continue to decrease during the post-PoA phase due to continuing radioactive decay, although for some radionuclides the hazard can increase due to the ingrowth of radioactive progeny. Ingrowth is accounted for in the assessment calculations presented in this PCRSA addendum.

The coastline is not notably eroding in the Sellafield area at present. However, it is anticipated that this will change in the future in response to climate change and sea-level rise. The coastline should not be expected to simply recede to the topographic contour that corresponds to the new sea-level. Instead, the coastal geomorphology is expected to evolve towards a new equilibrium state that reflects the altered sea-level, wave and sediment dynamics. The combination of increased sea-level and a likely increase in the frequency of storm events is expected to result in net offshore removal of sediment. Ultimately CLESA is likely to be disrupted by coastal erosion.

Disruption and dispersion of the wastes by coastal erosion will change the expected exposure situations and increase the impacts of the site compared with the general trend of decreasing risks expected during the post-PoA phase. However, once the facility has been completely eroded the impacts from the remaining radioactivity, which would be dispersed in the local coastal environment, are expected to return to their general decreasing trend.

3. System Description

3.1. Valley Development

At this stage only an outline concept has been developed for the approaches that would be used to develop, operate and close the valley area. A full conceptual design that would subsequently form the basis for preliminary and detailed design, is currently under development.

SL has estimated that extending CLESA into the valley area could provide up to around an additional 28,000 m^3 of disposal capacity. This would increase CLESA's volumetric capacity from 120,000 m^3 to around 148,000 m^3, which could support ongoing disposals for several additional years. The increase in the plan area would be about 3750 m^2, which is approximately 26% of the plan area of the existing facility.

The approximate extension to the base of the landfill is shown in Figure 2. The outline concept assumes the existing side slope liner would be extended across the valley area, allowing leachate to drain from the valley area to the cell sumps in the existing disposal area. This approach would be more straightforward to engineer than building a flow divide between the existing disposal area and the valley area, which would require installation of leachate management infrastructure in the valley area. Part of the valley area capacity extends vertically above the existing side slope liner, due to the slope of the valley sides. The side slope liner only needs to be extended over the part of the valley area that is southeast of the existing liner.

The design of the valley area liner is under development. The valley area liner would have a slope of around 1:6.5, compared with around 1:3 for the existing side slope liner. The initial concept is the valley area liner would be similar to the side slope liner, which from top to bottom comprises:

- 0.5 m thick geogrid reinforced soil protection layer.
- Non-woven protector geotextile / drainage geocomposite.
- 2 mm thick high density polyethylene geomembrane liner.
- Geosynthetic Clay Liner (GCL).

The EA has commented that they view the valley area liner as a side slope liner. However, it will be necessary to build confidence that a liner similar to the side slope liner will provide adequate leachate containment in an area that is less steeply sloping than the side slope. If there is not sufficient confidence in performance, the valley area liner could be optimised to be more similar to the liner in the basal part of the existing disposal area, which from top to bottom comprises:

- 100 mm thick sand protection layer.
- 2 mm thick high density polyethylene geomembrane liner.
- 500 mm thick bentonite enriched sand (BES) barrier, engineered to achieve a maximum permeability of 5×10^{-10} m/s.

If the valley area liner is similar to the liner in the basal part of the existing disposal area, then the volumetric capacity for waste will be reduced. For this PCRSA update we have assumed the valley area liner is similar to the side slope liner as this is consistent with Sellafield Ltd's initial plans, and this assumption maximises the volume of waste and therefore the potential radiological impacts. The outputs from this PCRSA addendum can be fed into optimising the valley area liner.

The profiles of the top of the waste, and the final restoration profile are shown in Figure 3 and Figure 4, respectively. A northwest to southeast cross section (Figure 5) shows the extent and slope of the extended liner and illustrates where wastes disposed to the valley area would be placed vertically above the existing side slope liner.

Some of the existing Calder Landfill and Calder Landfill Extension wastes would have to be reworked to provide the required profile for the valley liner, marry the valley area into the landfills, and maximise the volumetric capacity of the valley area. Reworking would involve excavating some of the wastes (cut) and then depositing them elsewhere in the facility (fill). This is illustrated by Figure 5, which shows locations where the valley area liner cuts through the current topography or is 'hanging' above the current topography. The volume of material that needs to be reworked is around 4,000 m^3. Note that there would be no removal of existing wastes for disposal to offsite facilities. Any cut materials that could not be used as fill would be disposed elsewhere on the Calder tips site. Assuming there are no authorisation restrictions on where cut materials can be reused as fill, the initial estimate is that 600 m^3 of cut materials could not be reused.

The following assumptions were made for the ORSA addendum (AECOM, 2022a) and are retained for this PCRSA addendum.

- The existing disposal area and the valley extension would be operated as a single phase.
- Wastes could be disposed to the valley area from when it is first available (i.e. the liner and any other supporting engineering has been emplaced and verified). Disposals to the valley area could begin before the existing disposal area is full.
- During the operational phase, surface runoff from the valley area would be managed in the same way as surface runoff from the existing disposal area. Runoff from the valley area would be directed downslope where it would mix with runoff from the existing disposal area and would then drain to the basal cell sumps in the existing disposal area. Runoff mixes with leachate in the sumps before being pumped to the discharge route.
- Leachate would be discharged via the current route (the Calder Interceptor Sewer, CIS[4]).
- The planned closure cap would be extended over the valley area, following the restoration profile already approved by the planning authority.

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[4] There are occasional discharges via the Sewage Treatment Works e.g. when leachate samples are being taken and when performing the extract pump capacity tests.

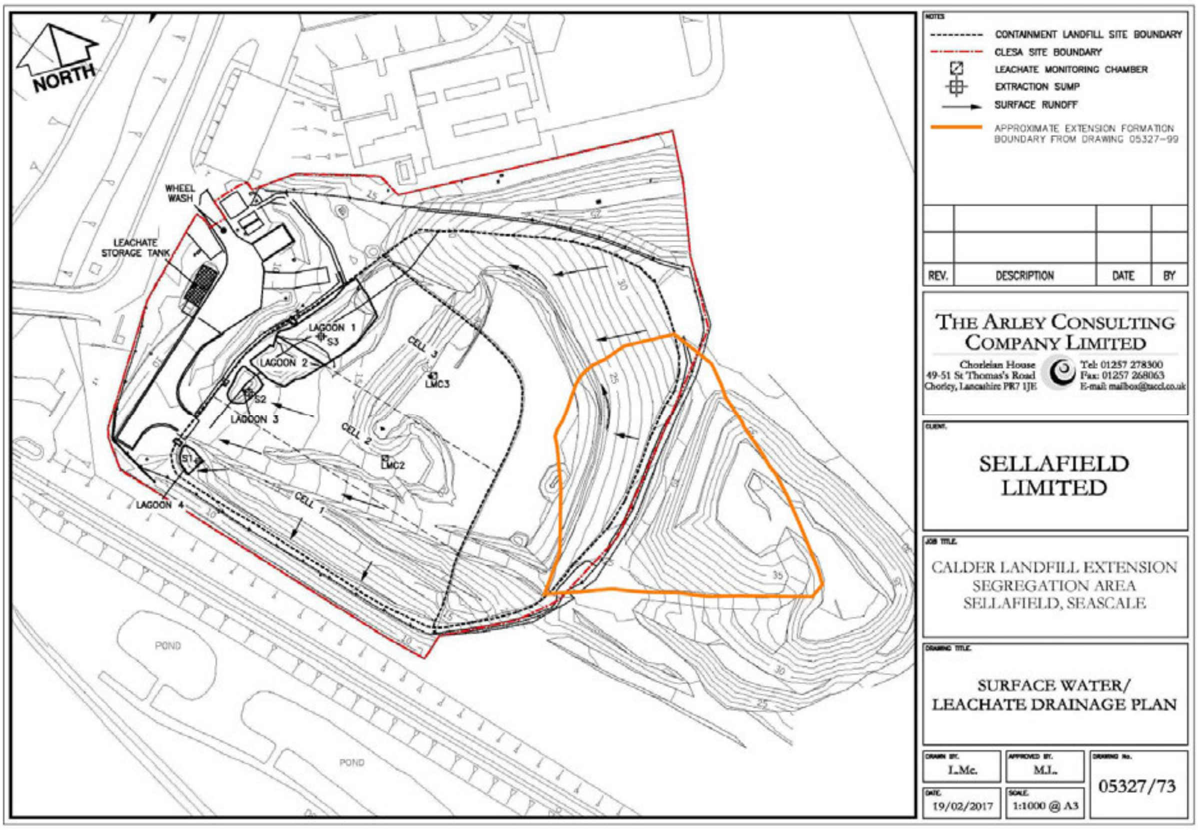

Figure 2. Extension of the base of the landfill

Figure 3. Possible top of the waste profile

Figure 4. Restoration profile

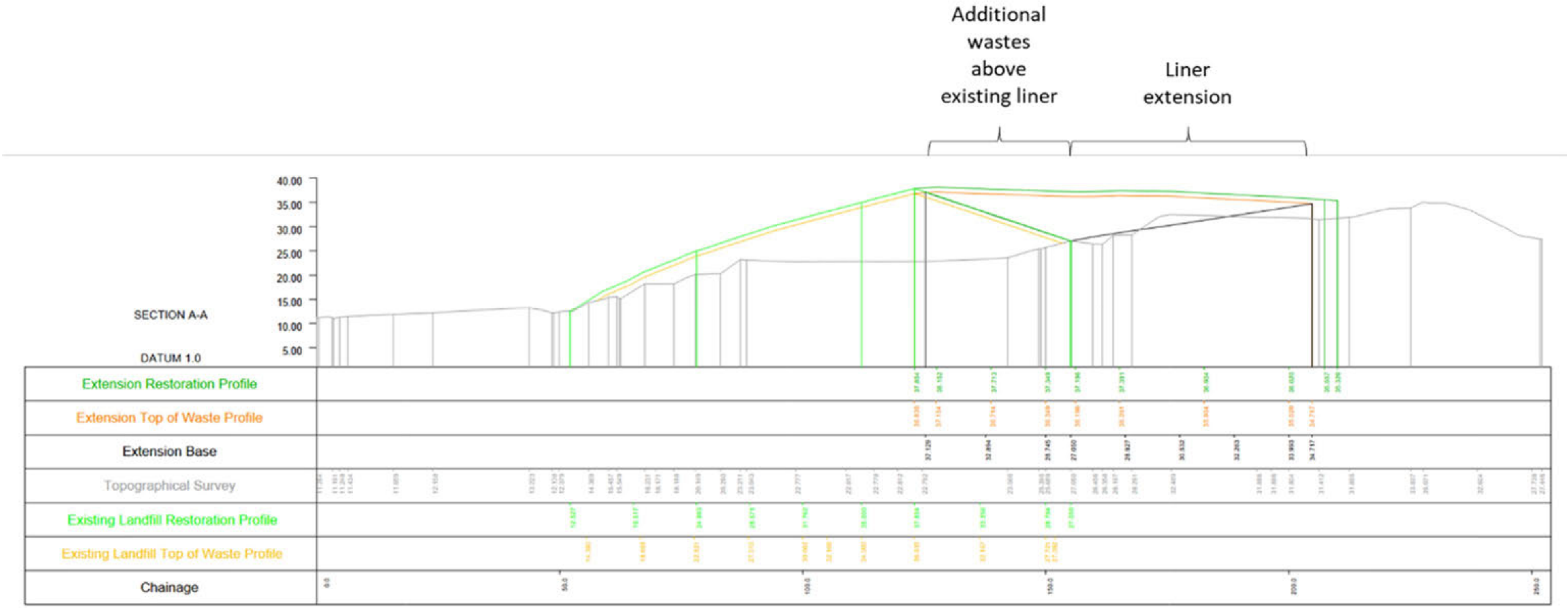

Figure 5. Cross-section A-A (see Figure 4)

3.2. Waste Characteristics

The wastes disposed to CLESA mainly comprise soil and spoil, with a smaller portion of demolition wastes (e.g. concrete and bricks), a small amount of organic material (dewatered sewage sludge, material from gutters, etc), and a very small amount of Man-Made Fibres (MFF) / Rockwool (AECOM, 2017a). The 2017 PCRSA (AECOM, 2017a) used the measured waste volume and records of the disposed mass to estimate the *in situ* bulk density and porosity of the wastes: 2030 kg/m^3 and 0.23, respectively. The PCRSA and ORSA assessment calculations made the simplifying assumption that the wastes are fully water saturated.

Review of the extended disposals dataset gives a similar *in situ* bulk density (2050 kg/m^3). This is within the variability that might be expected over time, therefore an *in situ* bulk density of 2030 kg/m^3 has been retained for consistency with earlier assessments. An improved estimate of other waste properties has been made for the updated assessments, recognising that the wastes are likely to be only partially water saturated, and to give an improved estimate of the dry bulk density for radionuclide sorption calculations. The updated waste properties are given in Table 1.

Table 1. Waste properties

Property	**Value**	**Notes**
In situ bulk density	2030 kg/m^3	From disposal data
Field capacity	0.2	Assumed value based on value for loam soils (mix of sand and clay). Assume in situ density correlates to wastes at or close to field capacity.
Water saturation at field capacity	0.8	Field capacity divided by porosity
Porosity	0.25	Estimate from comparison of *in situ* density and grain density of quartz (a major component of soils and spoil)
Dry bulk density	1830 kg/m^3	Dry bulk density needed to give the measured *in situ* density with the porosity and residual water saturation noted above

3.3. Radionuclide Fingerprint and Inventory

The 2017 PCRSA estimated the inventory in existing disposals using the electronic disposal records. The total disposed alpha and beta activity was available from electronic records, but the full radionuclide fingerprint of the existing disposals was not available as it is recorded in archived paper reports. The total alpha and beta activity was therefore partitioned between radionuclides using the fingerprint for CLESA disposals (2Y57) reported in the UK Radioactive Waste Inventory (UKRWI). The 2Y57 fingerprint is derived from disposals to CLESA from 22 projects where the full radionuclide fingerprint was recorded electronically.

The 2017 PCRSA assumed all future disposals would be at the maximum activity Permitted at that time, which was 37 Bq/g. These disposals were assumed to have the 'PCRSA fingerprint'. The PCRSA fingerprint differs from 2Y57 and is a generic radionuclide fingerprint developed for the original PCRSA (Nexia, 2006) that was considered representative of the wastes that might be disposed at CLESA.

Subsequent to receiving a Permit with higher radionuclide activity limits (Section 1), SL has tracked full fingerprints electronically. SL has disposed wastes from a number of projects with average consignment activities greater than 37 Bq/g. There have also been disposals of surface contaminated concrete blocks from the Windscale Pile chimney and disposal of a concrete mortuary containing a higher level of H-3 (around 0.5 TBq).

Disposal data from recent projects are still being collated, but the available records provide a more realistic insight into the potential activity levels and fingerprints of future disposals. Records that are still being collected are typically from higher volume, lower activity disposals, so the available records from recent disposals are likely biased towards higher activity disposals[5].

The activity levels and fingerprints of four waste types are compared in Figure 6 to Figure 9:

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[5] The data presented below are also presented in the 2022 ORSA addendum. Subsequent to the 2022 ORSA addendum, some additional disposal records have become available. These have an average activity of 3 Bq/g, supporting this statement.

- Disposals to 2020, which are typified by the 2Y57 fingerprint.
- Disposals post-2019 excluding the tritium mortuary and Pile chimney blocks.
- Disposals post-2019 excluding the tritium mortuary but including the Pile chimney blocks. (Note some of the Pile chimney blocks were disposed in 2019, but they have been included in this category as they do not have the 2Y57 fingerprint).
- The PCRSA fingerprint with a total activity of 37 Bq/g.

The average activity in post-2019 disposals is 27 Bq/g including the Pile chimney blocks and 17 Bq/g excluding the pile chimney blocks. The average activity in the Pile chimney blocks is 48 Bq/g. The average activity in disposals post-2019 is considerably higher than the average activity of disposals to 2020, which had an average activity of 2 Bq/g, but also lower than the total activity of the PCRSA fingerprint (37 Bq/g). Note the post-2019 data are considered to be biased towards higher activity disposals as data for higher volume, lower activity disposals are currently being collated.

Disposals post-2019 have a higher proportion of beta / gamma activity and a lower proportion of alpha activity compared with earlier disposals and the PCRSA fingerprint (Figure 7), and a lower average alpha activity concentration than earlier disposals (Figure 6). The concentrations of some of the key radionuclides are compared in Figure 8 and Figure 9. The beta-gamma activity in post-2019 disposals is dominated by Cs-137 and H-3. Much of the Cs-137 is associated with the Pile chimney blocks. Post-2019 disposals contain less Pu-241 than the PCRSA fingerprint and 2Y57 fingerprint. The beta-gamma fingerprint of recent disposals is anticipated to result in lower calculated operational and post-closure impacts than the PCRSA fingerprint and 2Y57 fingerprint, due to the higher content of H-3 and lower content of Pu-241.

The alpha activity in post-2019 disposals contain higher proportions of Ra-226 and Th-232 than the PCRSA fingerprint and the 2Y57 fingerprint, and lower proportions of U-238 and Pu-239 compared with the PCRSA fingerprint. The alpha fingerprint of recent disposals is anticipated to result in higher calculated operational and post-closure impacts than the PCRSA fingerprint and 2Y57 fingerprint, due to the higher content of Ra-226 and Th-232.

Based on the comparison it is more realistic to assume future disposals have an average activity of 37 Bq/g (somewhat cautious based on disposals to date) and a fingerprint based on recent disposals, including the Pile chimney blocks, but excluding the tritium mortuary because this is an outlier. This is expected to give an improved estimate of the potential impacts than the inventory assumed for future disposals in the 2017 PCRSA.

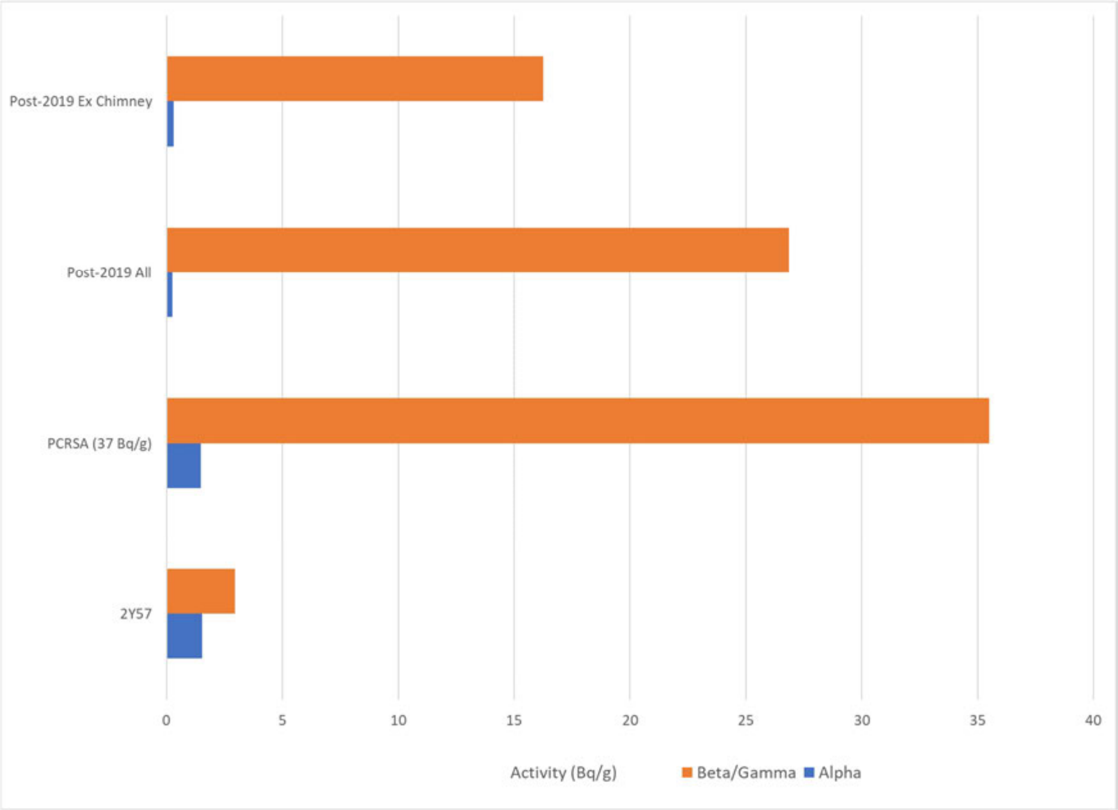

Figure 6. Activity concentrations (for clarity the PCRSA fingerprint scaled to 200 Bq/g is omitted)

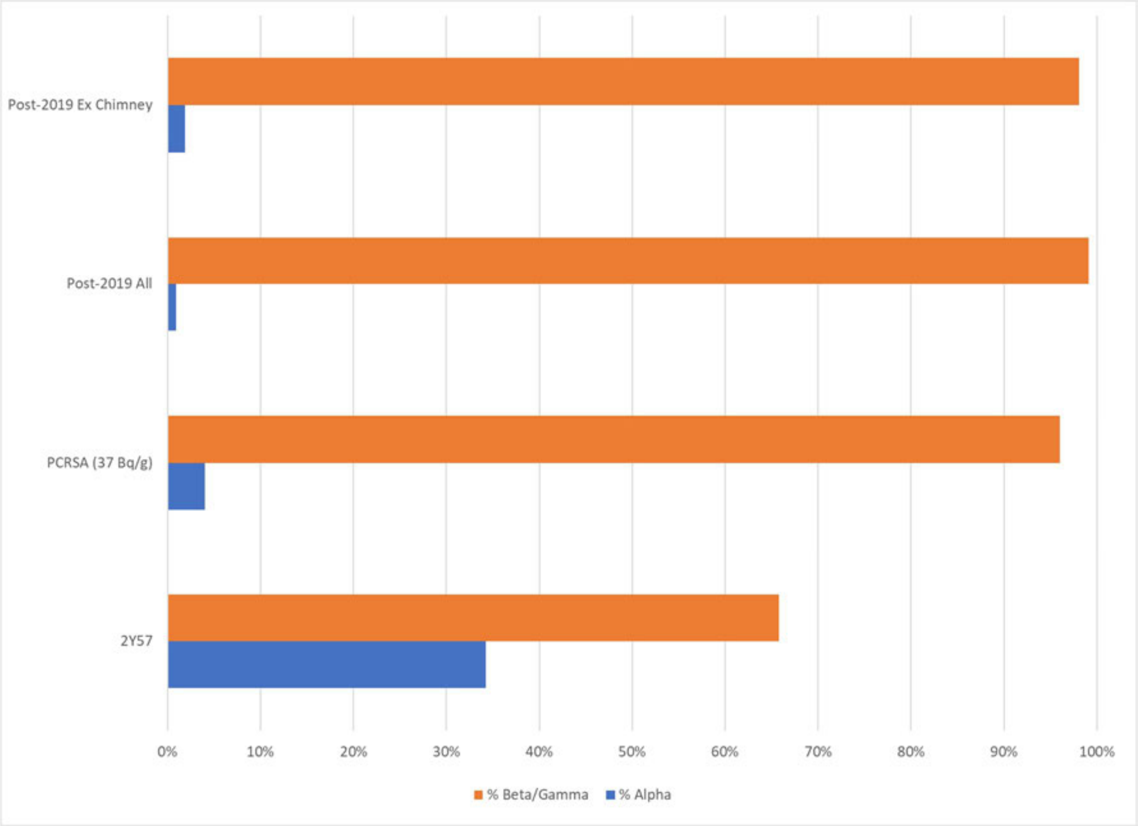

Figure 7. Activity proportions (PCRSA fingerprint with 200 Bq/g as PCRSA fingerprint with 37 Bq/g)

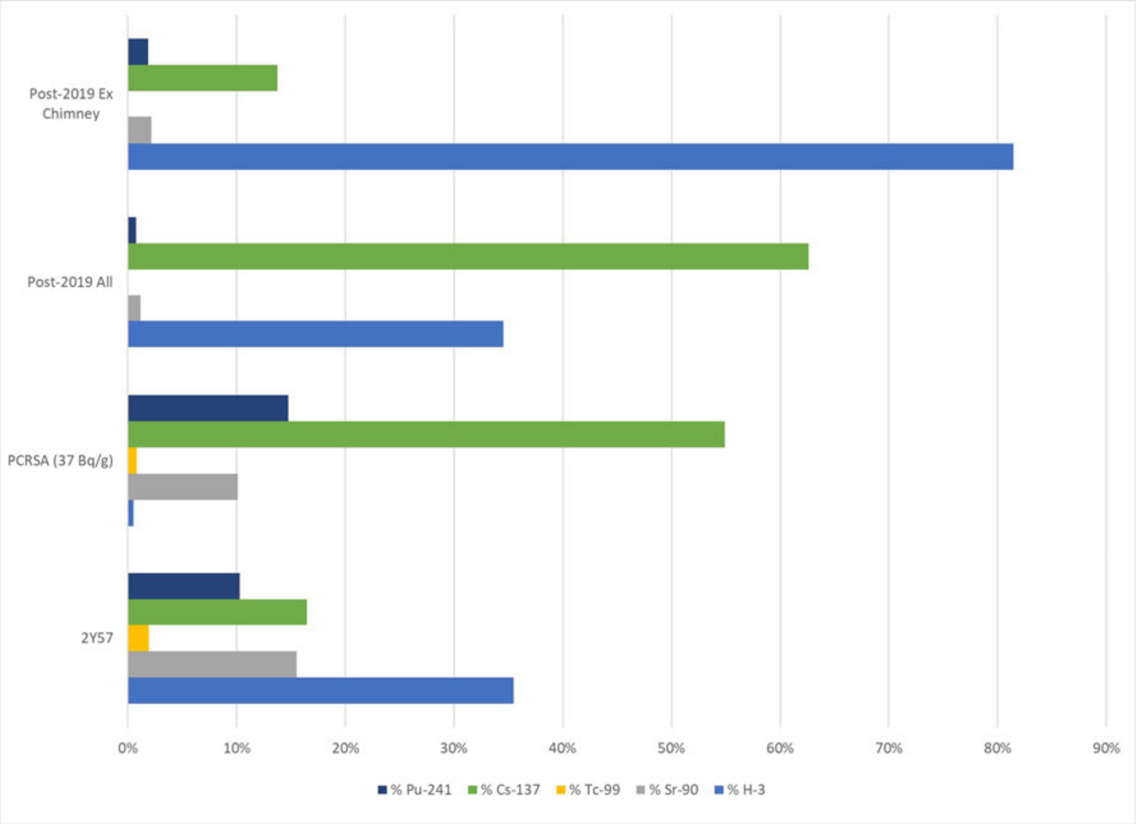

Figure 8. Proportions of key beta/gamma radionuclides (PCRSA fingerprint with 200 Bq/g as PCRSA fingerprint with 37 Bq/g)

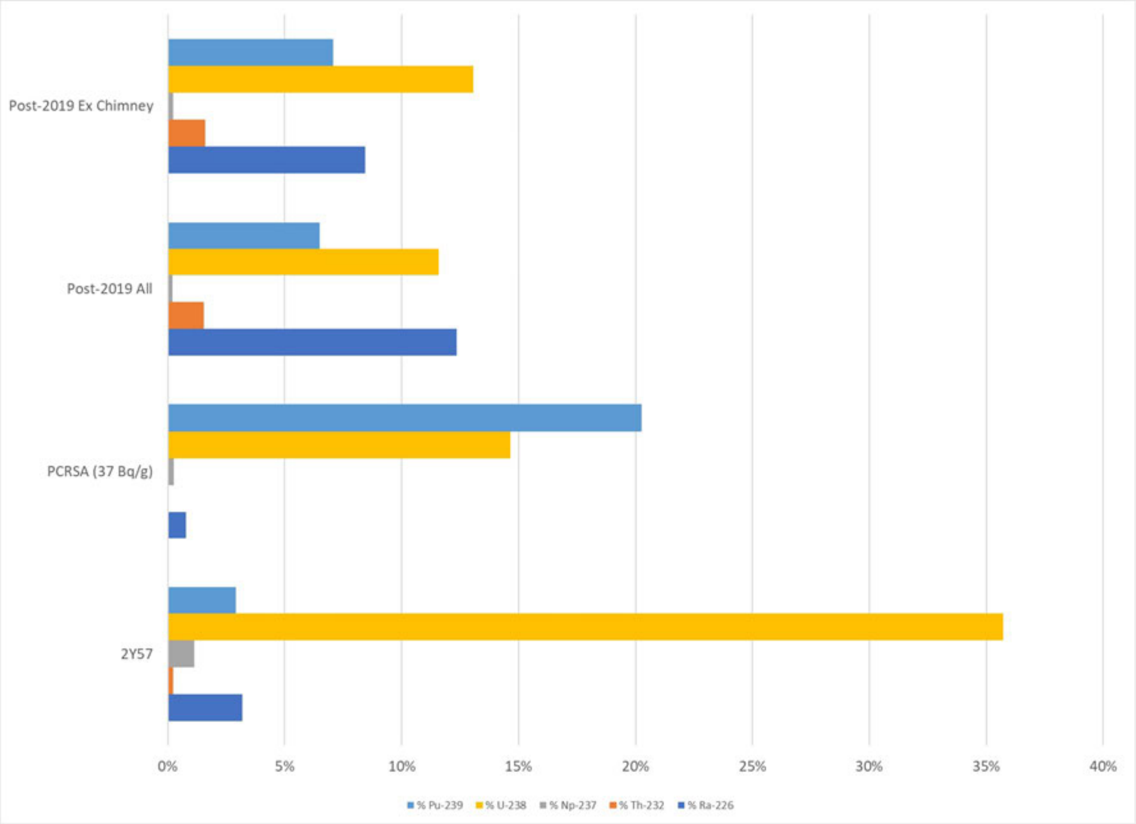

Figure 9. Proportions of key alpha radionuclides (PCRSA fingerprint with 200 Bq/g as PCRSA fingerprint with 37 Bq/g)

The existing and potential future inventories, and the assumed fingerprint of future disposals, are detailed in Table 2.

Permitted disposals to CLESA include a Ra-226 activity limit of 0.35 Bq/g in the top 3 metres of disposals in the top plane of the facility. This limits potential exposures from Rn-222 gas in the situation where a house is built on the facility at a time after the end of the PoA. The Ra-226 activity in the assumed fingerprint of future disposals is around an order of magnitude below this limit.

The 2017 PCRSA assessed the site occupant and smallholder intrusion events originally considered in the Low Level Waste Repository (LLWR) 2011 ESC. It noted that these events are unlikely for CLESA due to the small size of the facility and steep slope of the cap. Therefore, they were not used as a basis for setting activity limits. However, if they were applied, they would require activity limits to be lower than 200 Bq/g to a depth of around 3 m below the surface of the cap (AECOM, 2017a) to ensure that intrusion dose criteria set out in the GRA are met.

Extension of CLESA into the valley area means that CLESA wastes would be present below the relatively flat area at the crest of the cap. This increases the potential for an intrusion event with some similarities to the LLWR site occupant and smallholding events, although these events are still not directly applicable to CLESA. This PCRSA addendum therefore calculates the potential doses from a CLESA specific site occupancy event, which assumes the fingerprint for future disposals described in Table 2, and includes consumption of some foodstuffs grown on the cap. Then the implications for activity limits in shallow disposals below the crest of the cap are described.

Note that independent of this assessment, SL have stated that it should be plausible to optimise the emplacement strategy by managing receipt of some VLLW for placement at the top of the facility below the crest of the cap. The *in situ* thickness of material that it would be possible to manage for placement below the crest of the cap has not been assessed.

Table 2. Existing and potential future inventory, and assumed fingerprint of future disposals

Radionuclide	Existing disposals (TBq)		Potential future disposals (TBq)		Assumed fingerprint of future disposals (Bq/g)
	2003-2019	Post-2019*	Existing disposal area	Valley area	
Am-241	2.66E-03	1.07E-04	5.33E-03	3.13E-03	5.52E-02
Am-242m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C-14	1.86E-03	3.85E-04	1.93E-02	1.13E-02	1.99E-01
Ce-144	7.99E-04	6.87E-06	3.43E-04	2.02E-04	3.55E-03
Cl-36	3.20E-03	1.35E-05	6.74E-04	3.97E-04	6.98E-03
Cm-242	5.24E-05	1.68E-07	8.41E-06	4.95E-06	8.70E-05
Cm-244	2.66E-04	1.02E-06	5.08E-05	2.99E-05	5.25E-04
Co-60	2.93E-03	3.43E-05	1.72E-03	1.01E-03	1.78E-02
Cs-134	5.33E-04	1.86E-05	9.29E-04	5.47E-04	9.62E-03
Cs-137	2.90E-02	4.45E-02	2.22E+00	1.31E+00	2.30E+01
H-3	6.23E-02	2.45E-02	1.23E+00	7.21E-01	1.27E+01
I-129	1.07E-03	1.30E-06	6.50E-05	3.83E-05	6.73E-04
Nb-93m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nb-95	7.34E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni-63	3.20E-03	4.11E-05	2.06E-03	1.21E-03	2.13E-02
Np-237	1.07E-03	1.34E-06	6.71E-05	3.95E-05	6.94E-04
Pa-231	2.89E-03	4.82E-05	2.41E-03	1.42E-03	2.50E-02
Pb-210	2.89E-03	4.82E-05	2.41E-03	1.42E-03	2.50E-02
Pm-147	1.33E-03	1.61E-05	8.04E-04	4.73E-04	8.32E-03
Pu-238	1.33E-03	1.51E-05	7.56E-04	4.45E-04	7.82E-03
Pu-239	2.66E-03	4.15E-05	2.08E-03	1.22E-03	2.15E-02
Pu-240	2.40E-03	4.90E-05	2.45E-03	1.44E-03	2.53E-02
Pu-241	1.81E-02	5.45E-04	2.72E-02	1.60E-02	2.82E-01
Pu-242	1.14E-04	3.26E-08	1.63E-06	9.58E-07	1.69E-05
Ra-226	2.93E-03	7.89E-05	3.94E-03	2.32E-03	4.08E-02
Ru-106	5.33E-04	2.24E-05	1.12E-03	6.59E-04	1.16E-02
Sr-90	2.72E-02	8.17E-04	4.08E-02	2.40E-02	4.23E-01
Tc-99	3.46E-03	4.59E-06	2.30E-04	1.35E-04	2.38E-03
Th-229	0.00E+00	5.26E-09	2.63E-07	1.55E-07	2.72E-06
Th-230	2.66E-04	1.35E-05	6.74E-04	3.97E-04	6.98E-03
Th-232	2.66E-04	9.79E-06	4.90E-04	2.88E-04	5.07E-03
U-233	5.59E-03	1.12E-08	5.59E-07	3.29E-07	5.79E-06
U-234	2.74E-02	1.35E-04	6.77E-03	3.98E-03	7.01E-02
U-235	4.79E-03	4.60E-06	2.30E-04	1.35E-04	2.38E-03
U-236	3.20E-03	2.14E-06	1.07E-04	6.30E-05	1.11E-03
U-238	3.28E-02	7.40E-05	3.70E-03	2.18E-03	3.83E-02
Zr-93	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zr-95	1.28E-06	5.80E-09	2.90E-07	1.71E-07	3.00E-06
Total	2.49E-01	7.15E-02	3.58E+00	2.10E+00	3.70E+01

* Excludes the tritium mortuary containing around 0.5 TBq H-3

3.4. Disposal Operations

The maximum activity in waste consignments disposed before 2020 was 37 Bq/g (except for some blocks disposed from April 2019, which were the first disposals that made use of the new 200 Bq/g Permit limit). Most wastes disposed before 2020 had much lower activities, around 5 Bq/g. These wastes were mostly disposed loose, although a small amount of material was disposed in open top “builders’ bags” for the convenience of the consigner. The bagged material was taken to the landfill and then emplaced using heavy machinery, ripping open the sacrificial bags in the process. The waste was removed from the bags so it could be blended and compacted, allowing the landfill to be built.

Post-2019, consistent with CLESA’s updated Conditions For Acceptance (CFA), wastes above 37 Bq/g (the original maximum activity limit) have been bagged. This is for operational radiological protection while handling, dust minimisation, and to proportionately minimise the potential for water ingress to the waste and subsequent leachate generation.

The planning consent for CLESA has conditions to minimise nuisance. The CLESA operations manual (onefm, 2018) includes controls to minimise nuisance and health issues, including from dust. Radionuclide concentrations in soil are monitored along the south side of the site and the west ring road (Appendix B in Sellafield Ltd, 2021b). Samples from these locations could indicate whether any measurable deposition of radioactivity in windblown dust is occurring.

Bagged wastes have been emplaced carefully to minimise damage, and therefore minimise water ingress into the waste. The ESC (Sellafield Ltd, 2021a) notes that use of bags for disposals with higher activity levels forms part of SL’s waste emplacement strategy, and one of its objectives is to minimise interaction of water with the wastes. This objective is a BAT approach to reduce potential discharges and doses. The safety strategy and ESC are not reliant on the performance of the bags as an engineered barrier.

All waste >37 Bq/g is disposed in a ‘smartlift’ bag. The waste is buried immediately. Single items must be suitably wrapped or bagged. The majority of single items are Pile chimney bocks. These have been disposed in sealed PACTEC bags and mostly[6] placed with their contaminated face downwards. Placing the blocks with their contaminated face downwards provides operational shielding, but also provides another method to help to prevent water interacting with the contaminated surface. A different approach has been adopted for the tritium mortuary due to its large size. The mortuary has been covered with a tarpaulin before being covered with other wastes to further minimise water contact with the mortuary.

Bags and tarpaulins could take several hundred years to break down, depending on their thickness and the material they are made from.

3.5. Water Balance

Work has been undertaken for the 2022 ORSA addendum to improve understanding of CLESA’s water balance, focussing on the amount of water that runs-off the surface of the wastes and the amount of water that infiltrates the wastes.

Significant volumes of rainwater are observed running off the surface of the wastes. This is due to a combination of low waste permeability and operational measures to encourage and capture runoff and minimise infiltration into the wastes, e.g. maintenance of steep slopes and placement of temporary drainage ditches. This water is expected to be relatively clean compared with water that has infiltrated through the wastes. Runoff is directed through surface drains into the sumps[7], where it mixes with water that has drained through the wastes (i.e. leachate), before being pumped for discharge to the sea. In 2017 leachate from CLESA was discharged from the Factory Sewer to the mouth of the river Calder. Subsequently the discharge route has been changed to the CIS, which discharges 800 m offshore.

The improved estimate of the CLESA water balance is summarised in Figure 10.

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[6] Except where the conventional health and safety risks outweigh the benefits of placing blocks with the contaminated face downwards.

[7] A leachate retention system comprising a drainage ditch with headwalls into polysorb crates is used to control the rate of runoff into the sumps.

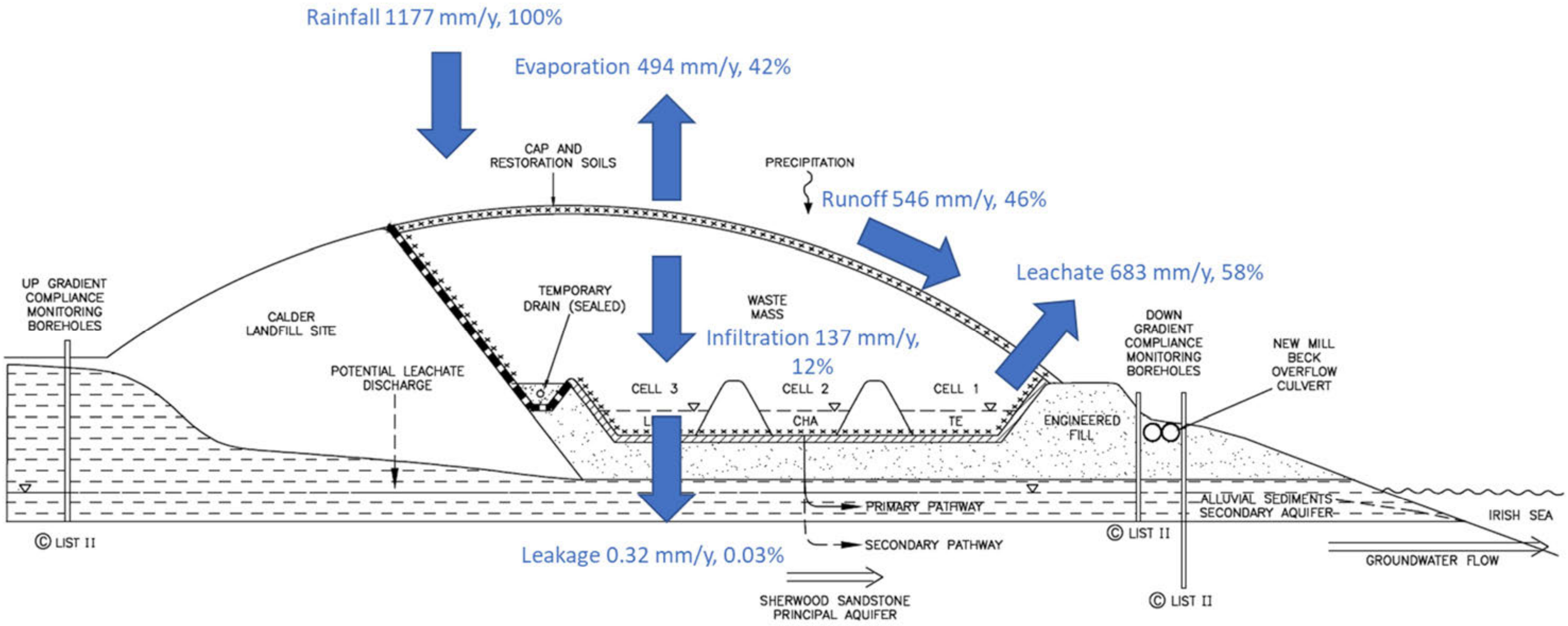

Figure 10. CLESA operational water balance

3.6. Closure Engineering

SL are currently developing an optimised (BAT) design for the closure engineering, including the cap, and a Closure and Aftercare Management Plan (CAMP) for the facility. This work fulfils Improvement Condition S1.2.5 of SL's EPR Permit (KP3690SX). In the absence of a conceptual closure engineering design, the 2017 ORSA and PCRSA (AECOM, 2017a,b) assumed the facility would have a 1 m thick cap and made cautious assumptions about the cap performance and durability:

> *"The CLESA cap would initially have a maximum initial hydraulic conductivity of 1E-9 m/s, which gives an infiltration of 32 mm/year assuming no significant head of water to drive flow through the resistive layer(s). The specification for CLESA's cap has not been developed, but there is increasing evidence that geomembranes will retain performance for several hundred years, i.e. significantly beyond design guarantee timeframes, BES layers may maintain their performance for even longer, and the combined performance of a BES layer and geomembrane may be greater than the summed performance of the individual resistive barriers as has been adopted for the LLWR ESC. For CLESA it is reasonable to assume infiltration through the cap is initially 32 mm/year, but this increases over 300 years until it reaches a maximum of 300 mm/year, i.e. it is assumed the cap has fully degraded by the time the site starts to be eroded."*

The 2017 ORSA and PCRSA noted the infiltration rate is likely to be lower than 32 mm/y when the cap is new, and it is unlikely the cap would be fully degraded 300 years post-closure, e.g. due to the anticipated durability of manmade or natural low permeability cap materials. Therefore, the performance assumptions are cautious in the context of potential radionuclide releases to groundwater.

The 2017 ORSA and PCRSA anticipated that after closure, active leachate pumping would cease relatively early during the period of control. For assessment calculations it was assumed that active leachate pumping stops immediately post-closure. It is still anticipated that active leachate pumping would cease relatively early post-closure, and for assessment calculations the simplifying assumption that leachate pumping stops immediately post-closure is retained.

The 2017 PCRSA assumed that the cap will meet the minimum specification required to minimise the risk of bathtubbing. It also noted that if considered necessary the closure engineering could include passive drainage measures to drain leachate to the geosphere in preference to allowing direct discharge to the surface (i.e. bathtubbing). Therefore, the 'Normal Evolution Scenario, NES' described by the 2017 PCRSA assumed bathtubbing would not occur. The potential impacts of bathtubbing were assessed as an 'Alternative Evolution Scenario, AES' that was considered less likely than the NES.

The draft outcomes from the closure engineering BAT (AECOM, 2023) include two conceptual cap designs to carry forward to the next design stage (Figure 11). Both cap designs are around 1 m thick. Option A is a conventional landfill cap design, and it is anticipated that this would have far better performance and durability than assumed in the 2017 PCRSA. Option C is a non-conventional design, and work is currently being undertaken to refine this option and understand its potential performance. Option C could involve a gravel drainage layer or a Geosynthetic Drainage Layer (GDL) that has a plastic (waterproof) backing. Although performance assessment calculations have not been undertaken, it is initially anticipated that the plastic backed GDL would perform better than a gravel drainage layer and would be preferred. There would be unsealed joins between adjacent GDL panels so infiltration into the waste is expected to be higher than Option A. Leakage might be reduced, but not fully preventing, by overlapping the panels, so water that flows out the side of the panel enters the adjacent panel.

Option C will only be carried forward if the 'as built' performance is at least as good as assumed in the 2017 PCRSA. The performance of the GDL variant of Option C is likely to degrade after several hundred years due to clogging because the GDL is thin, and therefore the volume of deposits needed to clog the channels in the GDL is low. Significant clogging would begin as the GDL's geotextile cover layer degrades, allowing sediment to enter the GDL. The lifetime of the GDL cover layer is uncertain but is anticipated to be several hundred years. The GDL could also weaken as it degrades, and compress under the weight of the overlying soils, thereby restricting flow within its layers as well as reducing the volume of sediment needed to clog the channels.

Updated water balance information (Section 3.5) indicates that infiltration into the (unvegetated) waste mass is around 137 mm/y. Therefore, even when the cap has fully degraded infiltration into the wastes is not likely to be higher than around 137 mm/y, rather than the 300 mm/y assumed in the 2017 PCRSA. Infiltration through the vegetated cap soil layer could be less than 137 mm/y due to additional loss of water by transpiration. Vegetation can reduce surface runoff by increasing surface roughness and increasing permeability of the surface. However, this will tend of be compensated for by increased runoff as interflow through the surface soils. Overall, with a fully degraded cap, infiltration into the wastes is likely to be <137 mm/y (under present day climate conditions).

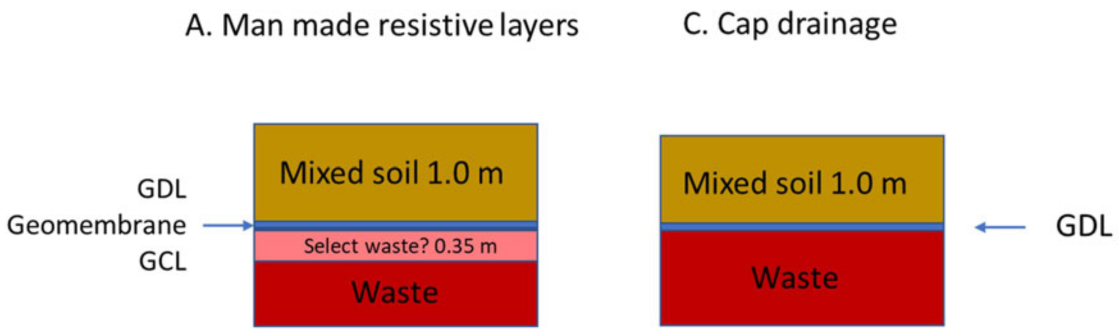

Figure 11. Conceptual cap design options

The performance of Option A might be sufficient to prevent bathtubbing from occurring. Bathtubbing is expected to occur with Option C, but the volumes of water discharging the ground and ground surface would be limited by the cap. For both cap options, passive drains could be used to capture and direct overtopping waters to the groundwater pathway in preference to discharging to the ground surface and surface soils. The cost of Option A plus passive drains might be disproportionate to the hazard of CLESA, so passive drains might not be preferred with Option A. However, Option C is expected to be less expensive than Option A, so use of passive drains is more likely to be proportionate with Option C.

There is confidence the closure engineering performance would be better than assumed in the 2017 PCRSA, but Options A and C could have significantly different performance. Therefore, performance assumptions are updated to be more realistic than assumed in 2017 but remain cautious as the preferred closure engineering design is still being developed. The updated closure engineering performance assumptions are:

- The cap is 1 m thick.
- Infiltration through the cap ‘as built’ is 32 mm/y.
- Infiltration through the degraded cap is 137 mm/y.

The manmade cap components are expected to have lifetimes of hundreds to potentially more than a thousand years in CLESA:

- The components would be protected from the weather, UV light, and oxygen.
- The waste contains little organic material and has been compacted into place, so there should be little settlement and low strain on the cap components.
- Geomembranes are expected to remain flexible and accommodate small settlement strains for hundreds of years to more than one thousand years (e.g. Needham et al., 2004; Rowe, 2022).
- The components will be in a chemically benign environment.
- However, as noted above, there could be clogging of a GDL on timescales of a few hundred years. Also, the steep slope of the CLESA cap would place the manmade components under greater strain from their own weight compared with facilities with shallower cap slopes. This would tend to reduce their lifetimes.

Overall, if, as assumed in the 2017 PCRSA, disruption of CLESA by coastal erosion begins 300 years post-closure, with Option A the cap could still be performing well, but with Option C it could be significantly degraded.

Updated timescales for the assessment scenarios are further discussed in Section 4.

3.7. Resource Potential

Only low-grade materials are disposed to CLESA with limited potential post-PoA resource value, e.g. as bulk fill material for landscaping. Although CLESA is very visible it is difficult to link this to the probability that materials would be recovered and reused, and when this could occur.

Significant processing, sorting and segregation would be needed to create materials of higher resource value, e.g. clays and clean sands. Concrete blocks could potentially be crushed to provide aggregate and hardcore. The potential opportunities to recover and reuse materials are considered in the assessment scenarios (Section 4).

3.8. Coastal and Riverine Evolution

It is anticipated that CLESA will be disrupted by coastal erosion. The wastes could also be exposed by riverine erosion on similar or shorter timescales.

The 2017 PCRSA used a best estimate assumption that disruption of CLESA by coastal erosion would begin around 300 years post-closure (2330). People might choose to protect the railway line from erosion for a period, and the railway embankment and the culverted section of Newmill beck would provide some additional resistance to erosion compared with the natural materials. These factors were accounted for in the best estimate of around 300 years.

The 2017 PCRSA used sea-level rise projections from the LLWR 2011 ESC and reviewed them against updated projections from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, AR5 (IPCC, 2013). The projections were used to inform a semi-quantitative assessment of the vulnerability of CLESA to coastal and riverine erosion, and the potential timing of erosion. AECOM (2017a) noted the emissions scenarios considered in the 5th IPCC report result in similar sea-level rises for the next few hundred years to those described for the LLWR 2011 ESC. However, they do not lead to the extreme long-term sea-level rises considered in the LLWR 2011 ESC.

There have been significant developments in understanding of sea-level rise, coastal and riverine evolution since the 2017 PCRSA:

- UKCP18 has provided updated climate projections for the UK to 2100, and sea-level level rise projections to 2300 using an ‘exploratory’ approach.
- ONR et al. (2022) have provided a position statement on use of climate projections including UKCP18.
- The Intergovernmental Panel on Climate Change (IPCC) has released their Sixth Assessment Report (AR6) (IPCC, 2021).
- SL has initiated work to improve its understanding of coastal erosion of the Sellafield site and evolution of the rivers (Calder and Ehen) and surface water courses (including Newmill beck).

The low sea-level rise projection used in the 2017 PCRSA is within the range described by UKCP18, while the high sea-level rise projection is greater than the maximum described by UKCP18 (Table 3).

Table 3. Comparison of sea-level rise projections from the 2017 PCRSA relative to the year 2000 AD, and from UKCP18 relative to the 1986-2005 baseline

	2017 PCRSA*		**UKCP18**[8]	
Year	**Low estimate (m)**	**High Estimate (m)**	**Low estimate (RCP2.6) (m)**	**High Estimate (RCP8.5) (m)**
2000	0	0	0	0
2100	0.14	0.74	0.14 to 0.56	0.34 to 0.94
2300	0.35	5.26	0.13 to 1.78	0.91 to 3.70
2500	N/A	N/A	N/A	N/A
3000	1.1	21.1	N/A	N/A

* Values after data in Towler et al. (2011) citing Fish et al. (2010). Levels for 2300 AD interpolated by AECOM (2017a).

Nuclear site regulators have set out a position statement on the use of climate projections (ONR et al., 2022). This includes the EA’s expectations:

“Flood Risk Assessments: Climate Change Allowances” guidance (Ref. 6), states that a range of likely climate change scenarios should be assessed, covering peak rainfall intensity, peak river flow, sea level rise, offshore

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[8] https://www.metoffice.gov.uk/research/approach/collaboration/ukcp

wind speed and extreme wave height. ***For sea level rise, these should be based on the 70th and 95th percentiles of the RCP 8.5 scenario for the specific cell(s) applicable to the site in question****.*

Sensitivity Studies: H++ is an example of a 'credible maximum' climate change scenario (see below). H++ should be assessed for developments that could be particularly vulnerable to the impacts of climate change, such as major infrastructure projects."

The sea-level rise projections used in the 2017 PCRSA are broadly consistent with these requirements although noting they are likely too extreme at 2300 and later times.

In 2017 LLW Repository Ltd developed a new set of climate change and sea-level rise projections for the next LLWR ESC. These projections are being used by SL in current work to improve understanding of coastal erosion of the Sellafield site and evolution of the rivers and surface water courses. The sea-level rise projections were based on projections from IPCC[9] (2013), combined with longer term projections from the IAEA MODARIA project (IAEA, 2016). Low and high sea-level rise projections were developed.

The 2017 LLWR low and high sea-level rise projections broadly cover the range of the UKCP18 projections, although the high sea-level rise projection is slightly lower than the highest UKCP18 projection for 2300 AD.

The LLWR low and high sea-level rise projections are broadly similar to the IPCC AR6 projections for SSP1.9 and SSP4.5, respectively. The IPCC AR6 projection for SSP8.5 has higher sea-level rise because it includes Marine Ice Sheet Instability (MISI) and Marine Ice Cliff Instability (MICI) that could cause additional and dramatic increases in sea-level rise. MISI and MICI were excluded from the IPCC AR5 projections for RCP8.5 because the significance of these processes was very uncertain at the time. Therefore, these processes are not included in the 2017 LLWR high sea-level rise projection.

Overall, the 2017 LLWR sea-level rise projections, which underpin SL's initial coastal erosion and riverine evolution work, are broadly consistent with the EA's expectations, i.e. the low and high projections drive a range of evolution scenarios, and the high projection is broadly consistent with the high percentile values for the UKCP18 RCP 8.5 scenario.

Key draft results from SL's initial coastal erosion and riverine evolution work are:

- Timescales to the start of disruption of CLESA by coastal erosion are longer than considered in the 2017 PCRSA and could be around 1,000 years. There may be a difference of a few hundred years between low and high sea-level rise projections, but this difference is probably similar to the magnitude of the uncertainties.
- Widening of the mouth of the river Calder and meandering would be limited over the next few hundred years. In the high sea-level rise projection, widening of the river mouth could lead to erosion of CLESA beginning in around 1,000 years.
- Extreme flood events could lead to some erosion of CLESA before disruption by coastal erosion begins. It is uncertain whether there would be enough erosion to expose the waste. Potentially damaging flood events would be more frequent under the high-sea level rise projection than the low sea-level rise projection increasing potential to expose the waste, but disruption by coastal erosion is likely to be earlier with the high sea-level rise projection than the low projection, so the wastes are more likely to be exposed by coastal erosion before riverine erosion.

Overall, it is concluded that:

- The low sea-level rise projection used in the 2017 PCRSA is reasonable.
- The high sea-level rise projection using the 2017 PCRSA is potentially too high at 2300, and certainly at later times.
- Disruption by coastal erosion may start later than assumed in the 2017 PCRSA.
- There may be some riverine erosion of CLESA by extreme flood events before the disruption by coastal erosion begins. However, this might not expose any waste.

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[9] IPCC (2013) provides climate change and sea-level projections to 2500 AD, but with the emphasis in climate-change projections being the period to 2100 AD, as well as some sea-level projections for the next few millennia (up to 7000 AD).

- The timescales for significant disruption of CLESA by riverine erosion are similar to the timescales for disruption by coastal erosion.

Updated timescales for the assessment scenarios are discussed in Section 4.

3.9. Exposure Pathways

The potential exposure pathways are unchanged from the 2017 PCRSA. Radionuclides can be transported away from the site as a gas, or through leaching and subsequent transport in groundwater.

Radioactive gases could migrate through the cap by diffusion or by advection within landfill gas. Landfill gas generation is expected to be small due to the low organic content of the waste (TACCL, 2023c), and to have nearly ceased by the end of the period of control because most of the organic materials are expected to have degraded by then. Therefore, diffusion is expected to be the dominant process for migration of radioactive gas post-PoA.

Leachate that drains through the liner is expected to pass sub-vertically through the underlying variably saturated geology and drain into the regional groundwater system. Leachate that enters any passive drains would also be directed into the regional groundwater system below the facility. Subsequent transport would be sub-horizontal, with groundwater containing dissolved radionuclides discharging at the coast, and potentially also to the mouth of the River Calder. Transport of radionuclides in colloids is not expected to be significant because they are expected to be impeded by the liner and Quaternary sediments.

3.10. Receptors, Habits and Potential Exposure Groups

3.10.1. Receptors

The potential receptors are unchanged from the 2017 PCRSA. They are:

- People using the CLESA site once controls have been removed (i.e. the post-PoA phase).
- Users of the coastal and riverine environment.
- Groundwater.
- Non-human biota.

People using the CLESA site could be exposed to radioactive gases released through the cap, through inadvertent intrusion into the wastes, or occupancy of a site contaminated by earlier intrusive activities. People using the coast and riverine environment could be exposed to contaminated groundwater discharges, waste exposed and disrupted by erosion.

The wastes disposed to CLESA are of little economic or aesthetic value. Therefore, it is unlikely there would be deliberate scavenging of materials as the wastes are exposed by coastal erosion. However, it is possible that some material could be retrieved. People could be exposed while retrieving materials, and through exposure to reused materials, e.g. in the unlikely event they are incorporated into the foundations of a house.

The mechanisms leading to human exposures are inadvertent ingestion, inhalation, consumption of contaminated water and foodstuffs, skin contact and external irradiation.

Groundwater can be impacted by leakage through the basal liner and overtopping the liner (bathtubbing), and non-human biota can be impacted by discharges of contaminated groundwater to the foreshore and, or mouth of the river Calder. Terrestrial non-human biota can be impacted by discharges of leachate to the ground surface and surface soils if bathtubbing occurs.

3.10.2. Habits

GRA Requirement R6 (Environment Agency et al., 2009) states that, “*After the period of authorisation, the assessed radiological risk from a disposal facility to a person representative of those at greatest risk should be consistent with a risk guidance level of* 10^{-6} *per year (i.e.1 in a million per year)*”.

The 2017 PCRSA assessed risks to recreational users of the coast. The recreational Potentially Exposed Group (PEG) was considered to have habits representative of those at greatest risk from occupying the eroding coast.

The PEG represents the people who spend the greatest time on the coast, for example a regular dog walker or angler. The recreational PEG is potentially exposed through:

- Exposure to *in situ* and eroding waste when CLESA is disrupted by coastal or riverine erosion.
- Occupancy of any land adjacent to CLESA that is contaminated by bathtubbing prior to disruption by erosion.

Parameterisation of the recreational PEG habits was informed by detail from surveys of how people use the West Cumbrian coast today, logical arguments for how people could occupy and use the eroding site frontage, and comparison against the LLWR 2011 ESC.

Additional habits data have been collected since the 2017 PCRSA, and disposals to the valley area increase the length of the coastline that would be impacted when CLESA is disrupted by coastal erosion. Therefore, habits information collected since the 2017 PCRSA is reviewed and then used to inform updates to the PEGs.

The EA, Food Standards Agency and ONR undertake regular surveys of the habits of people who use the West Cumbrian coast and land adjacent to the Sellafield site. (Currently the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) is contracted to undertake the surveys, so the surveys are colloquially termed CEFAS surveys.) The survey results are used to inform assessments of the doses from radioactive discharges from Sellafield presented in annual Radioactivity In Food and the Environment (RIFE) reports.

The surveys provide information specific to individual beaches along the West Cumbrian coast, including Sellafield beach, and combined information for the whole coastline. The information includes recreational and occupational uses.

In addition to describing the habits of people who use the coast, the surveys describe the time spent undertaking different activities, and the substrates the activities are undertaken on, for example whether fishing is undertaken from a sandy foreshore, or from rocks. Data also includes consumption rates for marine and terrestrial foodstuffs, and the survey responses are analysed to look for correlations between different potential radionuclide exposure pathways, e.g. time spent occupying the coast and consumption rates of marine foodstuffs.

Statistical information is presented including the number of observations, maximum and mean for the high-rate group, and the 97.5th percentile of all observations. The high-rate group is defined as all individuals with occupancy or intake rates above one-third of the highest observed rate for a given habit.

The number of people undertaking some activities on individual beaches can be small, so the statistical measures are not reliable. The statistical measures may be reliable when applied to data for the whole coastline due to the larger dataset. Some activities are undertaken by so few people the survey results are sensitive to who was questioned and changes in their habits, e.g. whether a person did or did not undertake an activity in a given year.

The most recent full survey was in 2018 (CEFAS, 2019), with reviews of shellfish and fish consumption, and intertidal occupancy in 2019 and 2020 (CEFAS 2020, 2021).

The 2018 CEFAS survey (CEFAS, 2019) identifies:

- One person who was angling and maintaining the riverbank on the river Calder and dog walking, and two people who were walking on the beach at Sellafield, within 0.25 km of the nuclear licensed site.
- Two people who were dog walking on Sellafield beach and one person who was angling to the south of the confluence of the rivers at Sellafield beach, between 0.25 km and 0.5 km of the nuclear licensed site.
- 16 people who were walking or dog walking from Seascale to Sellafield on the beach, between 0.5 km and 1 km from the nuclear site boundary.

Occupancy data for these people are presented in Table 4. One person spent 213 hours per year angling on the river Calder, maintaining the riverbank and dog walking. Some of the time would likely have been spent adjacent to CLESA and some further away, but the proportions are not known. Another person spent 70 hours per year angling on Sellafield beach, and it is assumed some of the time would have been adjacent to CLESA.

Table 4. 2018 occupancy rates for people in the Sellafield area (CEFAS, 2019)

Distance from nuclear licenced site	Activity	Hours per year	Notes
>0 to 0.25 km	Angling on the river Calder, maintaining the riverbank and dog walking	213	
	Walking	18	
	Walking	18	
>0.25 km to 0.5 km	Dog walking	104	
	Dog walking	78	
	Angling on Sellafield beach	70	
>0.5 km to 1km	Dog walking	365	
	Dog walking	241	
	Angling on the River Calder and dog walking	213	
	Dog walking	183	3 individuals with the same habits
	Dog walking	182	
	Dog walking	74	
	Dog walking	61	
	Dog walking	52	
	Dog walking	43	
	Dog walking	35	
	Dog walking	26	
	Dog walking	10	
	Dog walking	10	
	Dog walking	10	
	Dog walking	1	

3.10.3. Updated PEGs and Habits

In the 2017 PCRSA the recreational PEG was assumed to have different habits when exposed through coastal erosion, riverine erosion and bathtubbing (Table 5). Although the assessed situations were mutually exclusive, to improve clarity we now describe a recreational PEG, who is assumed to be a dog walker, and a separate angler PEG.

Dog walkers spent up to 365 hours per year on the beach (Table 4). However only a portion of this time would be spent adjacent to CLESA. The walk from Seascale to the mouth of the river Calder is about 2 km. The length of CLESA parallel to the coast, including the valley area, is about 160 m, so around 10% of the time spent walking from Seascale to the Calder and back could be adjacent to CLESA, i.e. 365 hr/y x 0.1 = 36.5 hr/y.

Examining the habits of dog walkers on the wider West Cumbrian coast indicates that there is a group of dog walkers who spend around 730 hr/y (~2 hr/day) on the coast. However, it is likely that a person walking for 2 hr would cover a larger distance than the 2 km from Seascale to Sellafield. Therefore, time spent adjacent to CLESA might not increase significantly compared with the 36.5 hr/y estimated above.

Cautiously, most exposed dog walkers are assumed to spend up to 70 hr/y on the coast adjacent to CLESA. This is an increase in occupancy compared with the 50 hr/y assumed in the 2017 ORSA. Consistent with the 2017 PCRSA, time is distributed across the cliffs, storm beach and foreshore.

The 2017 PCRSA assumed the recreational PEG spends 5 hr/y clambering on the cliffs at the back of the storm beach, formed by the eroding facility, and 45 hr/y on the storm beach and foreshore. Occupancy is divided between the storm beach and foreshore based on their relative areas, noting that on average the foreshore is 50% covered by the sea.

5 hr/y spent clambering on the cliffs was not underpinned by habits information but was considered cautiously realistic noting this behaviour is expected to occur and it involves exposure to the highest radionuclide concentrations. 5 hr/y is 10% of the total occupancy of the eroding site frontage assumed in 2017. Time spent clambering on the cliffs is increased to 7 hr/y, so it is still 10% of total occupancy of the eroding site frontage. The

remaining 63 hr/yr is distributed between the storm beach and foreshore using the same approach as the 2017 PCRSA (Table 5).

There are few data for angling on Sellafield beach. Two people undertake angling and dog walking. The division of time between these activities is unknown. A third person only undertakes angling, spending 70 hr/y on the Sellafield beach. Examining the habits of anglers on the wider West Cumbrian coast, they have similar occupancies to dog walkers, i.e. up to around 2 hr/day. It is assumed that the most exposed anglers could spend up to 70 hr/y on the eroding site frontage. Although anglers could fish from anywhere on the beach and foreshore, occupancy could be biased towards specific locations.

Table 5. 2017 PCRSA and updated PEG habits

PEG	Activity	Occupancy	Notes
2017 PCRSA			
Recreational PEG	Walking on a contaminated coastal path	5 hr/y	Path contaminated by bathtubbing prior to disruption.
	Occupancy of eroding site frontage	Cliffs 5 hr/y Storm beach 4.4 hr/y Foreshore 40.6 hr/y Total 50 hr/y	Time on cliffs assumed. Remaining occupancy distributed between storm beach and foreshore on an area basis, noting the foreshore is on average half covered by the tide.
	Angling on the river Calder	50 hr/y	Wastes exposed by riverine erosion prior to coastal erosion.
2022 Addendum			
Recreational PEG	Walking on a contaminated coastal path	5 hr/y	Path contaminated by bathtubbing prior to disruption.
	Occupancy of eroding site frontage	Cliffs 7 hr/y Storm beach 6.2 hr/y Foreshore 56.8 hr/y Total 70 hr/y	Time on cliffs assumed. Remaining occupancy distributed between storm beach and foreshore on an area basis, noting the foreshore is on average half covered by the tide.
Angler PEG	Angling on the river Calder	70 hr/y	Wastes exposed by riverine erosion prior to coastal erosion.

The 2017 PCRSA also described a beach user, who was assumed to occasionally drink a small amount of the groundwater that discharges to the foreshore. This is a hypothetical activity, i.e. it is not described in habits data. It could be undertaken by the recreational PEG, or it could be a different beach user that only spends a relatively small amount of time on the coast. Therefore, doses from consumption of beach seeps are assessed for a separate PEG. This is now formally termed the beach seeps PEG.

3.11. Uncertainties

Five potentially important conceptual model uncertainties are identified from review of the uncertainties assessed in the 2017 PCRSA, the results of the 2017 PCRSA, and consideration of the new information presented above:

- extent of water contact with the wastes;
- H-3 release rate from the mortuary;
- radionuclide sorption in passive drains;
- potential use of well water; and
- sorption distribution coefficient for Ra in the waste.

3.11.1. Extent of Water Contact with the Waste

Leachate modelling undertaken for the 2017 ORSA indicated there is limited interaction between the wastes and rainwater infiltrating the wastes. It was assumed that infiltration into the wastes is heterogeneous, reflecting spatial variations in temporary slope angles, and spatial variations in waste permeability. It was anticipated that once the facility has been capped infiltration into the wastes would be much lower, and flow through the wastes would be more uniform.

The 2022 ORSA addendum identified that bagging of the higher activity disposals should also limit water contact with the wastes. Although bags might be damaged during and after disposal, they should remain mainly intact and limit leaching from the wastes. Bags could take several hundred years to break down, depending on their thickness and the material they are made from.

The impact of bags on leaching from the wastes is uncertain. It is conceptualised that bags significantly limit leaching during the operational phase, but have much less effect post-capping, as the cap becomes the main feature limiting water contact with the wastes. Therefore, for simplicity the reference assumption is that the bags have no effect on leaching post-capping. This is anticipated to be a cautious assumption because it excludes any isolation of the wastes from infiltrating water provided by the bags, and any containment of leachate within the bags. Although leachate in the bags could have relatively high contaminant concentrations compared with the wider facility, leachate released from the bags would be diluted by mixing with much larger volumes of more dilute leachate in the base of the facility.

3.11.2. H-3 Release from the Mortuary

The concrete structure of the tritium mortuary is designed to limit leaching and contain H-3. However, the structure has been breached by coring to characterise the inventory. Water could infiltrate the core holes in the mortuary, but the tarpaulin that has been placed over the mortuary will provide a barrier to infiltration and flow of water through the mortuary. Therefore, the main mechanism of H-3 release from the mortuary may be diffusion, either to the surface of the mortuary or water filled core holes, rather than leaching.

Comparison of modelled and measured H-3 concentrations in leachate presented in the 2022 ORSA addendum indicate there is some leaching from the H-3 mortuary. Given that the H-3 inventory in the mortuary and other waste will have decayed significantly by the end of the PoA this uncertainty is not expected to have a significant impact on the post-PoA risks. Therefore, the availability of the H-3 inventory in the mortuary is assumed to be same as the availability of H-3 in other wastes, including bagged wastes, i.e. limited by the tarpaulin during the operational phase, but not limited thereafter.

3.11.3. Sorption in Passive Drains

Any passive drains through the unsaturated zone to the saturated geosphere would likely be filled with highly permeable coarse-grained material. The type of material that would be used has not yet been defined or optimised. There could be lower sorption of radionuclides onto these materials compared with the natural geological materials present in the unsaturated zone below the liner, due to lower content of clay and iron minerals.

3.11.4. Potential Use of Well Water

Wells are used along the West Cumbrian coast as small, local sources of drinking water. It is very unlikely that a well would be drilled down hydraulic gradient of CLESA due to the nearby availability of fresh surface water from the river Calder and Newmill beck, and because the quality of the groundwater could be low, e.g. impacted by saline intrusion. Although it is unlikely that a well would be drilled down gradient of CLESA after the end of the PoA, there is a small risk this could occur.

3.11.5. Waste Sorption Distribution Coefficient for Ra

The 2017 PCRSA retained radionuclide sorption distribution coefficients chosen for the original PCRSA. Sorption distribution coefficients are often significantly uncertain. The distribution coefficient chosen for sorption of Ra onto the waste has a significant effect on the calculated impacts if bathtubbing occurs.

4. Assessment Scenarios and Calculation Cases

4.1. Scenarios

Safety assessments typically investigate a number of scenarios that describe a range of future evolutions of the facility. The 2017 PCRSA assessed a Normal Evolution Scenario (NES) which describes the expected evolution of the facility and seven Alternative Evolution Scenarios (AES) which describe other, typically less likely outcomes. These were:

- (Inadvertent) human intrusion.
- Earlier than expected cap failure.
- Early erosion.
- Late erosion.
- Emergent land.
- Materials scavenging and reuse.
- Riverine erosion.

Assessment calculations undertaken for each scenario were structured into a reference case, and variant cases which explore conceptual model and parameter uncertainties.

The updated assessment scenarios and calculation cases are described in the following sub-sections. A new AES has been added: headland formation. The scenarios are summarised in Table 6. The summary descriptions include updates for this addendum, which are further described in Section 4.2.

Table 6. Summary of the scenarios

Scenario	**Summary**
Normal evolution scenario (NES)	
Normal evolution	The closure engineering substantially contains radionuclides in CLESA, maximising decay within the facility. Some activity is released in gas and to groundwater. The performance of the engineering degrades over time, but the cap remains intact isolating the wastes. As the engineering degrades the water level in the facility rises but the closure engineering, which might include passive drains, prevents water discharging to ground surface and surface soils at the perimeter of the cap. CLESA is disrupted by coastal erosion after several hundred years.
Alternative Evolution Scenarios (AES)	
Human intrusion	Three inadvertent human intrusion events are conceptualised. These comprise short-term exposures during site investigation activities or building a house on the crest of CLESA, and long-term exposures from occupying a house on the crest of CLESA.
Earlier than expected cap failure	The cap degrades more quickly than in the NES. If passive drains are present, these are also assumed to fail, e.g. through clogging. This results in bathtubbing of CLESA and discharge of water at the perimeter of the cap.
Early erosion	As the NES but disruption by coastal erosion starts earlier and proceeds more quickly.
Late erosion	As the NES but disruption by coastal erosion starts later and proceeds more slowly.
Emergent land	CLESA is not disrupted by coastal or riverine erosion. After a high-stand, that does not result in erosion of CLESA, sea-level falls below its present-day level and the groundwater pathway discharges to the newly emergent land.
Material recovery and reuse	Although CLESA is very visible it is difficult to link this to the probability that materials would be recovered and reused, and when this could occur. It is unlikely materials would be recovered and reused immediately after the end of the PoA, and for a period thereafter due to societal memory, and potentially planning controls. It is assumed low grade materials could be recovered after a period of around 300 years and used for landscaping or construction, resulting in short-term doses to people involved in materials recovery, and long-term doses to people exposed to the reused materials.
Riverine erosion	Erosion by the river Calder exposes wastes prior to disruption of CLESA by coastal erosion. People angling on the riverbank are exposed to the waste.
Headland formation	As CLESA is eroded, large waste blocks are left behind forming a 'rocky' headland. This is assumed to provide a preferential location for angling.

4.2. Calculation Cases

4.2.1. NES Calculation Cases

4.2.1.1. Reference Case

The NES is largely unchanged from the 2017 PCRSA. The 2017 PCRSA assumed the facility would be closed in the early 2030s (2030 was assumed for assessment calculations) and would remain under control until the end of the PoA at 2120. With valley development the facility would be closed later (assumed to be 2036 for assessment calculations), but the end of the PoA is unchanged.

The NES considers the groundwater, gas and coastal erosion pathways.

Groundwater Pathway

Water that infiltrates through the closure cap leaches radionuclides from the waste and transports them into the underlying groundwater. The performance of the cap decreases as it ages, and infiltration into the waste increases. In the 2017 PCRSA the cap was assumed to be fully degraded at 300 years post-closure, when disruption by coastal erosion was assumed to begin. This was a cautious assumption given that a closure engineering design was not available. It is likely that that cap Option A (Section 3.6) would have good performance for more than 300 years, while the performance of Option C could be reduced over timescales of a few hundred years due to progressive clogging of the GDL. The assumption that disruption by coastal erosion begins 300 years post-closure is retained (see further discussion below). The groundwater pathway assessment calculations retain the cautious assumption that the cap has fully degraded at this time, consistent with anticipated degradation of cap Option C. However, infiltration into the degraded cap is assumed to be lower than considered in the 2017 PCRSA based on the analysis in Section 3.6.

The cap will reduce infiltration into CLESA, however water levels in CLESA are expected to rise over time. Bathtubbing might occur with cap Option A and is expected to occur with cap Option C. The potential for bathtubbing to occur with cap Option A is uncertain, because the ‘as built' performance of Option A is expected to be around, i.e. a little above or a little below, that needed to prevent bathtubbing. Even if the ‘as built’ performance of Option A is sufficient to prevent bathtubbing, the cap is expected to degrade faster than the basal liner, resulting in rising water levels in the facility and ultimately bathtubing. However, CLESA may start to be disrupted by coastal erosion before bathtubbing occurs. Both capping options would reduce the amount of water discharging to the ground surface and surface soils compared with a simple soil cap. If passive drains of the preferred design identified by the closure engineering BAT (AECOM, 2023) are provided, then water should not discharge to the ground surface and surface soils. Water would be directed to deeper groundwater pathways instead (unless there are perched pathways through the waste mass and cap that are not intercepted by the drains). For the NES it is assumed that water does not discharge to the ground surface or surface soils.

Note that the groundwater pathway assessment calculations assume the cap has fully degraded 300 years post-closure[10]. This could imply that significant bathtubbing would occur before disruption by coastal erosion begins. However, significant bathtubbing is not expected to occur before disruption by coastal erosion begins, so the assumption the cap has fully degraded 300 years post-closure only reflects a cautious approach to the assessment calculations for releases to the groundwater. Risks are bounded by the earlier than expected cap failure scenario (Section 4.2.3) which assumes a maximum discharge of water to the ground surface and surface soils.

Radionuclides are transported in groundwater which discharges as freshwater springs to the inter-tidal zone. It is assumed that a beach user (the beach seeps PEG) occasionally drinks a small amount of this water. Marine biota could also be exposed to discharges from the inter-tidal zone springs, and freshwater biota could also be exposed if there is a groundwater pathway to the river Calder. The 2017 PCRSA showed that assuming all future disposals have a total activity of 37 Bq/g, with the PCRSA fingerprint, the dose rates to marine and freshwater biota would be below the chosen screening dose rates to non-human species without taking credit for dilution by river or seawater. Once dilution is accounted for the dose rates would be very low. The updated understanding of the potential future site inventory and the potential additional radiological impacts from development of the valley area are not sufficient to change this result, so dose rates to non-human biota are not reassessed.

Radionuclide discharges in beach springs would result in radionuclides being present in coastal sediments, entering marine waters, and returning to the land in sea-spray. Radionuclides would rapidly be diluted and dispersed by mixing with large volumes of seawater. The original 2006 PCRSA (Nexia, 2006) showed that risks to

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[10] This is considered a cautious assumption for cap Option A given the anticipated lifetime of the geomembrane (Rowe, 2022) and the expectation there will be little settlement or differential settlement of the waste, so little potential for increase in strain.

farmers, fishermen and bait diggers are very low, with peak risks of 1 x 10^{-10} y^{-1}, around an order of magnitude lower than risks from drinking beach seeps. On this basis, the 2017 PCRSA argued that risks to farmers, fishermen and bait diggers do not need to be assessed further. Developments since the 2017 PCRSA, including increased activity limits and proposed development of the valley area could not increase the facility radionuclide inventory sufficiently to change this argument.

The potential for a groundwater well to be located between CLESA and the coast has been identified as an uncertainty (Section 3.11.4). Given the very low likelihood of a well between the facility and the coast, the 2017 PCRSA excluded a well from the NES reference case and it was assessed as a variant case. The EA's comments on the 2017 PCRSA were supportive of this approach, and this approach is retained. NES variant case 1 (Section 4.2.1.2) includes a well.

Gas Pathway

The CLESA inventory would lead to generation of Rn-222 gas, and gases radiolabelled with H-3 and C-14, in particular tritiated water vapour and C-14 labelled methane or carbon dioxide. The 2017 NES assumed a house is built on CLESA following the end of the PoA, and this could lead to exposure to Rn-222 gas and radiolabelled gases.

The 2017 PCRSA noted that low permeability layers in the cap could significantly attenuate Rn-222 until they degrade, for example the time for Rn-222 to diffuse to the locations of small defects in a geomembrane would be significant compared with the half-life. However, construction of a house would inevitably lead to intrusion into the cap, likely penetrating through the cap low permeability layers, and potentially into the waste, which would increase the flux of Rn-222 gas into the house. Therefore, the Rn-222 gas pathway was assessed as an intrusion event.

Valley development increases the potential for development of a house over wastes disposed to CLESA, because the valley area underlies the relatively flat crest of the cap (Figure 4). A conceptual engineering design has been developed for a house on the crest of the cap to underpin the inadvertent human intrusion AES. Although CLESA's closure cap might not have a low permeability layer (Section 3.6) that must be breached (or degrade) to create a Rn-222 gas pathway, the conceptual house design shows that the cap would need to be locally removed to create a suitable area for foundations. Therefore, house construction and the Rn-222 gas pathway are assessed within the inadvertent human intrusion scenario.

H-3 and C-14 have much longer half-lives than Rn-222, so they are not expected to be significantly attenuated by the cap low permeability layers. However, potential exposures to H-3 and C-14 transported via the gas pathway are most significant for a person occupying the site, therefore they are also assessed within the inadvertent human intrusion AES.

Following the end of the PoA, people will be able to freely access the CLESA site. Doses from Rn-222, H-3 and C-14 gases outdoors are expected to be negligible and are not assessed in the NES. For example, assuming future disposals have an average of 50 Bq/g activity with the PCRSA fingerprint, the 2017 ORSA calculated that CLESA operatives spending 376 hr/y on the uncapped wastes would receive a dose of 4.7 µSv from Rn-222. Doses to people accessing (but not occupying) the facility for activities such as recreational use would be lower than this due to attenuation of Rn-222 provided by the cap, and likely lower occupancy rates.

Coastal Erosion Pathway

The 2017 PCRSA assumed CLESA would start to be disrupted by coastal erosion 300 years post-closure. Updated sea-level rise and coastal erosion projections indicate that disruption is likely to be later than assumed in 2017, with erosion of the facility proceeding more slowly (Section 3.8). Riverine erosion could also begin on similar timescales. Work to develop updated coastal erosion projections is still in progress, and the modelled erosion rates are sensitive to sea-level rise assumptions. The results of the 2017 PCRSA show that later erosion results in lower risks, because there is more time for radioactive decay of key radionuclides, and the longest plausible timescales are not sufficient for significant ingrowth. Projections of coastal erosion have substantial uncertainties over timescales of hundreds of years and longer. It is important the PCRSA, and therefore the ESC, includes an appropriate degree of caution so is not sensitive to these uncertainties and future changes to coastal erosion projections. Therefore, the NES cautiously retains the assumption that disruption of the facility by coastal erosion begins 300 years post-closure and is complete 400 years post-closure.

The 2017 PCRSA assessed the potential doses from surface contaminated concrete blocks (and bricks) exposed by coastal erosion. The dose rates from surface contaminated blocks could be higher than from bulk wastes with the same average activity concentration. The potential doses from blocks disposed to the existing disposal area and the valley area are the same.

Subsequent to the 2017 PCRSA it was noted that for certain alpha radionuclides it is mathematically possible for blocks to exist that could comply with CLESA's Permit but result in higher doses than the criterion of 20 µSv from one hour of close inspection. The relevant alpha radionuclides (e.g. Ra-226, Th-232) are only present at trace levels in Sellafield processes and waste streams, so it is very unlikely that blocks that could lead to doses above the target maximum could ever arise. Note the relevant alpha radionuclides are not present in the fingerprint of the Pile chimney blocks.

Valley development increases the opportunity to dispose of blocks to CLESA, although the current Pile chimney project is the only major demolition project that is expected to generate large numbers of blocks while CLESA is operational. It is appropriate to undertake some additional assessments to build confidence that it is very unlikely that doses from blocks would ever exceed the target maximum, as future minor works might generate small numbers of blocks which could be disposed to CLESA, and the timing of future major demolition projects could be brought forward.

The 2017 PCRSA showed that risks from exposure to relatively active particles derived from the surfaces of contaminated blocks are very low (around 1E-10 y^{-1}). The particle activities would be far below the levels that could give rise to deterministic health effects, so the risks from particles vary linearly with the total activity disposed. The number of blocks, block sizes, surface activity levels, and thicknesses of surface contamination are not important. Doses were calculated assuming the projected final radionuclide inventory is all in the form of particles derived from contaminated block surfaces. Although valley development provides greater opportunity for disposal of surface contaminated blocks, the existing calculation is sufficiently cautious, and the risks sufficiently low, that further assessment is not undertaken.

Riverine erosion is assessed as an AES because it would need to begin earlier than coastal erosion to result in a potentially different exposure situation.

4.2.1.2. Variant Case 1 – Well

The 2017 PCRSA assessed the potential doses to a person who gets all their annual drinking water supply (600 l/y; Nexia, 2006) from a well drilled on the south-west boundary of the facility. The well was assumed to be screened in the drift, as this would directly intersect the radionuclide transport path. AECOM (2017) noted that the well could also be drilled into the sandstone, but it may not directly intersect the radionuclide transport path and there would be greater dilution with clean water. Therefore, the assumption that the well is screened in the drift maximises the potential doses.

The 2006 and 2017 PCRSA's argued that the probability of there being a well in this location is low and assumed a scenario probability of 0.01. For example, the hydrogeology is not favourable, with the risk of saline contamination increasing over time as sea-level rises and the coast erodes. The river Calder and Newmill beck provide more easily accessible local water sources. The low likelihood of this case is accounted for in calculation of the risks.

4.2.1.3. Variant Case 2 – Passive Drains

The magnitude of radionuclide sorption onto passive drainage media has been identified as an uncertainty (Section 3.11.3). In the variant case there is assumed to be no sorption of radionuclides onto passive drainage media.

4.2.2. Human Intrusion AES Calculation Cases

The 2017 PCRSA assessed three inadvertent human intrusion events, that covered short-term and long-term exposures. They were based on the events assessed for the LLWR 2011 ESC (Hicks and Baldwin, 2011) that resulted in the highest doses from inadvertent human intrusion:

- Short-term doses from exposure to excavated wastes when drilling boreholes to investigate the site.
- Long-term doses from occupying a site contaminated by wastes exposed during sewage treatment plant construction for housing.
- Long-term doses from smallholding on a site contaminated by wastes exposed during dirty water settling tank construction.

The site occupancy and smallholding events were assessed in the 2017 PCRSA and the potential doses were shown to be below the GRA dose guidance level of 3 mSv. However, it was noted that these events have limited relevance for CLESA because of the small size of the facility, and steep slope of the cap. Therefore, these events were not used as a basis for specifying activity limits. The potential doses from borehole drilling were used to inform activity limits.

Extension of CLESA into the valley area increases the likelihood of the site occupancy and smallholding events, because CLESA wastes would be present under the relatively flat area at the crest of the cap (Figure 4). However, the area of the crest of the cap is too small to support several houses requiring a sewage treatment plant, or a smallholding (Hicks and Baldwin, 2011, assumed the smallholding has an area of 7,500 m^2). Therefore, a new site occupancy event has been developed that is relevant to CLESA's setting, geography and geotechnical conditions (Figure 12).

The new event assumes the crestal area is levelled and adjacent areas terraced to provide a large enough flat area for construction of a house and adjacent garden. Piles would be driven into the waste to support the house, and the house base slab would sit directly on the wastes. Terracing for the garden and an access road can be achieved without exposing the wastes.

There would be an excess of cut materials, so it is assumed these would be removed from the site and disposed or deposited in a landscaped mound at the base of the slope. In either situation there would be limited ongoing exposure to the excavated materials.

It is unlikely wastes would be deliberately incorporated into garden soils. Clean cap soils are more likely to be stockpiled and reused. However, a small amount of contamination of garden soils by excavated waste cannot be ruled out.

Although the site is too small for smallholding it is possible the occupiers could grow some fruit and vegetables. A kitchen garden with an area of 0.05 ha (500 m^2) could provide all the occupant's fruit and vegetables (Sumerling, 2012). This is broadly similar to the size of Area 3 in Figure 12. However, some of this area would be covered by the house and the exposed location would likely limit the amount of produce that is grown. For assessment calculations it is cautiously assumed that 5% of the garden soils comprise waste materials (this is consistent with the proportions assumed by Hicks and Baldwin, 2011, for a smallholder), and the garden provides one third of the occupiers' annual fruit and vegetables.

It is assumed the thickness of cap material remaining after terracing is sufficient to prevent roots extending into the waste and direct uptake of radionuclides into fruit and vegetables. The cap thickness might need to be locally increased at the crest of the cap, e.g. by 0.5 m, to build additional confidence in this assumption. This needs to be considered at the next cap design stage (AECOM, 2022c).

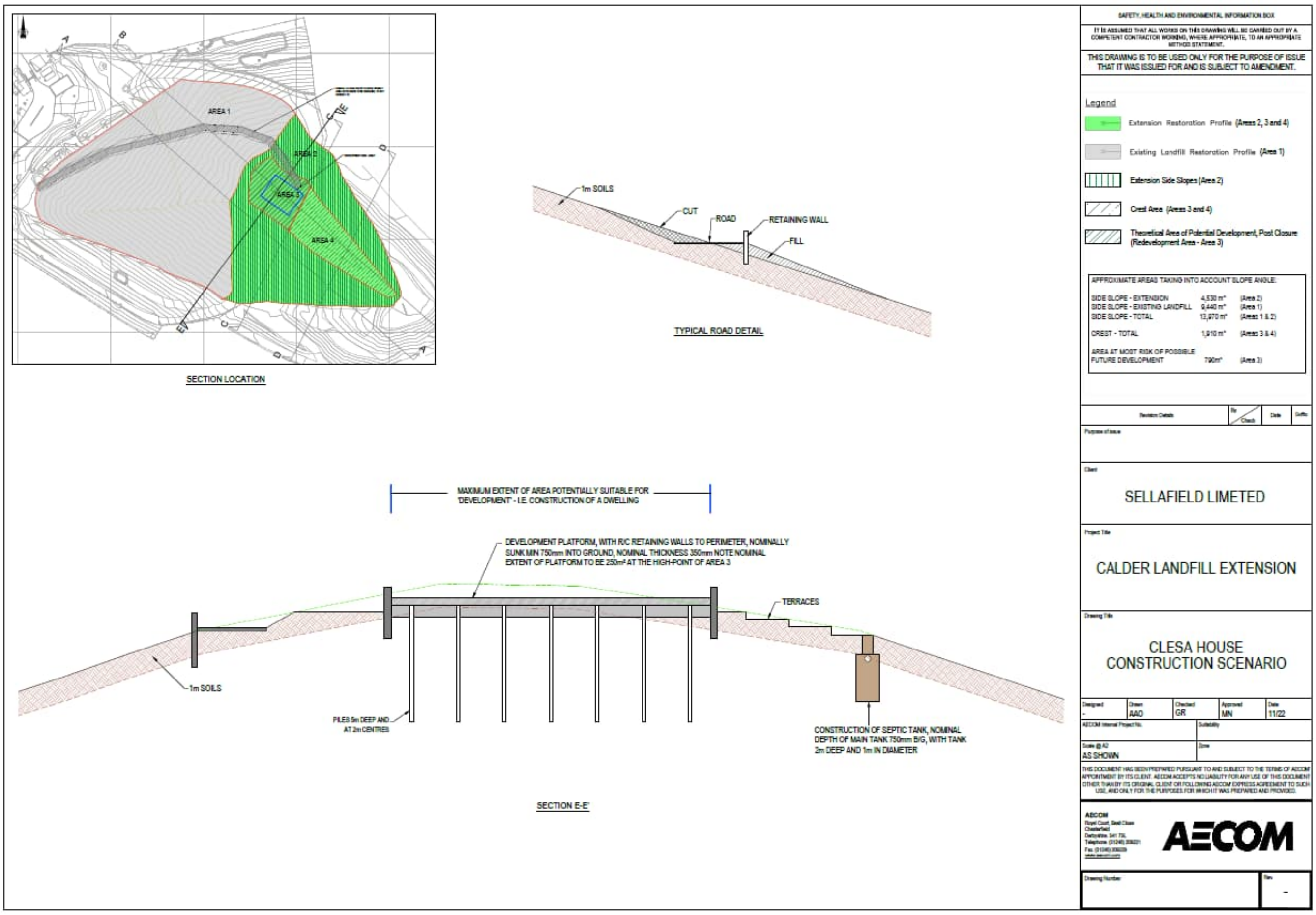

Figure 12. Conceptual design for construction of a house on CLESA

People would be exposed to radionuclides during house construction and subsequent site occupancy.

It is estimated that landscaping could take two months and the build of the house could take four to six months. Once the house base slab has been constructed exposure to the waste would be significantly reduced. Therefore, it is assumed a worker is exposed to the wastes for four months. Assuming a 37 hr working week, that is 640 hr exposure. The worker would be exposed by direct irradiation, inhalation and inadvertent ingestion.

A site occupant would be exposed in the house, and when in the garden assuming there is inadvertent contamination of the garden soils. In the house, exposures would be due to direct irradiation from the wastes, with radioactivity significantly attenuated by the base slab, inhalation of radioactive gases and consumption of foodstuffs grown in the garden. It is cautiously assumed there is not a vapour barrier in the house foundations which would attenuate radioactive gases. This is particularly relevant for radon which has a short half-life and therefore can decay significantly when attenuated by a vapour barrier.

In the garden a site occupant would be exposed by direct irradiation, inadvertent ingestion and inhalation of dust. It is assumed the occupier is always on-site, with 80% of the time spent in the house and 20% spent in the garden. 80% occupancy is a typical assumption for assessment of doses from Rn-222 gas (Limer and Thorne, 2011) and inhalation is expected to be a key dose pathway, e.g. compared with doses while working in the garden. Therefore, this is expected to be a cautious occupancy assumption.

4.2.2.1. Variant Case 1 – 3 m thick cap

The 2017 PCRSA assessed a variant case with a 3 m thick cap. This reduces the amount of waste that could be exposed by an intrusion event, especially the LLWR site occupant and smallholder events. Recent work to develop an optimised closuring engineering design has identified two cap designs to carry forward for further assessment (Section 3.6). These are both around 1 m thick. Therefore, this variant case is not reassessed.

4.2.3. Earlier than Expected Cap Failure AES Calculation Cases

4.2.3.1. Reference Case

In this scenario, earlier than expected cap degradation / failure leads to bathtubbing of CLESA and discharge of water to cap perimeter soils along the south-west and north-west sides of the site.

The 2017 PCRSA cautiously assumed all the water that infiltrates through the cap discharges to the cap perimeter soils, with no leakage through the landfill liner. The water was then assumed to drain vertically downwards through the perimeter soils into the underlying unconsolidated (drift) geology. This results in a small area of contaminated ground that is often boggy. It was argued that due to the local geography and boggy conditions it is unlikely that the affected area would be occupied significantly. It was assumed a coastal path traverses the area, and regular recreational users of the coast (the recreational PEG) would be exposed when walking across the contaminated area.

The 2017 conceptual model is retained, but with some refinements. The cap performance for Option A might be sufficient to prevent bathtubbing from occurring in the NES (AECOM, 2022d), but the cap performance for Option C is not expected to be sufficient to prevent bathtubbing from occurring. Option C would likely be used in combination with passive drainage measures to minimise the likelihood of bathtubbing. Option A could also potentially be used in combination with passive drains, although this is more likely to be disproportionately expensive. For both Option A and Option C, this scenario is assumed to involve both early failure of the cap, and failure (clogging) of any passive drains. This would lead to the maximum amount of water discharging to the cap perimeter soils, i.e. all the water that infiltrates through the cap, again assuming no leakage through the landfill liner.

For Option C, water would discharge adjacent to the spill point at the western ‘corner’ of the landfill, contaminating the land adjacent to the south-west and north-west sides of CLESA, as assumed in the 2017 PCRSA. For Option A the cap geomembrane would be tied-in (i.e. sealed to) the geomembrane in the liner. As the cap degrades, water levels in the facility could rise above the level of the spill point and top of the basal liner, until they discharge higher upslope through defects in the cap geomembrane. The water would then run downslope, within the GDL if it is still functioning, as interflow through the restoration soils and, or over, the cap surface. This could result in some localised contamination of the lower cap slopes and areas of soil adjacent to the perimeter of the cap. The areas of contaminated soil would likely be adjacent to the south-west and north-west sides of CLESA.

For both Options A and C, the 2017 PCRSA conceptual model that regular recreational users of the coast (the recreational PEG) are exposed by walking on a contaminated coastal path is retained. Terrestrial biota occupying the discharge zone would also be exposed. In the 2017 PCRSA, this exposure situation resulted in the highest calculated dose rates to non-human biota.

4.2.3.2. Variant Case 1 – Radium Sorption

The 2017 PCRSA showed that Ra-226 dominates the potential impacts for this AES. Radium sorption distribution parameters for the waste and soils are significantly uncertain. These are key parameters affecting the behaviour of Ra-226, and therefore the calculated impacts. This variant case explores the impacts of uncertainty in the distribution coefficient for sorption of radium onto the waste.

4.2.4. Early Erosion AES Calculation Cases

In the 2017 PCRSA, the early erosion AES assumed that disruption of CLESA by coastal erosion begins 200 years post-closure and proceeds more quickly than the NES. Early erosion led to higher risks from Cs-137 because there is less time for radioactive decay. However, the peak risks during coastal erosion are from Ra-226, which has a half-life of 1600 years, so these would not be significantly different to the NES.

Recent work to improve understanding of coastal and riverine evolution has shown that disruption by coastal erosion is more likely to begin later than assumed in the 2017 PCRSA NES, rather than earlier. The NES in this addendum retains the 2017 PCRSA NES assumption that disruption of the facility by coastal erosion begins 300 years post-closure. This is now considered to be a more cautious assumption than was considered for the 2017 PCRSA.

Peak groundwater pathway risks were unchanged from the NES because they occur before 200 years post-closure.

Given that early erosion is less likely than considered in the 2017 PCRSA, early erosion led to similar peak risks to the NES in the 2017 PCRSA, and the NES is now more cautious by assuming disruption by coastal erosion begins 300 years post-closure, the early erosion AES is not assessed for this addendum.

4.2.5. Late Erosion AES Calculation Cases

In the 2017 PCRSA, the late erosion AES assumed that disruption of CLESA by coastal erosion begins 400 years post-closure and proceeds more slowly than the NES. The peak risk from coastal erosion was slightly reduced by late erosion, because there is time for a small amount of additional decay of Ra-226, compared with the NES. The peak groundwater pathway risk occurs before 200 years post-closure, so it was not changed by late erosion.

In the 2017 PCRSA the late erosion AES led to risks that are the same as, or slightly lower than the NES. Therefore, the late erosion AES is not assessed for this addendum.

4.2.6. Emergent Land AES Calculation Cases

This scenario assumes CLESA is not disrupted by coastal or riverine erosion. More than 100,000 years in the future, colder climate conditions lead to sea-level fall and contaminated groundwater discharges to emergent land. The 2017 PCRSA argued this scenario is very unlikely and does not need to be assessed. Current work to develop an improved understanding of coastal and riverine evolution of the Sellafield site further supports this position, and this scenario is not assessed in this addendum.

4.2.7. Materials Recovery and Reuse AES Calculation Cases

This AES assumes that materials are recovered from the facility and reused. Although CLESA is very visible it is difficult to link this to the probability that materials would be recovered and reused, and when this could occur. It is unlikely materials would be recovered and reused immediately after the end of the PoA, and for a period thereafter due to societal memory, and potentially planning controls. Therefore, it is assumed low grade materials could be recovered after a period of around 300 years. This is similar to the timescales when disruption by coastal erosion is assumed to begin (Section 4.2.1) and materials would be exposed, potentially further attracting scavenging / recovery.

The recovered materials could be bulk waste or surface contaminated concrete blocks / bricks. Potential uses include for scavenged / recovered materials include construction and landscaping. These would be low-grade materials and would need significant processing before being incorporated into building materials.

Consistent with the 2017 PCRSA, it is considered that the most likely opportunity (although still very unlikely) for construction use is as hardcore placed in the foundations of a house. A concrete base slab would then be poured over the hardcore.

Blocks and bricks might be crushed before being incorporated in the foundations of a house. Short-term doses from crushing blocks and bricks would be similar to the doses from retrieving the materials, except there could be some additional exposure from inhalation of dust generated during crushing. This is assumed to be limited as people should not need to be in proximity to crushing machinery while it is operating, and there may be operational measures to limit dust generation and inhalation, such as water spraying, dust extraction, PPE, etc. Therefore, the focus is on short-term doses to the person retrieving the materials and the long-term doses to house occupants.

Short-term doses associated with using retrieved materials for landscaping or construction would be similar to, or lower than, the doses associated with retrieving the materials. Long-term doses from materials used for landscaping would be lower than associated with occupancy of a house incorporating retrieved materials. Retrieved materials would not be suitable as top-soil for growing foodstuffs.

The 2017 PCRSA assumed that recovery begins 300 years post-closure, when the facility starts to be disrupted by coastal erosion. A scavenger retrieves some materials from the eroding facility. Bricks and concrete blocks are then incorporated into the foundations of a house, resulting in exposure of the occupants. Therefore, the most important exposure situations remain consistent with those assessed in the 2017 PCRSA.

The 2017 PCRSA showed that CLESA’s bulk activity and hotspot limits would control doses to significantly below the regulatory dose criterion of 20 mSv for short-term exposures and 3 mSv for long-term exposures. The regulatory dose constraint could only mathematically be exceeded for bricks or blocks containing high levels of certain alpha emitters such as Ra-226 and Th-232. This situation is not plausible because there are no plants at

Sellafield (current or historic) that handle, or handled, materials where these isotopes form a substantial component of the activity.

Valley development would not change the types of waste disposed, and changes to the activity limits are not being proposed. Therefore, this AES does not need to be assessed further.

4.2.8. Riverine Erosion AES Calculation Cases

This scenario is only relevant if disruption of CLESA by riverine erosion beings before disruption by coastal erosion. The 2017 PCRSA assumed that disruption by riverine erosion beings 200 years post-closure, i.e. 100 years before the facility starts to be disrupted by coastal erosion. It was assumed that riverine erosion results in wastes being exposed in a steep bank several metres above the river Calder. Slumped waste materials are also present on the riverbank, below the waste exposed *in situ*. The site was assumed to remain in this condition until it starts to be disrupted by coastal erosion at 300 y post-closure. It was assumed there is preferential occupancy of the contaminated area for angling, and anglers are exposed through occupancy of the contaminated riverbank. The probability of this scenario occurring could not be quantified, but it was argued to be a cautious, low likelihood scenario.

The riverine erosion scenario is still considered to be a cautious, low likelihood scenario. River erosion would expose waste along the north-west side of CLESA. Riverine erosion is not expected to expose wastes disposed to the valley area. The erosion front might never progress as far as the valley area, and even if it could the valley area is likely to be disrupted by coastal erosion before it could be disrupted by riverine erosion. Therefore, this AES does not need to be assessed for the valley area. It is reassessed for the existing disposal area because the habits of the angler PEG have been updated (Section 3.10).

4.2.9. Headland Formation

A recent survey of the habits of people using the West Cumbrian coast (CEFAS, 2019) identifies that rocky headlands can be a preferential place for fishing. As CLESA erodes, blocks could potentially accumulate on the storm beach forming an artificial headland. It is significantly uncertain whether the number of blocks and their distribution in CLESA could result in the formation of a headland. If a headland could form, it is difficult to project the geomorphology and whether the headland could be attractive for fishing. Cautiously it is assumed that a headland could form, but this situation is treated as an AES due to the significant uncertainties. The probability of this scenario cannot be quantified, so potential risks to people fishing from an artificial headland are calculated assuming the scenario occurs, i.e. unit probability. The implications of the scenario probability for risks are then discussed qualitatively.

5. Assessment Models and Calculations

This section describes the approaches used to assess the scenarios and calculation cases. A range of calculation approaches are used, including qualitative or semi-quantitative arguments, simple analytical calculations and more detailed quantitative computer models. One model may be used to assess several scenarios and calculation cases, so the assessment approach is described for each pathway, rather than for each scenario or calculation case. Where numerical models are used, the model configuration and parameterisation, and input data are described.

The assessment models for all pathways and calculation cases use the updated fingerprint and inventory information described in Section 3.3. This is consistent with the scenarios and calculation cases assessed in the 2022 ORSA addendum.

5.1. Groundwater Pathway

5.1.1. Groundwater Pathway Reference Case

A groundwater pathway model was developed for the 2017 PCRSA using the GoldSim software tool (GoldSim Technology Group, 2022). The wastes were represented in the model using a single compartment with homogeneous physico-chemical conditions and radionuclide concentrations. Cautiously, radionuclide leaching during the operational phase was excluded from the model, maximising the radionuclide inventory remaining at closure.

This model was further developed for the 2017 ORSA to represent the wastes and conditions during the operational phase in more detail. The model was calibrated against measured leachate radionuclide concentrations and used to calculate potential future aqueous discharges in response to increased activity limits. The 2017 ORSA model was further developed for the 2022 ORSA addendum, including representation of the valley area. The 2022 ORSA model has been further developed for this PCRSA addendum to also represent radionuclide releases to groundwater post-PoA, i.e. one model is now used to represent releases from CLESA to the groundwater pathway, and then transport in the groundwater pathway, from the first waste disposals in 2006 to the time of disruption of the site by coastal erosion. This provides a more consistent and more transparent approach across assessment timeframes.

The current model structure is shown in Figure 13. Seven waste compartments are to represent the various volumes and fingerprints of wastes disposed at different times:

- The three lowest waste compartments, in the existing disposal area, represent existing disposals to the end of 2019 which are consistent with the facility’s original activity limits.
- The fourth compartment, in the existing disposal area, represents disposals between January 2020 and July 2022 which are consistent with the facility’s increased activity limits.
- The fifth and sixth compartments, in the existing disposal area, represent potential future disposals, which are assumed to have a bulk activity of 37 Bq/g and the fingerprint described in Table 2.
- The seventh compartment, in the valley area, represents potential future disposals, which are assumed to have a bulk activity of 37 Bq/g and the fingerprint described in Table 2.

The model is further described in the 2022 ORSA addendum, including the timings assumed for future disposals. (Note the sequencing of future disposals to the existing disposal area and the valley has little effect on the calculated discharges or impacts during the PoA.)

Infiltration into the wastes has been updated to reflect the updated cap performance assumptions described in Section 3.6, i.e. consistent with the 2017 PCRSA cap infiltration is cautiously assumed to be 32 mm/y ‘as built’, and increases linearly to a new maximum value of 137 mm/y at 300 years post-closure. Note that this updates the cap performance assumed in 2022 ORSA addendum, which included the same cap performance assumptions as the 2017 ORSA and PCRSA, i.e. cap infiltration ‘as built’ is 32 mm/y and this increases linearly to 300 mm/y at 300 years post-closure. Therefore, it is expected that radionuclide releases to groundwater during the period of control following closure and before the end of the PoA will be a little lower than calculated in the 2022 ORSA addendum.

The physical properties of the waste are updated with the new parameter values described in Section 3.2. These updated parameter values were also used for the 2022 ORSA addendum.

The is only one change to the assumed geochemical conditions, sorption distribution coefficients and solubility limits compared with the 2017 PCRSA. The 2017 PCRSA assumed solubility limits and sorption distribution coefficients for Tc-99 in the waste that are consistent with reducing conditions. As the model now considers the whole lifetime of the facility, solubility limits and sorption distribution coefficients for Tc-99 in the waste are now consistent with oxidising conditions during the operational phase and reducing conditions post-closure (AECOM, 2022a).

The thickness of the unsaturated zone is greater below the valley area than the existing disposal area. Water that infiltrates through the cap over the valley area could potentially drain through any defects in the liner below the valley area, or flow downslope over the liner and drain through any defects in the liner in the existing disposal area or enter passive drains. The additional thickness of unsaturated zone below the valley area is not included in the assessment model because only some of the water draining from the valley area would drain through defects in the liner below the valley area.

Passive drains to groundwater are not represented explicitly in the assessment model but are considered as part of the unsaturated zone. Radionuclides might sorb more weakly onto drainage media than the unsaturated natural geology, and this is assessed in variant case 2 (Section 5.1.3). BES in the basal liner is also not represented explicitly in the assessment model but is included in the unsaturated zone. Some radionuclides may sorb more strongly onto the BES than the natural geology, but this is not represented in the assessment model, which is a conservative assumption. Therefore, the fluxes of radionuclides that could sorb strongly onto clay minerals in the BES may be overestimated.

In the 2017 PCRSA assessment model the saturated geosphere was discretised into five compartments. This results in an amount of numerical dispersion in the transport calculation that is similar to the expected amount of hydrodynamic dispersion. The model did not represent any reduction in the length of the groundwater pathway as the coast erodes but has now been improved to allow erosion of the groundwater pathway to be represented in the assessment. Representing erosion of the pathway by evolving the configuration and parameterisation of the model is complex to implement, so a simple but proportionate approach is used instead. Risks from consumption of beach seeps are calculated for two discharge locations: one at the present-day location of the coast; and the other a future coastal location, close to the facility boundary, i.e. shortly before CLESA starts to be disrupted by coastal erosion. Discretisation of the groundwater pathway has been increased to ensure that the amount of numerical dispersion is a reasonable representation of the expected amount of hydrodynamic dispersion for both discharge locations.

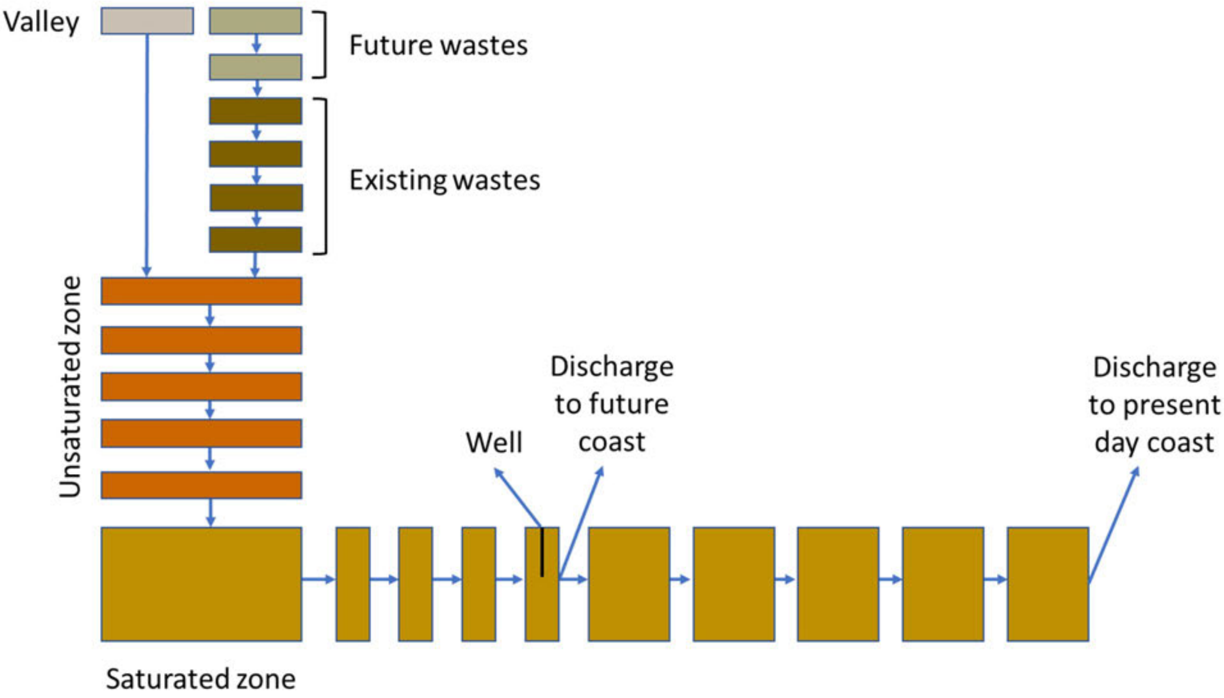

Figure 13. Compartments and transfers between compartments in the groundwater pathway model

5.1.2. Groundwater Pathway Variant Case 1 – Well

Implementation of this case is unchanged from the 2017 PCRSA. The structure of the groundwater pathway model has been improved (Figure 13), so radionuclide concentrations in groundwater are taken from a different model compartment, but the assumed location of the well relative to CLESA has not changed. The well is assumed to be located on the south-west boundary of CLESA. Discretisation of the groundwater pathway between CLESA and the well has been increased, giving a more realistic representation of the amount of hydrodynamic dispersion along the groundwater pathway to the well.

5.1.3. Groundwater Pathway Variant Case 2 – Passive Drains

In this case it is assumed there is no leakage through the liner, and all leachate is instead directed to groundwater pathway by passive drains. The passive drains are filled with highly permeable coarse gravel. There may be limited sorption on the drain material, so this case explores the extreme assumption of no sorption in this part of the model. This is implemented in the groundwater pathway model by setting the sorption distribution coefficient (Kd) in the unsaturated zone compartments to zero for all radionuclides. Sorption in the groundwater pathway, from the base of the passive drains to the coast, is represented.

5.2. Gas Pathway

A person occupying a house constructed on the cap (Section 4.2.2) could be exposed to H-3, C-14 and Rn-222 gases. The principal pathway is expected to be inhalation; doses from immersion are expected to be negligible in comparison. C-14 in the form of $^{14}CO_2$ gas can be incorporated into fruit and vegetables growing in the garden by photosynthesis. Therefore a site occupant is assumed to be exposed by ingesting the fruit and vegetables.

Ingestion of fruit and vegetables is expected to dominate doses from C-14 (Limer et al., 2011), so doses from ingestion of C-14 in fruit and vegetables are calculated, but doses from inhalation of C-14 gas are not calculated.

5.2.1. H-3 Gas

The 2017 PCRSA argued that doses from inhalation of H-3 gas would be negligible after the end of the PoA due to the small inventory, the number of half-lives of decay, and loses through operational discharges. This was derived from similar arguments made for the LLWR, which has a larger H-3 inventory, but also longer period for decay of most disposals. The H-3 inventory has increased significantly since the 2017 PCRSA, so a simple quantitative calculation is undertaken to build confidence this argument is still true.

The 2017 ORSA and 2022 ORSA addendum used results from the IAEA BIOsphere Modelling and ASSessment (BIOMASS) programme to estimate the flux of H-3 gas from CLESA. The same approach was used in the PoA assessment for the LLWR 2011 ESC (LLWR, 2011a). The BIOMASS programme was concerned with developing and improving capabilities to predict the transfer of radionuclides in the environment. Fluxes of H-3 gas are estimated by scaling relevant results from the BIOMASS programme by the H-3 concentration in CLESA leachate. In the BIOMASS results, the maximum gas flux is 4.8E+03 Bq/m^2/y from a H-3 concentration in the aquifer of 1E+07 Bq/m^3. The H-3 flux, $F_{H\text{-}3}$ (Bq/y), is calculated as:

$$F_{H\text{-}3}\ (Bq/y) = C_{H\text{-}3}\ (Bq/m^3) * A\ (m^2) * 4.8E{+}03\ (Bq/m^2/y) / 1E{+}07\ (Bq/m^3)$$

Where,

$C_{H\text{-}3}$ is the concentration of H-3 in CLESA leachate (Bq/m^3)

A is the area of the house, i.e. 150 m^2.

This is converted into a release rate, $\lambda_{H\text{-}3}$ (y^{-1}), for input to GoldSim, by dividing by the amount of H-3 of tritium in CLESA:

$$\lambda_{H\text{-}3}\ (y^{-1}) = A\ (m^2) * 4.8E{+}03\ (Bq/m^2/y) / (1E{+}07\ (Bq/m^3) * V\ (m^3))$$

Where,

V is the volume of waste (m^3)

The H-3 gas concentration in the house is then calculated by modelling the house as a single compartment in GoldSim. The properties of the house are given in Table 7. The dose is then calculated using the relevant breathing rate and dose factor given in the LLWR radiological handbook (LLWR, 2011b).

Table 7. Properties of the house

Parameter	**Value**	**Notes**
House footprint and volume	150 m^2 375 m^3	Footprint from Ministry of Housing, Communities and Local Government (2019). Assume a single-story dwelling (cautiously minimises house volume) with ceiling height of 2.5m.
House ventilation rate	1 hr^{-1}	Limer and Thorne (2011).

5.2.2. C-14 Gas

The 2017 PCRSA argued that doses from the uptake of C-14 in foodstuffs would be low by comparison with the assessment undertaken for the LLWR trenches. Subsequently the 2017 ORSA and 2022 ORSA addendum used LLWR assessment results for the trenches to estimate the potential flux of C-14 gas from CLESA during the PoA. The same approach is used to make a quantitative estimate of the potential flux of C-14 gas post-PoA, and then the flux is used to calculate the potential doses from the consumption of C-14 in fruit and vegetables grown in a garden located on the cap:

- Fig 4-1 of Sumerling (2012) gives the ‘average flux of C-14 bearing gas from the trenches for the Reference Case (Bq/m^2/y)’. At 2164, i.e. 84 y after closure of the LLWR trenches (which is the same length of time between CLESA closure and the end of the PoA), the flux is ~4.2E+03 Bq/m^2/y.
- This flux is scaled (reduced) by a factor of 0.3 to reflect the smaller C-14 inventory in CLESA (0.03 TBq) compared to the LLWR trenches (0.1 TBq).

- The flux is also scaled (reduced) by a factor of ~0.05 to reflect the lower mass of organic waste in CLESA (1.5E+04 te) compared to the LLWR trenches (3.1E+05 te), and therefore the lower amounts of bulk and C-14 labelled gases that are expected to be microbially generated in CLESA compared with the LLWR trenches.
- The scaled peak flux from CLESA is 6.3E+01 Bq/m^2/y.
- In the LLWR assessment, the exposure group 'PEG D' gets all their fruit and vegetables from a kitchen garden on the LLWR cap. Table 7-1 of Sumerling (2013a) gives the biosphere dose factor for PEG D as 9.70E-08 mSv per Bq/m^2/y. A CLESA site occupant is assumed to get one third of their fruit and vegetables from the kitchen garden, so the relevant dose factor is 3.23E-08 mSv per Bq/m^2/y.
- The peak dose to a CLESA site occupant from consumption of C-14 in foodstuffs is (6.3E+01 Bq/m^2/y) * (3.2E-08 mSv per Bq/m^2/y) = 2E-06 mSv.

5.2.3. Radon Gas

Exposure to radon gas is only expected to be significant indoors where the gas can potentially accumulate. Doses outside will be small in comparison due to atmospheric dispersion, so only doses indoors need to be assessed. Limer and Thorne (2011) present three methods for calculating the Rn-222 concentration indoors:

- An empirical relationship between the concentration of Rn-222 in soil pore gas and Rn-222 gas in the house.
- An empirical relationship between the concentration of Ra-226 in soils and Rn-222 gas in the house.
- Mechanistic modelling approach.

The first method was used by Limer and Thorne (2011) to calculate doses from occupancy of a house built on the LLWR cap above the LLWR trenches. The calculation used a site-specific emanation fraction of 0.15, based on comparison of the estimated Ra-226 inventory in the LLWR trenches and the concentrations of Rn-222 gas measured in probes that penetrate the trench wastes. The same calculation approach was used in the 2017 CLESA PCRSA to calculate the potential doses from Rn-222 gas in a house built on the top of the facility. The calculated doses were used to derive the Ra-226 activity limit of 0.35 Bq/g in the top 3 metres of disposals in the top plane of the facility.

The LLWR 2011 ESC also assessed doses from occupancy and smallholding on a contaminated site. Concentrations of Rn-222 gas in a house were calculated using the second empirical approach. It is noted the second empirical approach led to higher Rn-222 concentrations per unit Ra-226 concentration in the wastes, and therefore more restrictive limits on Ra-226 concentrations in shallow disposals, than the first empirical approach. The difference is due to differences in the empirical factors, and the emanation fraction for the trench wastes used by Limer and Thorne (2011). There is significant variability in the data underpinning both empirical relationships, and therefore significant uncertainty in both relationships.

These two empirical approaches have been compared in more detail before selecting a preferred approach for calculating doses from a CLESA site occupancy event (Section 4.2.2). A mechanistic model has also been implemented in GoldSim to provide an additional line of evidence. The mechanistic model represents the wastes and house base slab each using five compartments. Migration of Rn-222 gas into the house is by diffusion. Calculated Rn-222 concentrations in the house are dominated by the small proportion of Rn-222 that diffuses relatively quickly, and therefore is subject to relatively little radioactive decay in the waste and base slab. The model has been discretised to ensure numerical dispersion does not adversely affect the calculated proportion of Rn-222 that diffuses relatively quickly.

- Five compartments are used to represent the waste and five compartments are used to represent the house base slab. Discretisation of a barrier into five compartments results in a breakthrough curve that very closely matches the analytical solution (Quintessa, 2022).
- Most of the Rn-222 gas in the house would come from the waste immediately below the slab. Therefore, the waste compartment thicknesses increase with increasing distance below the slab. 'Waste5' has a small thickness, so the flux of Rn-222 from the waste into the overlying slab is not overestimated due to numerical dispersion.

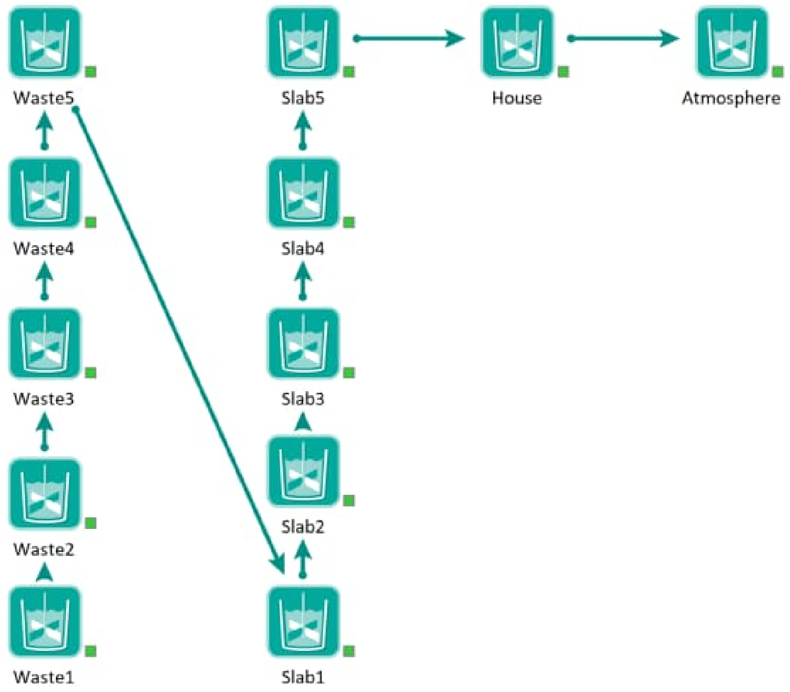

Figure 14. Structure of the GoldSim model of Rn-222 diffusion into a house

The Rn-222 model parameterisation is described in Table 8.

Table 8. Parameterisation of the Rn-222 model

Parameter	Value	Notes
Waste thickness	3 m	Most of the Rn-222 entering a house is expected to be sourced from the top 3 m of the waste, and this is reflected in the Ra-226 activity limit in CLESA's Permit. A model sensitivity test was undertaken with a waste thickness of 5 m. This only resulted in a very small increase in the calculated Rn-222 concentration in the house, confirming that most of the Rn-222 is derived from Ra-226 in the top 3 m of waste.
Emanation fraction	0.25	Yu et al. (1993). A generic literature value has been selected for CLESA as the emanation fraction for the LLWR trenches might include a component of radioactive decay between the point of Rn-222 generation and the trench probe.
Slab thickness	0.35 m	Figure 12
Slab porosity	0.1	Assumed value for structural concrete
Unsaturated waste porosity	0.1875	Assume the waste has low water saturation under the cap and the house. Unsaturated porosity calculated from total porosity of 0.25 and assumed 25% water saturation.
Diffusivity of Rn-222 gas	1.1E-5 m^2/s	Yu et al. (2001)
Waste effective diffusivity	2E-6 m^2/s	Yu et al. (1993). Note the waste effective diffusivity varies with water saturation. The value used is within the range given by IAEA (2013), of 9E-7 m^2/s and 7E-6 m^2/s, for soils with a water saturation of less than 0.25.
Slab effective diffusivity	7.4E-8 m^2/s	Yu et al. (2001) gives a value of 3E-7 m^2/s, and notes this is cautious compared with the value of 6E-09 m^2/s U.S. Nuclear Regulatory Commission, to account for cracks and penetrations in the base slab. A diffusivity of 3E-7 m^2/s is approximately equivalent to a 1 mm crack every 4 cm, i.e. a highly cracked base slab. The chosen effective diffusivity value is equivalent to a 1 mm crack every 25 cm.
House footprint and volume	150 m^2 375 m^3	Footprint from Ministry of Housing, Communities and Local Government (2019). Assume a single-story dwelling (cautiously minimises house volume) with ceiling height of 2.5m.
House ventilation rate	1 hr^{-1}	Limer and Thorne (2011).

The Rn-222 concentrations in the house calculated using the three methods are compared in Table 9. The three methods give similar results, especially when variability in the empirical data and uncertainty in the empirical relationships is considered. Therefore, the first method, which underpins the current Permitted activity limit in shallow disposals is retained for calculation of doses from Rn-222 in the CLESA site occupancy event for consistency with the 2017 PCRSA.

Table 9. Comparison of the Rn-222 concentrations in a house calculated using three methods

	Empirical relationship 1	Empirical relationship 2	Mechanistic model	Notes
Ra-226 concentration in the waste	48 Bq/kg * 2030 kg/m^3 = 97,440 Bq/m^3	0.048 Bq/g = 48 Bq/kg	0.048 Bq/g	Table 2
Rn-222 concentration in soil gas	14,616 Bq/m^3	-	-	Assume an emanation fraction of 0.15*porosity (Limer and Thorne, 2011). Note the porosity term cancels out in the calculation.
Rn-222 concentration in the house	22 Bq/m^3	48 Bq/m^3	28 Bq/m^3	Empirical ratios of 1.5E-3 (-) and 1 (kg/m^3), respectively, from Limer and Thorne (2011).

In the LLWR 2011 ESC and CLESA 2017 PCRSA, the dose from inhalation of radon gas was then calculated using the time spent in the house (assumed to be 80% of a year) and a dose factor of 3.6E-06 mSv per Bq h m^{-3} (including an equilibrium factor of 0.4). Recommended dose factors for Rn-222 have subsequently been subject to international review and update. ICRP (2018) provides a summary of recommendations for assessing doses from Rn-222, including recent updates in the International Commission on Radiological Protection's (ICRP's) recommendations for Rn-222 dose coefficients. These dose coefficients are based on ICRP 137 (2017) and recommend that for buildings and underground mines a dose coefficient of 3 mSv per mJ h m^{-3} (approximately 10 mSv per working level month) be used. This corresponds to a dose coefficient of 6.7E-06 mSv per Bq h m^{-3}, when expressed in terms of Rn-222 gas exposure (assuming an equilibrium factor of 0.4). This is an increase of a factor of ~2 compared with the dose coefficient used in the 2017 PCRSA. This will lead to increases in calculated doses from Rn-222 by a factor of ~2 for the same Ra-226 concentration in the waste, and a decrease by a factor of ~2 in the maximum acceptable Ra-226 concentration in shallow disposals.

5.3. Coastal Erosion

5.3.1. Exposure to Bulk Wastes

The 2017 PCRSA assessment model of the potential radiological impacts from coastal erosion of CLESA followed the modelling approach used in the LLWR 2011 ESC (Towler et al., 2011). The 2017 model has been updated to include the valley area, and the model parameterisation has been changed to include updates to the facility inventory and geometry and the assumed PEG habits.

The LLWR 2011 ESC assessment modelling approach assumes that although sea-level rise is unlikely to be monotonic, very rapid rise leading to inundation of the facility is unlikely to occur. It is expected that as the coast erodes it will retain its current form. As sea-level rises the protection provided by the storm beach will be reduced and material will be eroded more frequently from the cliffs at the back of the storm beach and the shore platform beneath the beach. Gravel and cobble sized material will be deposited on the storm beach, increasing the beach volume and protection against coastal erosion, while sand will be transported further offshore to the foreshore, the sea-bed below the local coastal waters adjacent to the eroding facility, and the sea-bed along the rest of the regional St Bees to Ravenglass sediment sink cell. Sands on the foreshore, local offshore and regional St Bees to Ravenglass sediment sink cell will move with each tidal cycle and will mix. Clay and silt will be transported further offshore to the Eastern Irish Sea mud belt.

Over long-timescales it is assumed the volumes of the coastal features are constant and there is a volume balance, with the volume of material eroded from the cliffs (V, m^3/y) balanced by the volume of material deposited in the regional St Bees to Ravenglass sediment sink cell (Figure 15). Sand on the foreshore, local offshore and regional sediment sink cell moves with each tidal cycle, so there is continuous mixing with net offshore transport. In the assessment model, silt and clay sized material is cautiously assumed to be retained in the St Bees to Ravenglass sediment sink cell, instead of being further dispersed and diluted by transport to the Eastern Irish Sea mudbelt.

The modelling approach assumes that radionuclides are evenly distributed across materials with different grain sizes, so radionuclides are not preferentially retained on the storm beach or preferentially transported offshore. If large numbers of concrete blocks are disposed to CLESA they could preferentially accumulate on the storm beach as the facility erodes, increasing the total activity on the beach compared with erosion of bulk materials. The 2017 PCRSA considered this possibility and showed that it is not credible that the activity in a pile of blocks / bricks on the storm beach could exceed the activity limit for bulk disposals, i.e. 200 Bq/g. Therefore, accumulation of blocks on the beach should not significantly increase the calculated radiological risks compared with coastal erosion of the bulk wastes, assuming the blocks and bulk wastes have broadly similar fingerprints. This conclusion is not changed by valley development, so the assumption that radionuclides are evenly distributed across materials with different grain sizes is retained.

In the 2017 PCRSA, the facility was represented more simply than in the LLWR 2011 ESC, with the 2017 PCRSA presenting arguments for representing CLESA using a single model compartment. Representation of CLESA in the model has been updated to include the valley area. The existing disposal area and valley area are represented as two separate compartments (Figure 15), reflecting the different geometries of the two disposal areas.

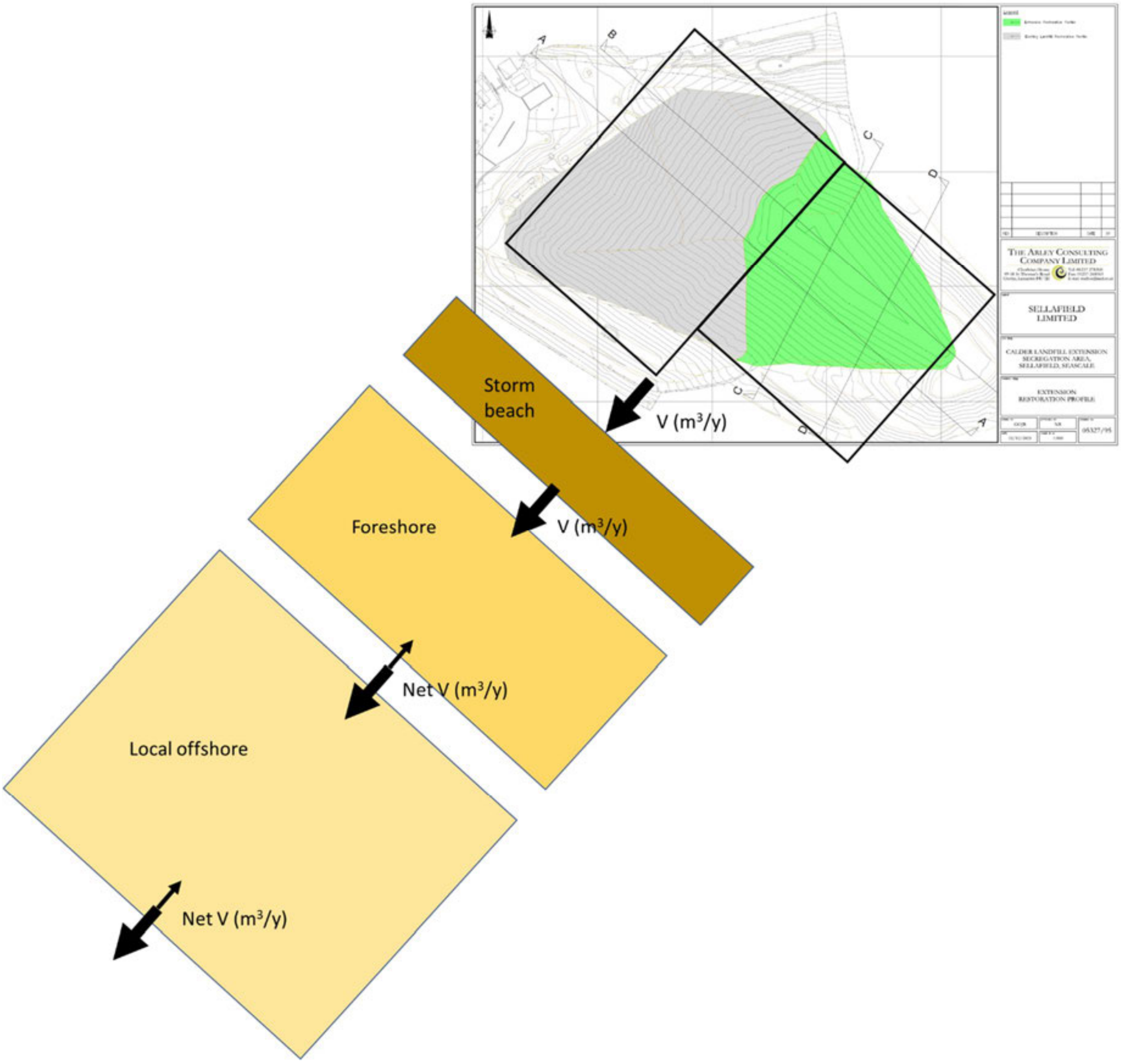

Figure 15. Compartments and transfers between compartments in the coastal erosion model (St Bees to Ravenglass sediment sink cell not shown)

The 2017 PCRSA model assumed constant geometry during erosion of CLESA. The model has been improved to include changes to the volumetric erosion rate (V, m^3/y) during erosion of CLESA, rather than assuming a constant volumetric erosion rate. This provides a more realistic model representation of erosion of the facility. This update is further explained in the following.

As CLESA is eroded the height of the facility above the erosion front increases to a maximum and then decreases. Therefore, the volume of material eroded per unit distance eroded increases to a maximum and decreases. An increase in the volume of material eroded per unit distance eroded would tend to provide more beach building material, resulting in a bigger beach that reduces the erosion rate, and vice versa. Assuming CLESA and the adjacent Calder tips contain similar grain size materials to the adjacent lower lying land, CLESA and the adjacent Calder tips could potentially erode relatively slowly and evolve into an island on the foreshore before they are eventually fully eroded.

The conceptual model of the geomorphology of the eroding coastline, and the localised evolution of CLESA, is not sufficiently developed to underpin time varying erosion rates in the assessment model. Therefore, the assessment model makes the simplifying assumption that CLESA (and the adjacent Calder tips) erode at a constant linear recession rate (this may be slower than the adjacent land), with the volumetric erosion rate (V, m^3/y) varying as the facility erodes.

This volumetric erosion rate is then calculated from the recession rate (m/y) and the area of material being eroded. The area of material being eroded is calculated for nine vertical sections (E1 to E5 for the existing disposal area, and V1 to V4 for the valley area, Figure 16 and Table 10). In the assessment model, the volumetric erosion rate is interpolated linearly between each vertical section.

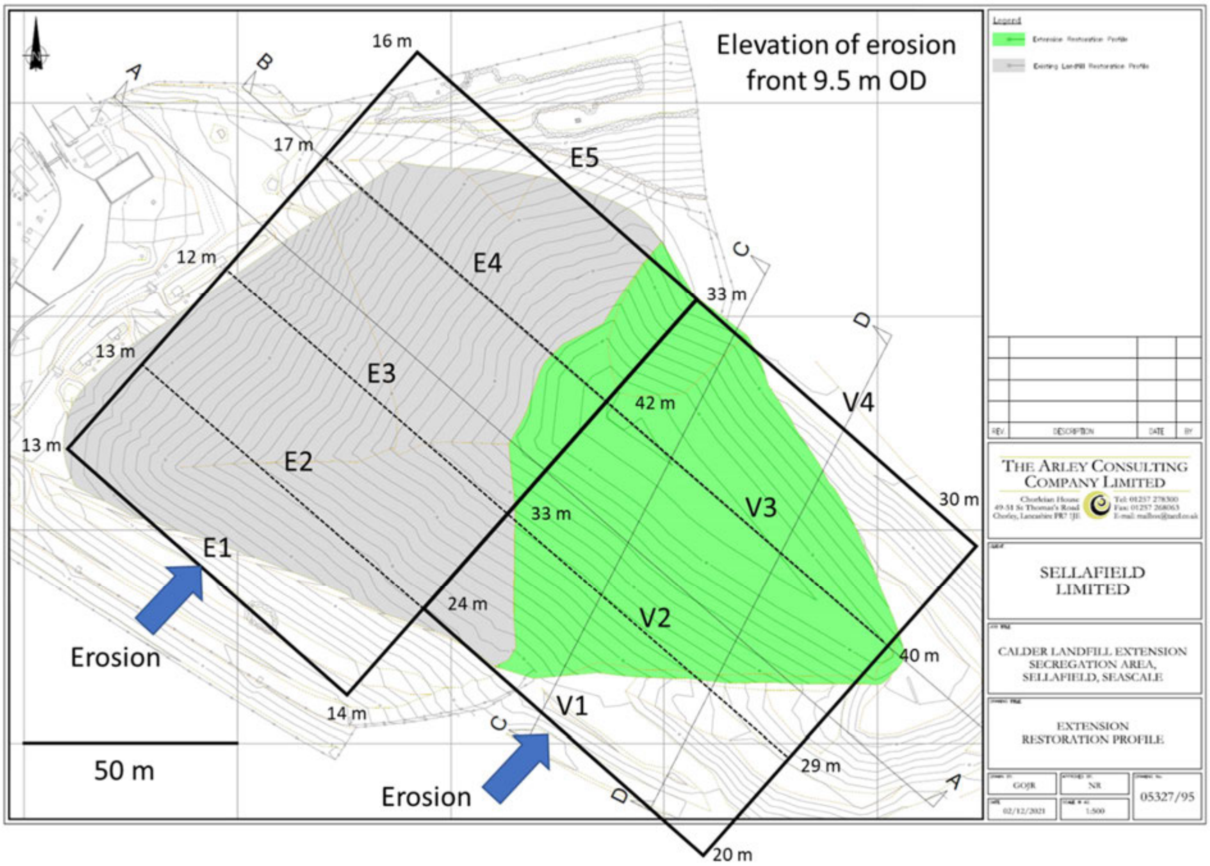

Figure 16. Vertical fence-lines used to calculate the volume of material eroded per unit distance erosion

The geometries of the storm beach, foreshore, local offshore and St Bees to Ravenglass sediment sink compartments are unchanged from the 2017 PCRSA. The mixing rates between these compartments are also unchanged, although the net offshore transport rate (V, m^3/y) has been updated, as described above.

The sea-level is assumed to be 3 m AOD when CLESA is eroding (Section 3.8). Present day, the back of the storm beach is around 6.5 m above mean sea-level. Assuming the size of the storm beach is not significantly reduced in the future as the coast erodes, the elevation of the erosion front would be around 9.5 m AOD. This would intersect the bottom of CLESA's basal liner, so wastes disposed to the existing disposal area would be exposed just above beach level in the cliffs at the back of the storm beach (Figure 17). Wastes disposed to the valley area would be exposed higher in the cliffs (Figure 17).

Table 10. Cross-sectional areas of vertical fence lines in Figure 16

Fence line	Area (m^2)
E1	348
E2	782
E3	1130
E4	1738
E5	1303
V1	1086
V2	1868
V3	2737
V4	1912

The 2017 CLESA PCRSA calculated potential doses to recreational users of the coast. The recreational PEG is retained. As described in Section 3.10.3, the recreational PEG is assumed to spend time on the storm beach and foreshore in front of the eroding facility, and a small amount of time walking at the back of the storm beach adjacent to the cliffs and clambering on the cliffs.

Time spent at the base of the cliffs, and clambering on the cliffs, involves time spent directly on the wastes, clean geological materials underlying the wastes and slumped materials (talus) at the base of the cliffs. Therefore, doses are calculated using radionuclide concentrations averaged over the cliff face and conservatively assuming the cliff is a semi-infinite slab source. The areas of waste and underlying geology used to calculate the average cliff concentrations (Figure 17) are taken from cross-section line B-B' (Figure 15) where the thickness of waste is greatest, and the thickness of underlying geology is smallest. The areas are given in Table 11.

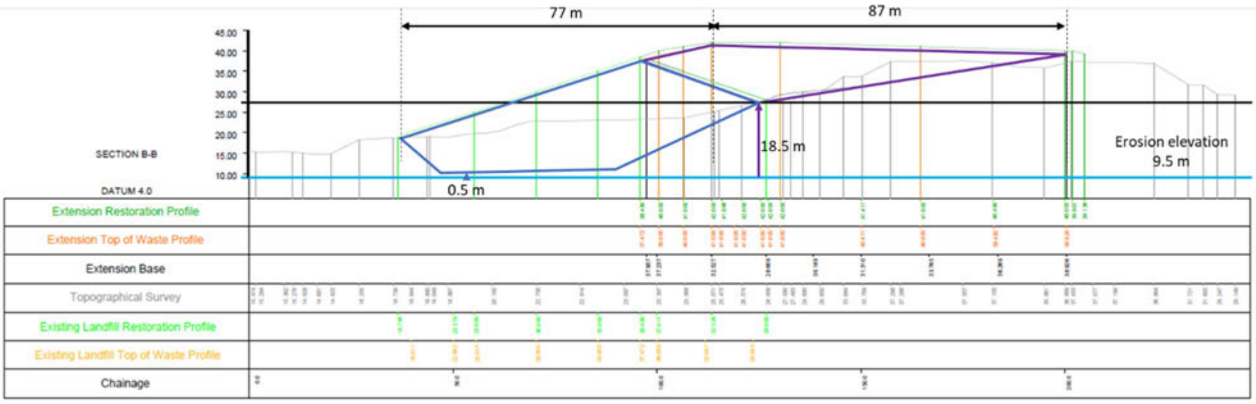

Figure 17. Areas of waste and underlying geology used to calculate the average cliff concentrations (see section line B-B' in Figure 15)

Table 11. Areas used to calculate area weighted average radionuclide concentrations in the cliff

Description	Area (m^2)
Waste in the existing disposal area	1438
Waste in the valley area	755
Underlying geology	2202

In the 2017 PCRSA, people clambering on the cliffs were assumed to be simultaneously exposed to external irradiation from wastes in the cliffs and slumped wastes at the base of the cliffs. Both sources were assumed to have the same radionuclide concentrations, and both sources were treated as semi-infinite slabs with exposure at 1 m. This approach uses standard dose factors from the literature and is cautious because it is not geometrically possible.

The external irradiation dose factors for a semi-infinite slab are conceptualised considering a sphere of radius 1 m centred on a person standing on the source, with the base of the sphere touching the source (Figure 18). Photon paths from the semi-infinite slab source intersect the bottom half of the sphere. Simultaneous exposure to two semi-infinite slabs implies photon paths intersect the whole surface of the sphere, and therefore there is a source directly above the person. This is not possible in this situation. At worst, when standing the base of the cliffs, between the cliffs and wastes slumped onto the storm beach, photon paths would intersect less than three-quarters of the surface of the sphere. Therefore, the model has been updated to calculate doses using dose rates for a semi-infinite slab scaled by a factor of 1.5, rather than 2.

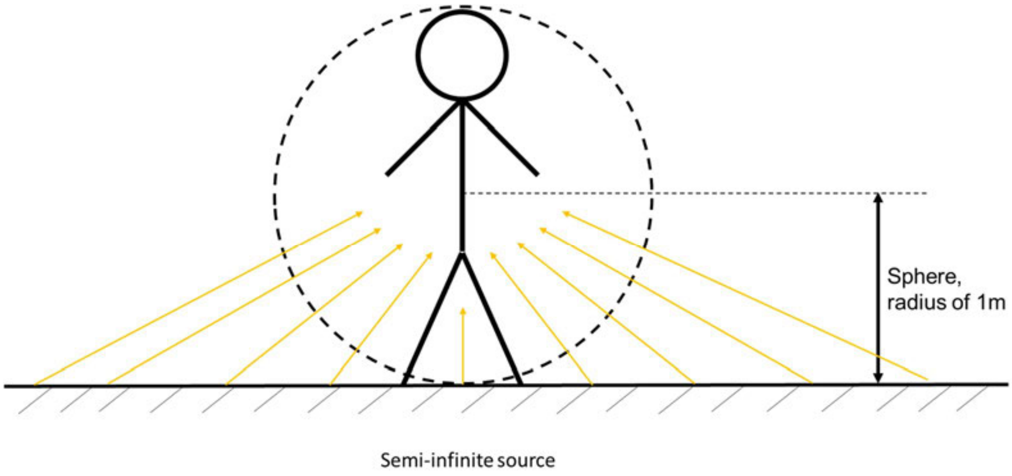

Figure 18. Geometrical assumptions underpinning dose factors for semi-infinite surface and slab sources

Similar logic indicates a person would be exposed to external irradiation from the cliffs when on the beach and foreshore. The area of the sphere intersected by photon paths decreases with increasing distance from the source, and therefore so does the dose rate. The assessment model has been updated to include external irradiation doses from the cliffs while on the storm beach. Dose factors for a semi-infinite slab are scaled by a factor of 0.2, based on the geometry assumed for the local occupational PEG described in the LLWR 2011 ESC (Towler et al., 2011). External irradiation doses from the cliffs while on the foreshore are expected to be negligible compared with doses from the foreshore, so they are not included in the assessment model.

The habits of the recreational PEG have been updated. Occupancy of the contaminated coast is increased from 50 hr/y in the 2017 PCRSA to 70 hr/y. The increased occupancy considers the results of habits surveys undertaken post-2017, and the increase in the length of coastline that would be impacted by the eroding facility with valley development (Section 3.10). The distribution of time spent on the eroding coast between the cliffs, beach and foreshore is described in Table 5.

5.3.2. Exposure to Blocks

The 2017 PCRSA assessed the potential doses from surface contaminated concrete blocks (and bricks) exposed by coastal erosion. The dose rates from surface contaminated blocks could be higher than from wastes where the activity is more evenly distributed through the whole volume of the waste. Maximum surface activity limits for blocks were calculated based on the potential doses calculated from a case involving close inspection of blocks assuming they are exposed by coastal erosion 300 years post-closure. The potential doses from hotspots with equivalent activity levels, and relatively active particles derived from the contaminated surfaces of blocks / hotspots were also assessed. It was assumed that in addition to complying with the maximum surface activity limit, individual blocks would also comply with the consignment activity limits.

The potential doses from blocks disposed to the existing disposal area and the valley area are the same, therefore additional assessment calculations are not needed for the valley area. Development of the valley area does increase the opportunity for the disposal of blocks, and disposal blocks from a wider range of sources with a wider range of fingerprints. However, the current Pile chimney project is the only major demolition project that is expected to generate large numbers of blocks while CLESA is operational.

Subsequent to the 2017 PCRSA it was noted that for certain alpha radionuclides it is mathematically possible for blocks to exist that could comply with CLESA's Permit but result in higher doses than the criterion of 20 μSv from one hour of close inspection. The relevant alpha radionuclides (e.g. Ra-226, Th-232) are only present at trace levels in Sellafield processes and waste streams, so it is very unlikely that blocks that could lead to doses above the target maximum could ever arise. Note the relevant alpha radionuclides are not present in the fingerprint of the Pile chimney blocks.

The relevant alpha radionuclides need to form a notable portion of the total activity, and the blocks would have to be larger than the maximum block size considered in the 2017 PCRSA (a sphere with a radius of 0.6 m giving a mass of ~2 tonnes for structural concrete), or activity would need to penetrate into the block giving a thicker layer of contamination than the 1 mm assumed in the 2017 PCRSA.

The approach used in the 2017 PCRSA to calculate potential doses from blocks is used to calculate the potential doses from blocks that are larger than considered in the 2017 PCRSA, and where activity has penetrated into the surface. The results are used to identify simple criteria, which supplement the existing Permit limits, that could be applied to check the acceptability of any blocks arising in the future with non-trivial levels of alpha contamination.

5.3.3. Headland Formation

As CLESA erodes a headland could be formed from surface contaminated blocks. A new ‘angler’ PEG is introduced who is assumed to regularly fish from the headland. The headland is assumed to form after 350 years post-closure, once CLESA is partly eroded. The headland is assumed to be formed from blocks with an average bulk activity of 50 Bq/g, based on the average activity of the Pile chimney blocks (Section 3.3). For a given average bulk activity the thickness of contamination would be greater on larger blocks than smaller blocks, so larger blocks would result in higher doses. The blocks are assumed to weigh 10 tonnes each, which is greater than typical for the Pile chimney blocks, and therefore likely to be cautious.

The blocks may be bagged when disposed, e.g. the Pile chimney blocks. It is assumed bags are partially degraded but potentially intact when they are exposed in the cliffs by coastal erosion. Bags may be ripped open as blocks slump onto the storm beach, but if not, they will degrade and break apart on timescales of a few years when exposed to UV, storm waves and abrasion in the coastal environment. Therefore, credit is not taken for containment of loose contamination by bags.

Although wave splash and abrasion in the coastal environment would be expected to remove significant loose contamination from the surface of the blocks (AECOM, 2017), cautiously it is assumed there is no significant erosion of the contaminated surfaces, reducing the activity the angler is exposed to. The angler PEG is assumed to spend 70 hr/y fishing from the headland (Section 3.10.3).

Doses are calculated for two waste fingerprints: the Pile blocks fingerprint, and the assumed future bulk waste fingerprint. The surface activity concentration is assumed to be at the Permitted limit, i.e.

beta/gamma activity (Bq/g) / 40,000 (Bq/g) + alpha activity (Bq/g) / 1700 (Bq/g) = 1

This leads to different contaminated layer thicknesses for the two fingerprints: 0.42 mm for the Pile chimney fingerprint and 0.49 mm for the fingerprint of recent disposals. (Note these thicknesses assume uniform activity concentration with depth. These layers are sufficiently thin that any decrease in the activity concentration with increasing depth into the surface is not important).

Doses are calculated due to external irradiation from the blocks and inadvertent ingestion of surface contamination (secondary ingestion). External irradiation doses are calculated using standard literature dose factors for a semi-infinite surface source (LLWR, 2011b). Ingestion doses are calculated using a secondary ingestion coefficient of 10^{-4} (mg/hr)/(mg/m^2) of removable contamination and assuming that only 1% of the surface activity present is removable on contact (Sumerling, 2013b).

5.4. Inadvertent Human Intrusion

For all human intrusion calculations, the assessment models cautiously assume there is no loss of radioactivity by leaching during the operational phase, or post-closure. Only radioactive decay and ingrowth are considered.

5.4.1. Borehole Driller

The borehole driller is assumed to be exposed to excavated material from 7 boreholes; 5 drilled into the existing disposal area and 2 drilled into the valley area. The number of boreholes is based on the spatial density of site investigation boreholes assumed in the LLWR 2011 ESC.

The 5 boreholes in the existing disposal area are assumed to be 20 m deep and the radionuclide concentrations in the excavated material are the average of the existing and assumed future wastes disposed in this area, plus clean material from the cap. The 2 boreholes in the valley area are assumed to be shallower, at 10 m deep, and end before penetrating the basal liner. If the boreholes were assumed to be the same depth as the boreholes in the existing disposal area, this would increase the exposure time of the borehole driller but decrease the average concentration of the excavated material, because the borehole would penetrate the original Calder landfill and its extension where the average activity of waste is much lower.

The borehole driller is assumed to be exposed through external irradiation, inhalation of radioactive dust and inadvertent ingestion. The site investigation works are assumed to take 96 hours based on the durations described in Hicks and Baldwin (2011). The dose calculations are described by Hicks and Baldwin (2011) and are not repeated in detail here. They include calculation of external doses from the pile of excavated spoil adjacent to the borehole. Doses are calculated using standard dose factors for a semi-infinite slab multiplied by a scaling factor to account for the finite dimensions of the pile of spoil. Hicks and Baldwin (2011) used a scaling factor of 0.1 for the pile of spoil from a 20 m deep borehole. The pile of spoil would be smaller for a 10 m deep borehole than a 20 m deep borehole, and therefore the scaling factor would be less than 0.1. However, cautiously, the scaling factor of 0.1 is also applied to the 10 m deep boreholes.

5.4.2. House Construction

The construction worker is assumed to be exposed through external irradiation, inhalation of radioactive dust and inadvertent ingestion. The mathematical models for the dose calculations are the same as those for the borehole driller, except that external doses are calculated assuming the area of waste exposed at the ground surface is large enough to the treated as a semi-infinite slab.

As described in Section 4.2.2, the construction worker is assumed to be exposed to the wastes for 640 hours. Dose factors, dust loadings and inhalation rates are taken from the LLWR radiological handbook (LLWR, 2011b).

5.4.3. Site Occupancy

A site occupant is assumed to always be present. They spend 80% of their time indoors and 20% outdoors (Section 4.2.2). Inside they are assumed to be exposed by external irradiation, inhalation of radioactive gases (Section 5.2) and consumption of fruit and vegetables grown in the garden. Outdoors they are exposed through external irradiation, inhalation of dust and inadvertent ingestion of soil.

In the assessment calculations, doses from external irradiation indoors and outdoors are calculated assuming the exposed wastes are a semi-infinite slab. However, indoors the house base slab provides significant shielding. The base slab is assumed to be 350 mm thick (Figure 12). The amount of shielding is radionuclide specific. The key radionuclide for external irradiation is assumed to be Cs-137 and its daughter Ba-137m. The concrete half-thickness for Cs-137/Ba-137m, i.e. the thickness of concrete needed to reduce the dose rate by half, is 48 mm (NRC, 2011). Therefore, the dose rate is reduced by a factor of 0.5^(350mm/48mm) = 0.006. This is expected to be a small overestimate because at this number of half-lengths there would be some ‘buildup’[11] which would reduce the effectiveness of shielding. Therefore, the shielding factor is rounded up to 0.01.

Doses from inhalation of radioactive gases and ingestion of fruit and vegetables contaminated by C-14 gas are calculated using the approaches described in Section 5.2. Doses from inhalation of dust, inadvertent ingestion of soil, and ingestion of fruit and vegetables that have taken up radionuclides from contaminated soil are calculated using the models and data described by Hicks and Baldwin (2011).

5.5. Bathtubbing

5.5.1. Bathtubbing Reference Case

Bathtubbing is only considered to occur in the earlier than expected cap failure scenario. This scenario is unchanged from the 2017 PCRSA. The cap is assumed to degrade over a 100 year period, so the cap is nearly fully degraded at the end of the period of authorisation. It is assumed there are not any passive drains, or the passive drains are not functioning as designed. Therefore, bathtubbing begins shortly after the end of the PoA and water discharges to the ground surface and surface soils along the south-west and north-west sections of the

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[11] Photons that are scattered towards the receptor by the shielding material.

cap perimeter (Figure 19). In the assessment calculations bathtubbing is assumed to begin at the end of the PoA, and all the water that infiltrates through the cap is assumed to discharge at the perimeter of the cap.

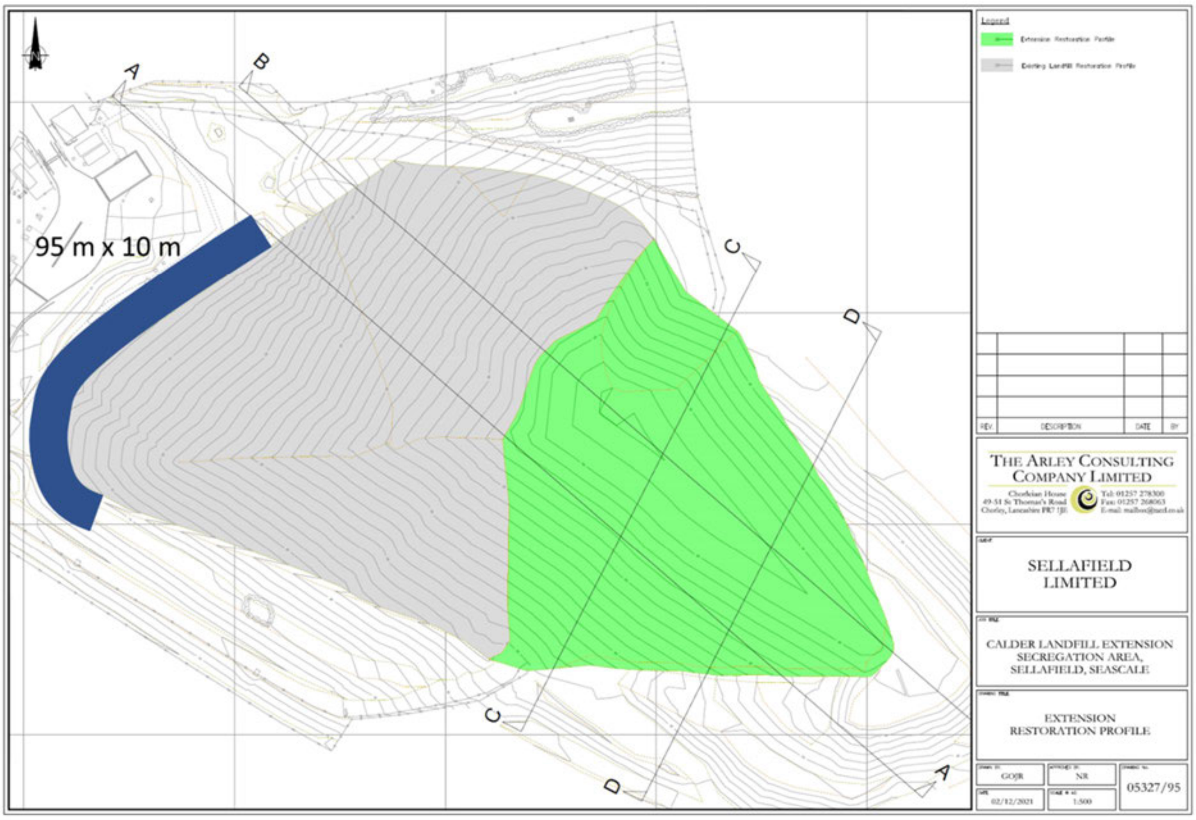

Figure 19. Area of soil assumed to be impacted by bathtubbing

The ground in the discharge area is boggy at times, and radionuclides are present in the water and sorbed onto the soil. The soil is assumed to have the same properties of the drift geology. The zone is assumed to be only 10 m wide and 0.3 m deep, so radionuclides are concentrated into a relatively small area. The 2017 PCRSA assessment model did not include leaching from the soils in the discharge area by rainfall. This process has been added into the assessment model to make it more realistic.

The amount of Hydraulically Effective Rainfall (HER) draining through the soil to the underlying geology is assumed to be 683 mm/y in the assessment model. This is based on the present day CLESA water balance (Section 3.5). This value does not include additional water from runoff from the cap, or losses through transpiration. However, this simplification is not expected to have a large impact on the calculated doses and conclusions drawn from the assessment.

Recreational users of the coast (the 'recreational' PEG) are assumed to spend time on this contaminated ground, for example there may be a coastal path around the base of the cap, although this is a cautious assumption as the ground could often be boggy. The extent of the area of contaminated ground is similar to the 2017 PCRSA, so the assumed exposure time is unchanged, i.e. 5 hr/y (Section 3.10.3). Doses occur due to external irradiation, inadvertent ingestion and inhalation.

Doses to non-human biota are calculated using version 2.0 of the ERICA assessment tool (the 2017 PCRSA used ERICA version 1.2.1). Consistent with the approach used in the 2017 PCRSA, a Tier 2 assessment of potential dose rates to terrestrial non-human biota is undertaken. Dose rates are calculated using soil radionuclide concentrations at 300 years post-closure, because the 2017 PCRSA showed this leads to higher dose rates than soil radionuclide concentrations shortly after the end of the PoA. H-3 and C-14 are treated as gases in ERICA. These radionuclides are not included as the concentrations would be very small compared with the concentrations of more strongly ionising radionuclides present in the soil and soil porewater. Default ERICA equilibrium concentration ratios and occupancy factors are used. However, only biota that could reasonably be supported by the media present in the contaminated area have been included in the assessment.

5.5.2. Bathtubbing Variant Case 1 – Radium Sorption

The reference case retains sorption distribution coefficients chosen for the original PCRSA (Nexia, 2006). The values chosen for Ra were 6E-03 m^3/kg for sorption onto the waste and 0.49 m^3/kg for sorption onto the unconsolidated (drift) geology. The bathtubbing reference case assumes soils in the area impacted by bathtubbing are derived from the drift geology, and therefore also have a sorption distribution coefficient of 0.49 m^3/kg.

The sorption distribution coefficient chosen for the waste is inconsistent with the value chosen for the drift, given that the waste is mainly soil and spoil. It is also lower than values typical for soils, and the value chosen for sorption onto soil in the LLWR trenches in the LLWR 2011 ESC. IAEA (2010) gives a mean sorption distribution coefficient of 2.5 m^3/kg for 51 soil samples (range 1.2E-02 m^3/kg to 9.5E+02 m^3/kg) while Kelly et al. (2011) chose a value of 0.1 m^3/kg for soil in the LLWR trenches. In this variant case a sorption distribution coefficient of 0.49 m^3/kg is assumed for the waste.

5.6. Riverine Erosion

The riverine erosion scenario is unchanged from the 2017 PCRSA. It is assumed that riverine erosion undercuts the north side of CLESA, resulting in slumping and exposure of the wastes. Note riverine erosion only exposes wastes in the existing disposal area, it does not expose wastes in the valley area. The wastes would be exposed in a steep bank, at an elevation several metres above the river. The steep bank would extend down to river and slumped material would be present on the bank. People (the angler PEG) are assumed to spend time standing on the slumped material fishing.

Note the area that could be impacted by riverine erosion is not increased by valley development, but recent habits data indicates that the most exposed individuals could spend more than 50 hr/y angling, so a value of 70 hr/y has been adopted (Section 3.10.3). The updated assessment calculations also explore the impacts of the updated fingerprint for future disposals (Section 3.3) on the calculated doses.

The assessment modelling approach has been updated to provide a slightly more realistic calculation of risks. The angler is assumed to be exposed to the slumped wastes and *in situ* wastes exposed higher up the riverbank from 200 y post-closure (Section 4.2.8). Cautiously it is assumed there is no dilution by slumped capping materials or slumped geological materials that underly CLESA. Doses from external irradiation are calculated using dose factors for a semi-infinite slab source and a geometry factor of 1.5 for the reasons discussed in Section 5.3.1.

6. Assessment Results

6.1. Normal Evolution Scenario

6.1.1. Reference Case

6.1.1.1. Groundwater Pathway

The risks from drinking foreshore seeps are assessed at two locations, 150 m from the edge of the facility (at the current closest beach location, Figure 20) and 20 m from the edge of facility (representing the pathlength shrinking due to coastal erosion, Figure 21). In both cases, the risks from drinking foreshore seeps are dominated by I-129, with H-3 being the key contributor at early times, and C-14 being the key contributor at later times. With the shorter pathlength, there is an increased contribution from sorbing radionuclides that migrate relatively slowly (including Np-237).

The calculated peak risk from drinking foreshore seeps at the current beach location is 3.0E-08 y^{-1}, so well below the risk guidance level of 1E-06 y^{-1}. This is a factor of two lower than the peak risk from the 2017 PCRSA NES groundwater reference case (6.5E-08 y^{-1}), but very similar to the calculated peak risk for the 2017 PCRSA variant case where leaching during the operational period was included (3.3E-08 y^{-1}). With the shorter pathlength, the peak risk is slightly higher at 3.1E-08 y^{-1}.

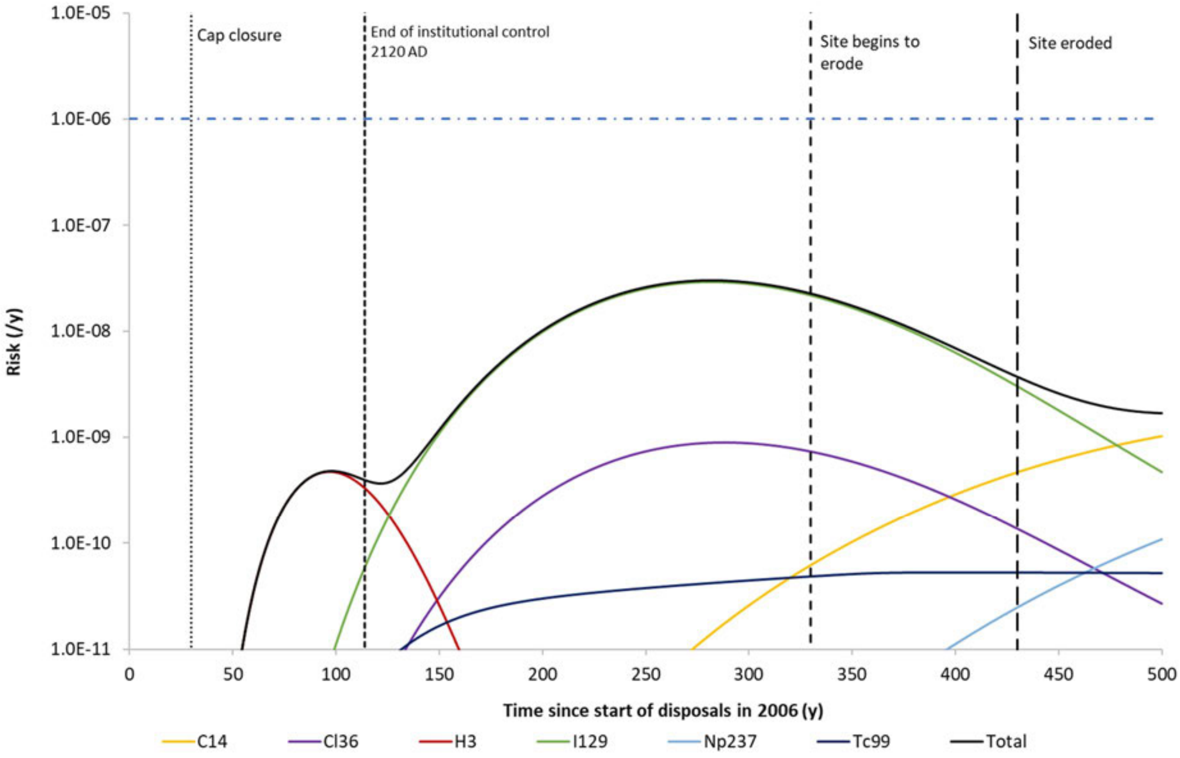

Figure 20. NES reference case risks to the beach seeps PEG from drinking water from the current foreshore location, compared with the GRA risk guidance level of 1E-06 y^{-1}

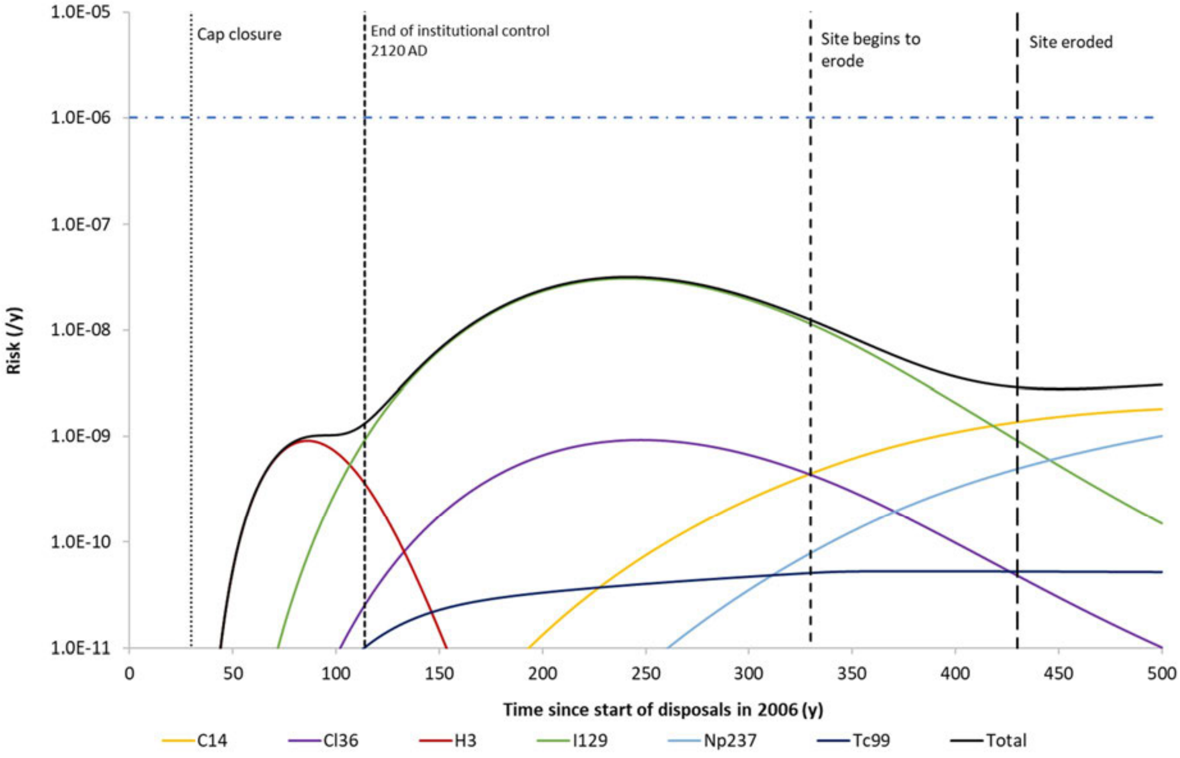

Figure 21. NES reference case risks to the beach seeps PEG from drinking water from the foreshore location after coastal erosion, compared with the GRA risk guidance level of 1E-06 y^{-1}

6.1.1.2. Coastal Erosion Pathway – Exposure to Bulk Wastes

The calculated peak risk from exposure to the eroding facility is 1.7E-08 y^{-1}, which is nearly two orders of magnitude below the risk guidance level (Figure 22). Risks are dominated by Ra-226 and other actinides. The largest contributor to dose is the time spent on the storm beach, during which the recreational PEG is now also assumed to be exposed to some external irradiation from waste in the cliffs. The peak risk is slightly higher than the 2017 CLESA PCRSA (1.1E-08 y^{-1}), which reflects the higher Ra-226 concentration assumed for future disposals, longer facility and increased recreational PEG occupancy.

The risks from long-lived radionuclides are approximately constant with time while the site is being eroded, with some variation due to the changing volumetric erosion rate, but then decrease once erosion is complete and the residual wastes are gradually transported away from the storm beach and foreshore to offshore sediment sinks. Doses from Cs-137 decrease during the period of erosion due to decay.

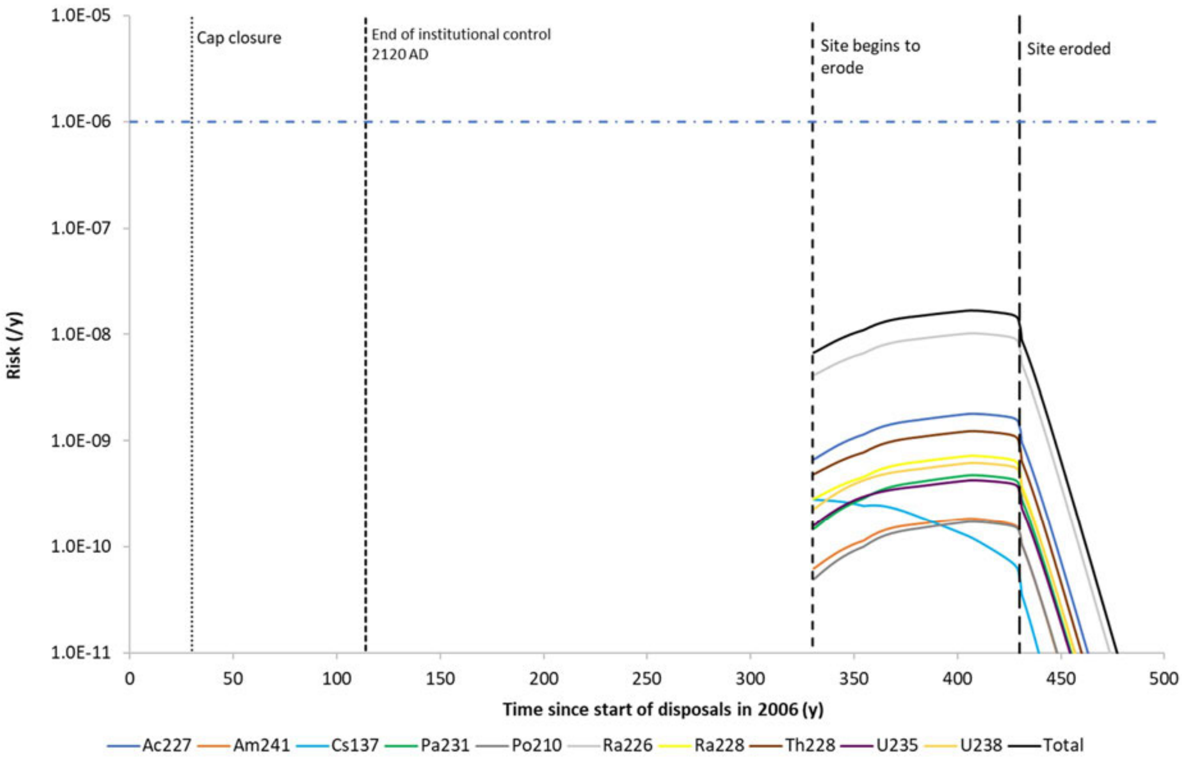

Figure 22. NES reference case risks to the recreational PEG during erosion of CLESA, compared with the GRA risk guidance level of 1E-06 y^{-1} (only the top 10 radionuclides contributing to dose are shown)

6.1.1.3. Coastal Erosion Pathway – Close Inspection of Blocks

The tables below show the doses from blocks of different sizes at 300 y. Dose rates rather than risks are presented in this instance because the relevant radiological criterion is a maximum of 20 µSv from one hour of close inspection (this corresponds to the risk target of 1E-6 y^{-1} for a single inspection event). The first column of each table relates to a similar block size and surface contamination thickness to that considered in the 2017 PCRSA. The subsequent columns present the doses assuming larger and heavier blocks, and greater thicknesses of contamination.

- Table 12 shows the doses from I-129. This is the most limiting beta / gamma emitting radionuclide. Blocks with a mass >10 tonnes and 1.5 mm thickness of contamination could theoretically lead to dose rates greater than the criterion of 20 µSv/hr. However, it is not credible that such blocks could be consigned to CLESA.

- Table 13 shows the doses from Cs-137, which is expected to dominate the beta / gamma activity of surface contaminated blocks. For CLESA's maximum surface and consignment activity limits, the dose rate cannot exceed the criterion of 20 µSv/hr.

- Table 14 and Table 15 show the doses from U-238 (this more limiting than U-234) and Pu-239 respectively. These radionuclides are likely to be present in wastes from the Sellafield site. For the CLESA maximum surface activity limits, it is unlikely that the criterion of 20 µSv/hr would be exceeded, because the thickness of contamination would have to be greater than ~2 cm over the entire surface of a very large block.

- Table 16 shows the doses from Th-232. This is the most limiting alpha emitter. Blocks with masses >2 tonnes, or with greater than 1 mm thickness of contamination, theoretically lead to dose rates greater than the criterion of 20 µSv/hr. Ra-226 and some of the alpha emitters expected to be only minor contributors to contamination give similar dose rates. However, it is very unlikely that blocks generated at the Sellafield site would contain sufficient Ra-226, Th-232, etc to lead to dose rates exceeding 20 µSv/hr.

These results provide confidence that the existing surface and bulk activity constraints should ensure that the potential dose rates from blocks that could reasonably be expected to be consigned to CLESA would give rise to dose rates less than the criterion of 20 µSv/hr, even if the block size and, or thickness of contamination exceed that assumed in the 2017 PCRSA.

Table 12. Doses from blocks with I-129 surface contamination at 300 y post-closure

Radius	m	0.6	1	1.5	0.6	0.8	1
Thickness of Contamination	m	1.00E-03	1.00E-03	1.00E-03	2.00E-03	1.33E-03	1.47E-03
Surface Activity	Bq/g	40000	40000	40000	20000	40000	40000
Mass of Block	kg	2.2E+03	1.0E+04	3.4E+04	2.2E+03	5.1E+03	1.0E+04
Block Activity	Bq/g	200	120	80	200	200	176
Dose rate	µSv/hr	12.5	13.6	14.4	12.5	17.5	20.0

Table 13. Doses from blocks with Cs-137 surface contamination at 300 y post-closure

Radius	m	0.6	1	1.5	0.6	0.8	1
Thickness of Contamination	m	1.00E-03	1.00E-03	1.00E-03	2.00E-03	1.33E-03	1.67E-03
Surface Activity	Bq/g	40000	40000	40000	20000	40000	40000
Mass of Block	kg	2.2E+03	1.0E+04	3.4E+04	2.2E+03	5.1E+03	1.0E+04
Block Activity	Bq/g	200	120	80	200	200	200
Dose rate	µSv/hr	0.1	0.1	0.1	0.1	0.1	0.2

Table 14. Doses from blocks with U-238 surface contamination at 300 y post-closure

Radius	m	0.6	1	1.5	0.6	0.8	1
Thickness of Contamination	m	1.00E-03	1.00E-03	1.00E-03	2.00E-03	2.20E-02	1.95E-02
Surface Activity	Bq/g	1700	1700	1700	850	1700	1700
Mass of Block	kg	2.2E+03	1.0E+04	3.4E+04	2.2E+03	5.1E+03	1.0E+04
Block Activity	Bq/g	8.5	5.1	3.4	8.5	140.3	99.5
Dose rate	µSv/hr	1	1	1	1	20	20

Table 15. Doses from blocks with Pu-239 surface contamination at 300 y post-closure

Radius	m	0.6	1	1.5	0.6	0.8	1
Thickness of Contamination	m	1.00E-03	1.00E-03	1.00E-03	2.00E-03	2.00E-02	1.95E-02
Surface Activity	Bq/g	1700	1700	1700	850	1700	1700
Mass of Block	kg	2.2E+03	1.0E+04	3.4E+04	2.2E+03	5.1E+03	1.0E+04
Block Activity	Bq/g	8.5	5.1	3.4	8.5	127.5	99.5
Dose rate	µSv/hr	1	1	1	1	20	20

Table 16. Doses from blocks with Th-232 surface contamination at 300 y post-closure

Radius	m	0.6	1	1.5	0.6	0.8	1
Thickness of Contamination	m	1.00E-03	1.00E-03	1.00E-03	2.00E-03	1.00E-03	1.00E-03
Surface Activity	Bq/g	1700	1700	1700	850	1450	1250
Mass of Block	kg	2.2E+03	1.0E+04	3.4E+04	2.2E+03	5.1E+03	1.0E+04
Block Activity	Bq/g	8.5	5.1	3.4	8.5	5.4	3.8
Dose rate	µSv/hr	20	27	32	20	20	20

6.1.2. Variant Case 1 – Well

6.1.2.1. Groundwater Pathway

Similar to the beach seeps, risks from consumption of well water are dominated by I-129, with C-14 and Np-237 being larger contributors to risk at later times. The calculated peak risk is 9.4E-08 y^{-1} assuming the probability of a well being drilled and utilised for drinking water within an area that intersects the groundwater plume, before the facility is disrupted by coastal erosion, is 0.01. This ‘scenario probability’ is consistent with the 2006 PCRSA and 2017 PCRSA. The peak risk is slightly lower than the 2017 CLESA PCRSA well variant case, 2.0E-07 y^{-1}.

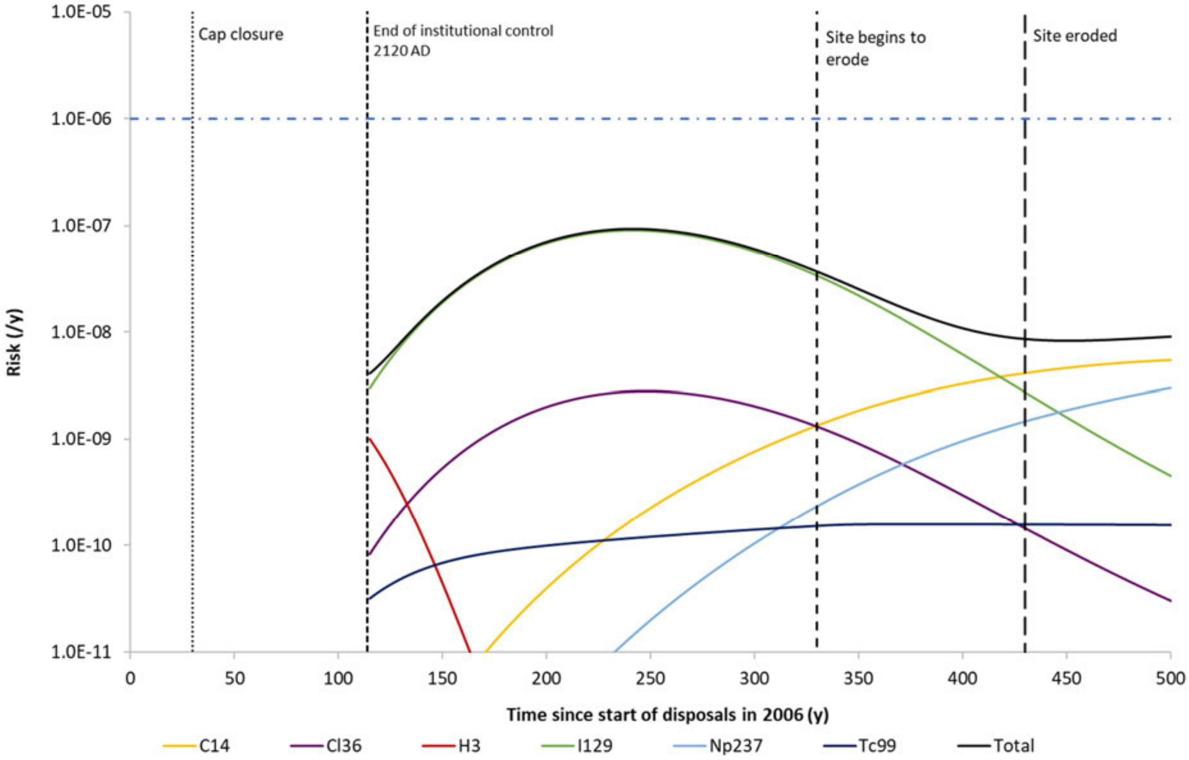

Figure 23. NES variant case 1 risks from drinking well water, assuming a probability of there being a well of 0.01, compared with the GRA risk guidance level of 1E-06 y^{-1}

6.1.3. Variant Case 2 – Vertical Drains

6.1.3.1. Groundwater Pathway

The calculated peak risk from drinking foreshore seeps at the current beach location (150 m pathlength) is 3.2E-08 y^{-1}, slightly higher than the reference case (3.0E-08 y^{-1}). The key radionuclides contributing to the risks are unchanged from the reference case (Figure 24). The increase in risk is small because the pathlength through the unsaturated zone is a minor component of the total groundwater pathlength, and the key radionuclides do not sorb, or sorb weakly. Therefore, risks are not sensitive to the extent of sorption in the unsaturated zone below the wastes.

The calculated peak risk from drinking foreshore seeps at a future beach location after coastal erosion (20 m pathlength) is 3.5E-08 y^{-1} (Figure 25), also slightly increased compared with the reference case (3.1E-08 y^{-1}). In this situation the unsaturated zone is a notable component of the overall groundwater pathlength. Therefore, the timings of the peak risks are earlier than the reference case for radionuclides that sorb.

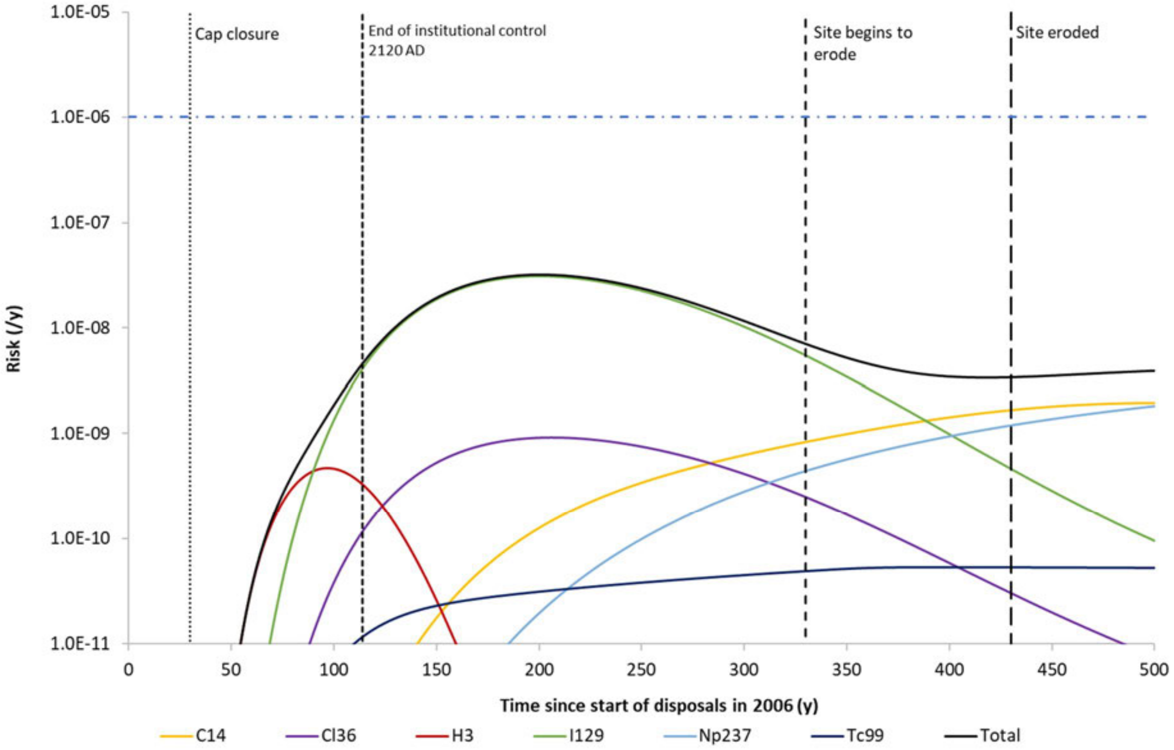

Figure 24. NES variant case 2 risks to the beach seeps PEG from drinking water at the current foreshore location, compared with the GRA risk guidance level of 1E-06 y^{-1}

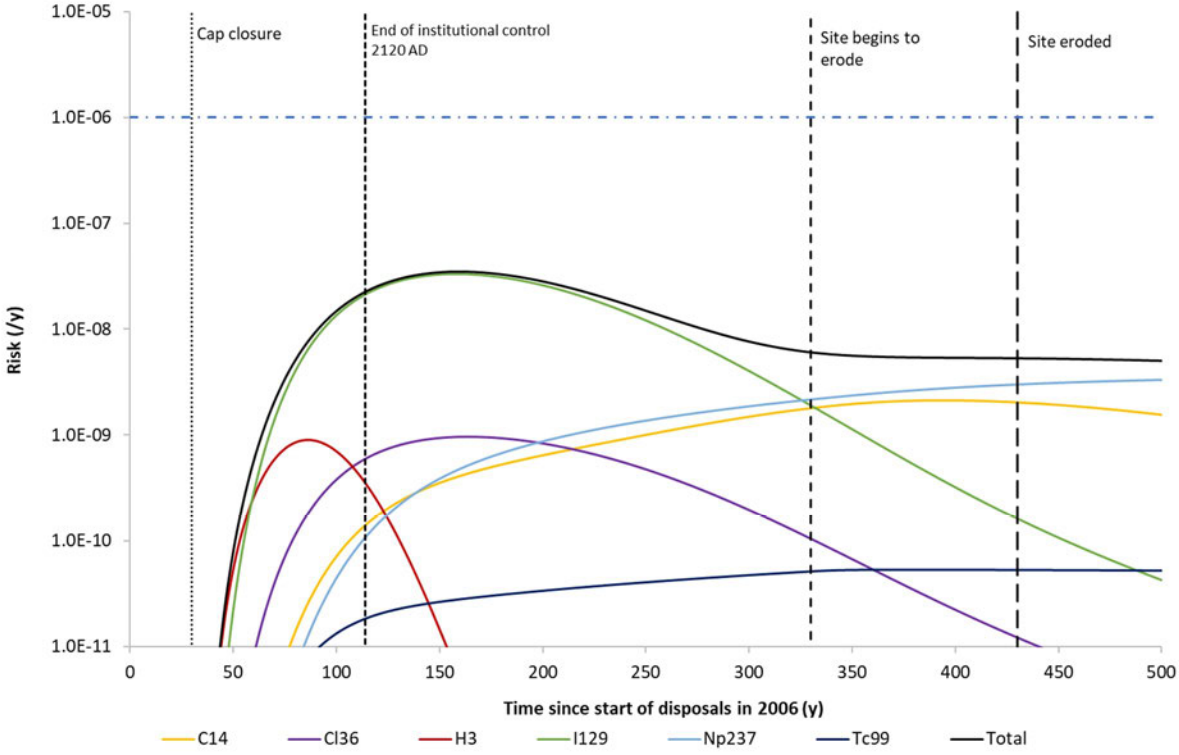

Figure 25. NES variant case 2 risks to the beach seeps PEG from drinking water at the foreshore location after coastal erosion, compared with the GRA risk guidance level of 1E-06 y^{-1}

6.2. Human Intrusion AES Calculation Cases

6.2.1. Reference Case - Site Occupant

Calculated doses are presented for each exposure pathway, followed by the total dose to a site occupant.

6.2.1.1. Gas Pathway

As calculated in Section 5.2.2, the peak dose due to consumption of C-14 in fruit and vegetables is 2E-06 mSv. Doses from the H-3 and Rn-222 gas pathways are calculated in GoldSim as described in Section 5.2.1 and 5.2.3 respectively.

Figure 26 shows the dose to a site occupant due to inhalation of H-3 gas while indoors. The peak dose is very low, 2.2E-07 mSv, and occurs immediately following the period of institutional control.

Figure 27 shows the dose to a site occupant due to inhalation of Rn-222 gas while indoors. The peak dose is 0.76 mSv and is mainly insensitive to the time at which the site becomes occupied. This is lower than the GRA dose guidance level for long-term exposures, 3 mSv.

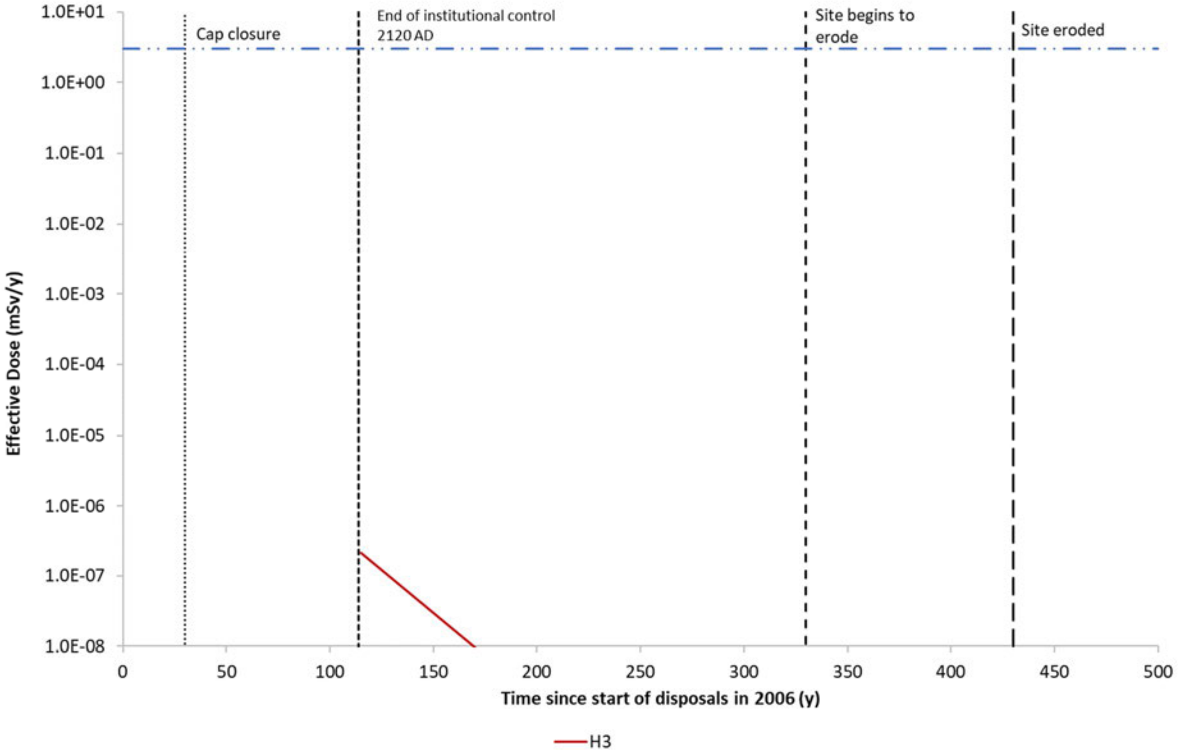

Figure 26. Dose to a site occupant from inhalation of H-3 gas compared with the GRA dose guidance level for long-term exposures of 3 mSv

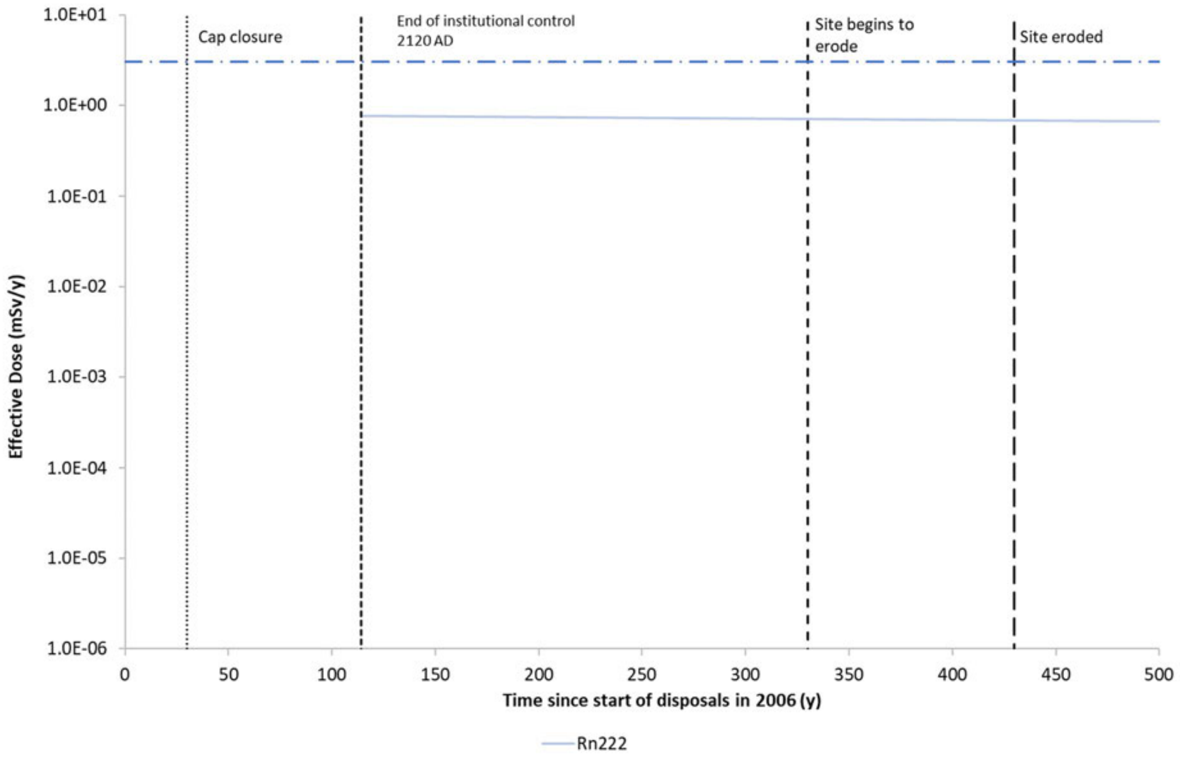

Figure 27. Dose to a site occupant from inhalation of Rn-222 gas compared with the GRA dose guidance level for long-term exposures of 3 mSv

6.2.1.2. External Irradiation Pathway

Figure 28 shows the dose to a site occupant due to external irradiation, during both indoor and outdoor occupancy of the site. The peak dose is 3.4E-02 mSv and occurs immediately following the period of institutional control. The key radionuclides contributing to dose are Cs-137 and Ra-226.

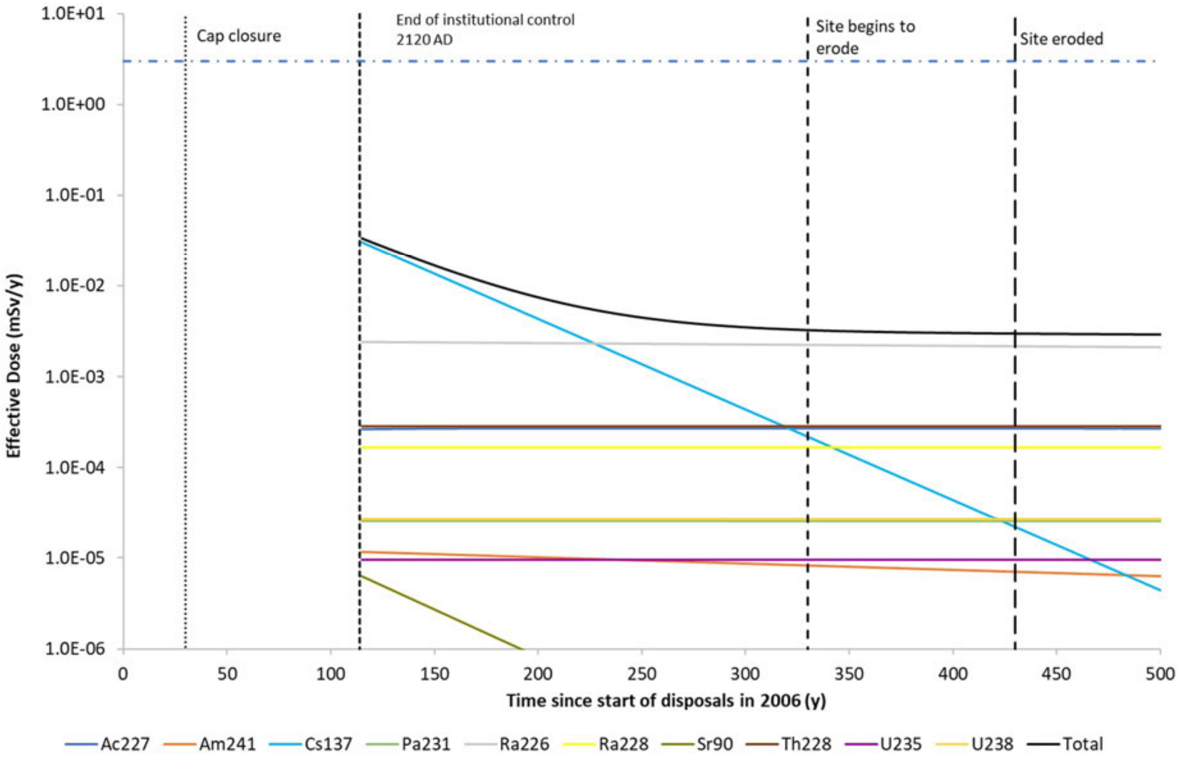

Figure 28. Dose to a site occupant due to external irradiation, indoors and outdoors, compared with the GRA dose guidance level for long-term exposures of 3 mSv (only the top 10 radionuclides contributing to dose are shown)

6.2.1.3. Inhalation Pathway

Figure 29 shows the dose to a site occupant due to inhalation of dust while outdoors (doses from inhalation of Rn-222 and H-3 gas outdoors are assumed to be negligible compared with the indoor doses).

The peak dose is 1.7E-04 mSv and is mainly insensitive to the time at which the site becomes occupied. The key radionuclides contributing to dose are Pa-231, Am-241 and Ac-227.

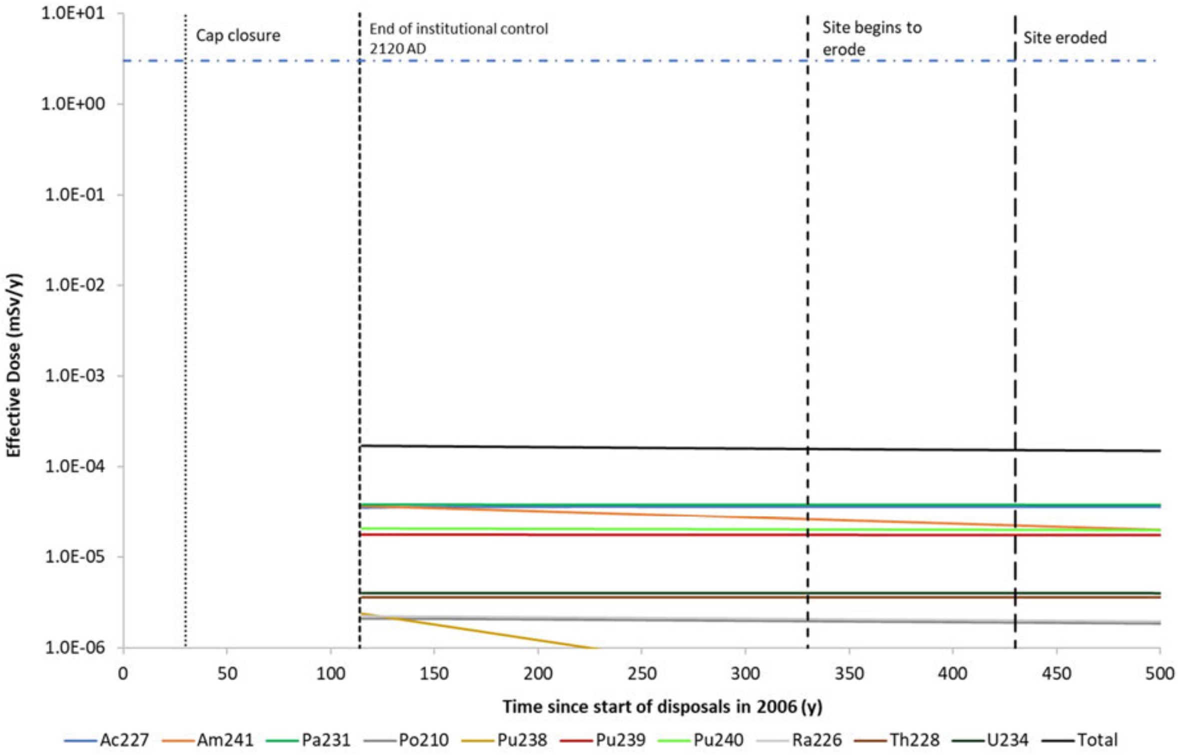

Figure 29. Dose to a site occupant due to inhalation while outdoors, compared with the GRA dose guidance level for long-term exposures of 3 mSv (only the top 10 radionuclides contributing to dose are shown)

6.2.1.4. Ingestion Pathway

Figure 30 shows the dose to a site occupant due to ingestion of crops (excluding the dose due to C-14 which is calculated in Section 5.2.2). The peak dose is 5.5E-03 mSv and occurs immediately following the period of institutional control. The key radionuclides contributing to dose are Cl-36, Cs-137 and Po-210.

Figure 31 shows the dose to a site occupant due to inadvertent ingestion of soil. The peak dose is 1.0E-04 mSv and the key radionuclides contributing to dose are Po-210 and Pb-210.

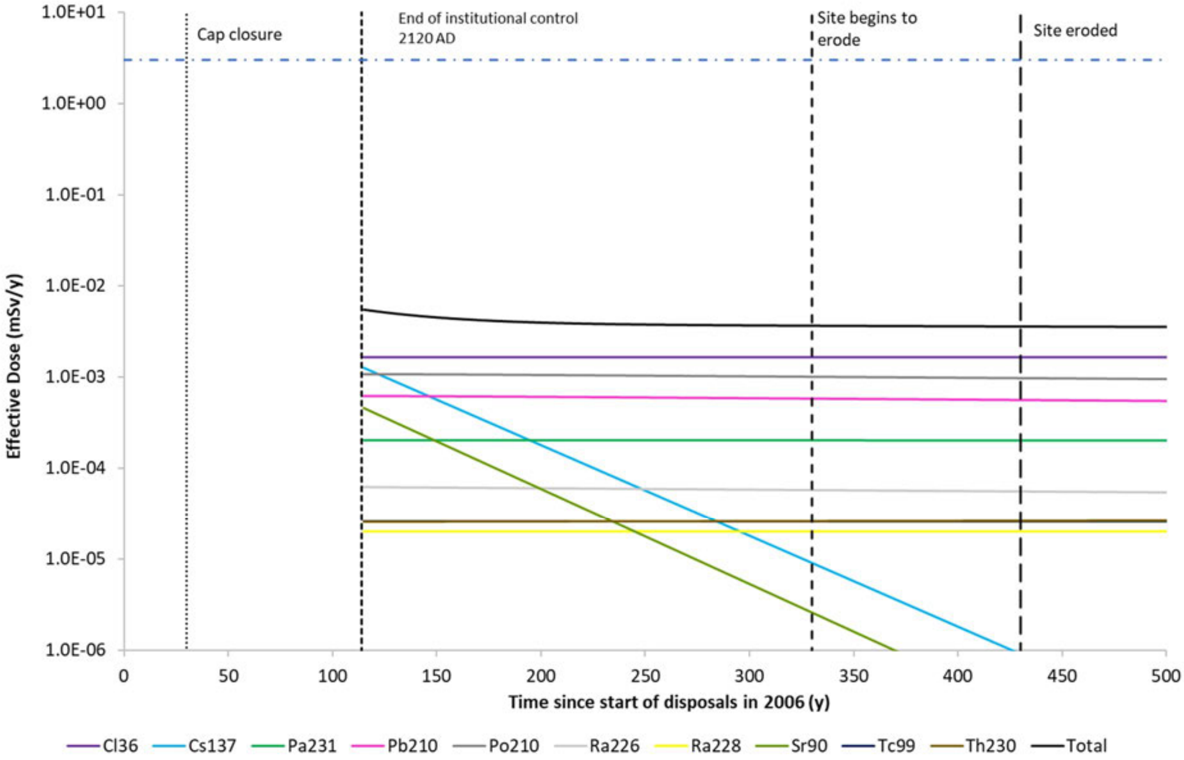

Figure 30. Dose to a site occupant due to ingestion of crops (excluding C-14), compared with the GRA dose guidance level for long-term exposures of 3 mSv (only the top 10 radionuclides contributing to dose are shown)

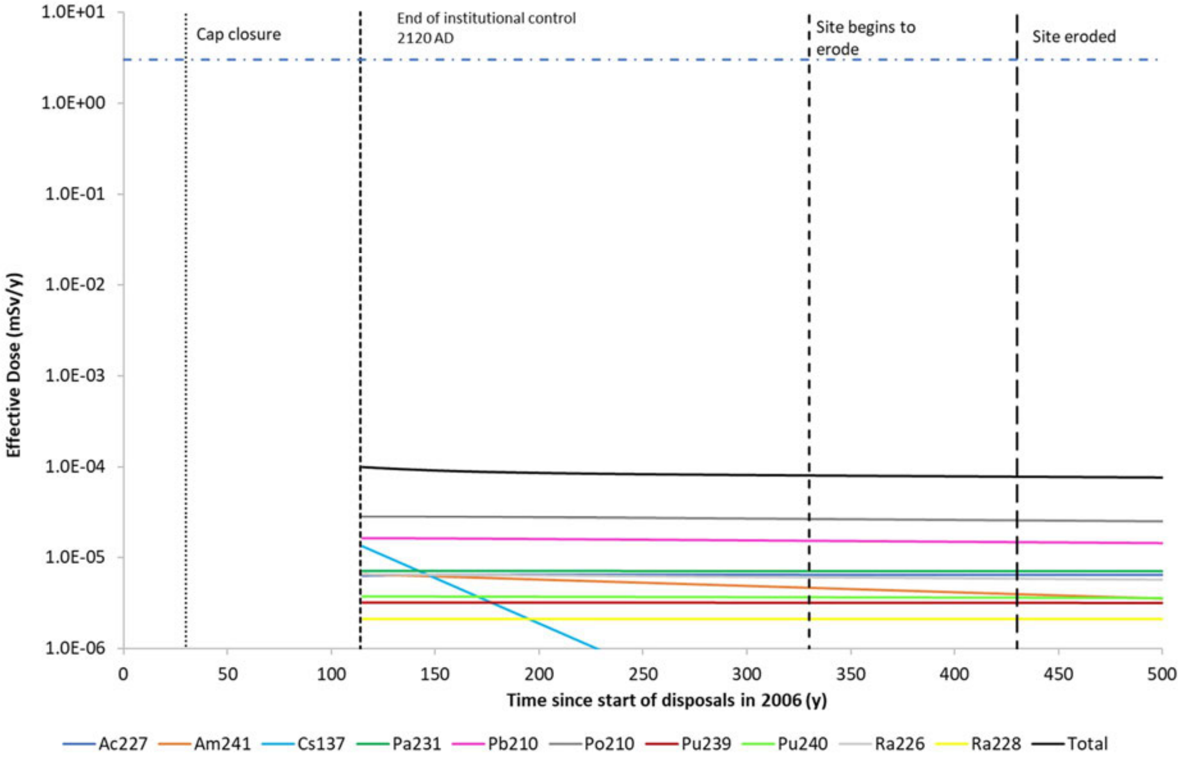

Figure 31. Dose to a site occupant due to inadvertent ingestion of soil, compared with the GRA dose guidance level for long-term exposures of 3 mSv (only the top 10 radionuclides contributing to dose are shown)

6.2.1.5. Total Dose

The calculated peak dose to a site occupant is 0.80 mSv, occurring immediately following the period of institutional control (Figure 32). The dominant exposure pathway is inhalation of Rn-222 gas.

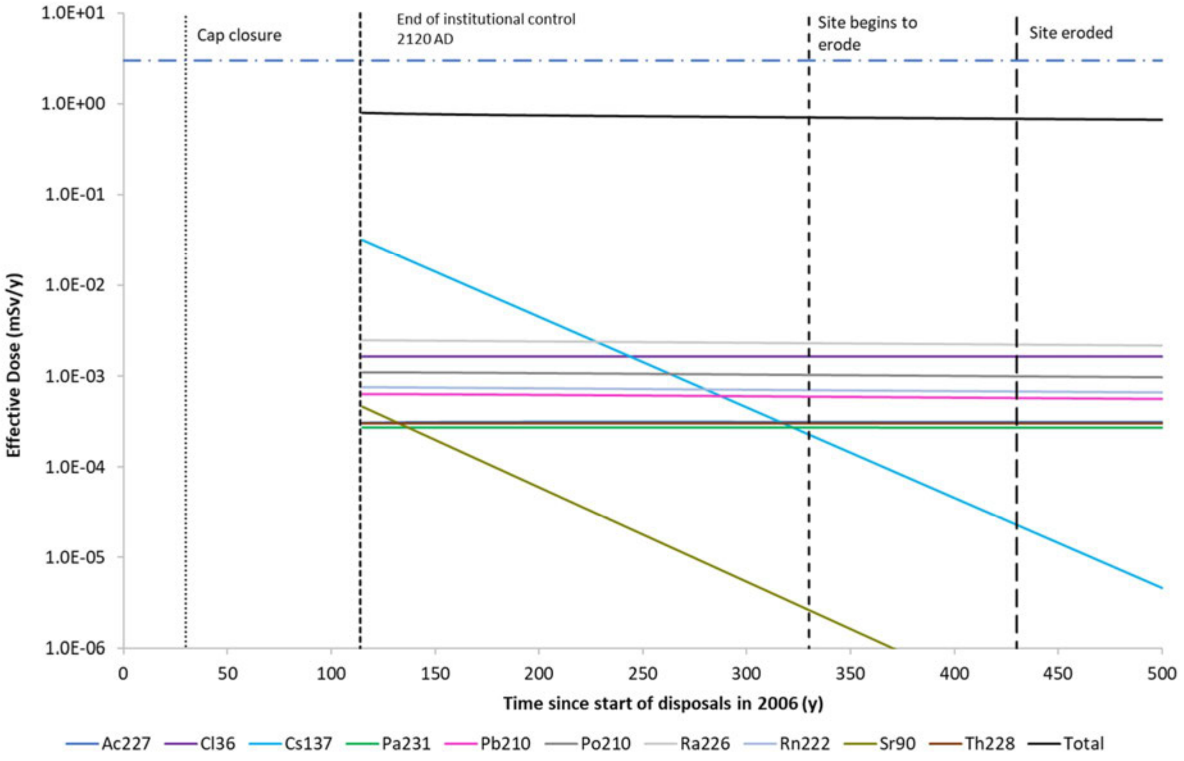

Figure 32. Doses to a site occupant compared with the GRA dose guidance level for long-term exposures of 3 mSv

6.2.2. Reference Case - House Construction Worker

Calculated doses are presented for each exposure pathway, followed by the total dose to the construction worker.

6.2.2.1. External Irradiation Pathway

Figure 33 shows the dose to a house construction worker during construction of a house on the site due to external irradiation from the wastes. The peak dose is 0.12 mSv and occurs immediately following the end of the PoA. Cs-137 provides the largest contribution to dose, followed by Ra-226.

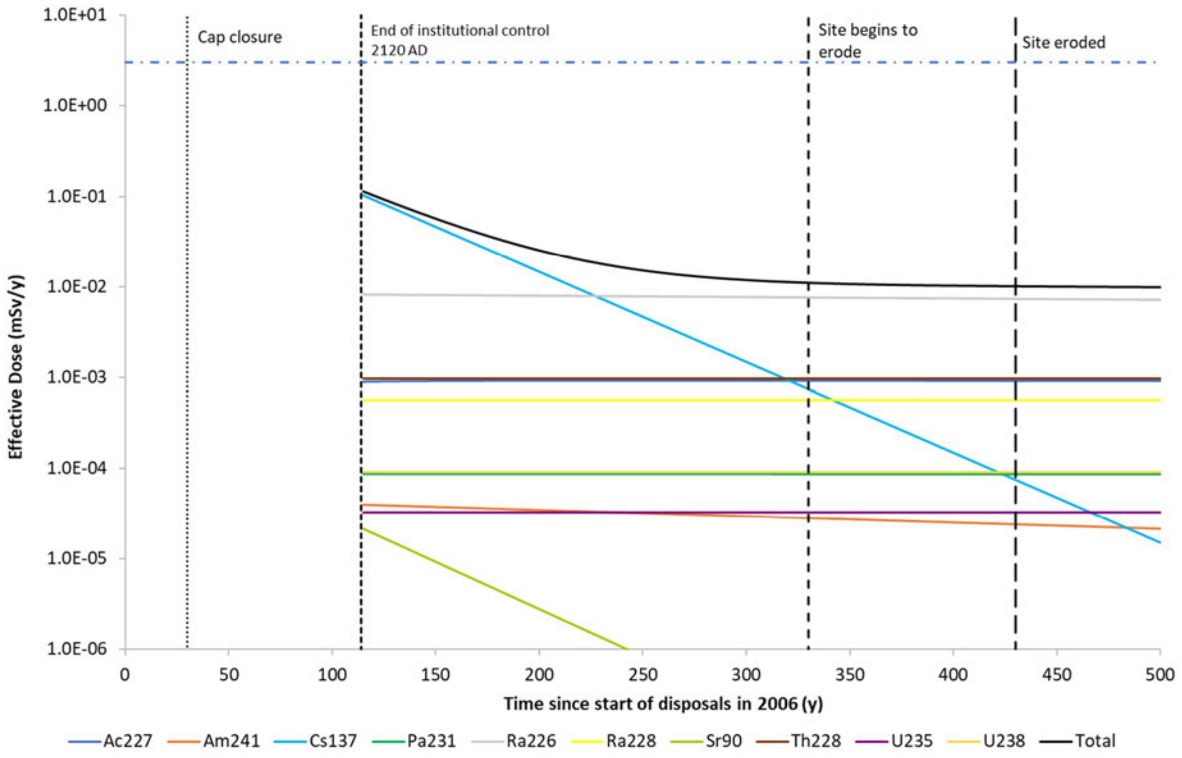

Figure 33. Doses from construction of a house due to external irradiation, compared with the GRA dose guidance level for short-term exposures of 20 mSv (only the top 10 radionuclides contributing to dose are shown)

6.2.2.2. Inhalation Pathway

Figure 34 shows the dose to the house construction worker due to inhalation. The peak dose is 7E-03 mSv and is mostly insensitive to the timing of house construction after the PoA. The key radionuclides contributing to dose from inhalation are Pa-231, Am-241 and Ac-227.

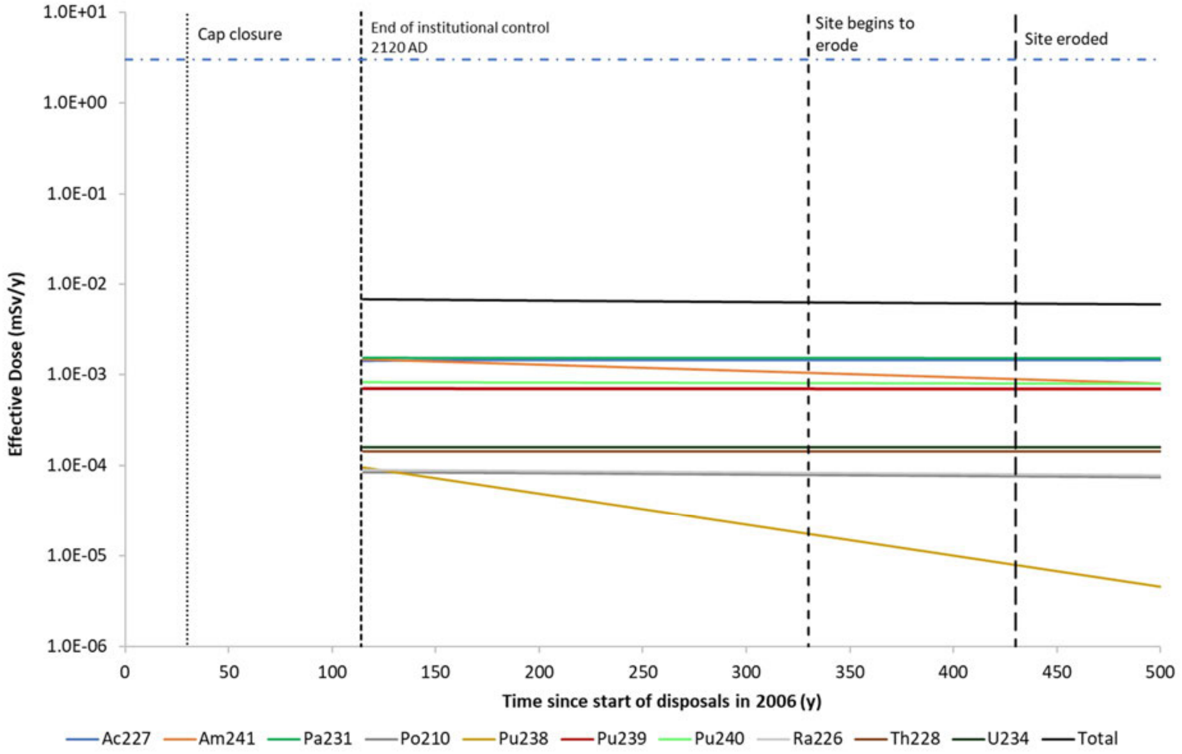

Figure 34. Doses from construction of a house due to inhalation, compared with the GRA dose guidance level for short-term exposures of 20 mSv (only the top 10 radionuclides contributing to dose are shown)

6.2.2.3. Ingestion Pathway

Figure 35 shows the dose to the house construction worker due to inadvertent ingestion. The peak dose is 5E-04 mSv and is mostly insensitive to the timing of house construction after the PoA. The key radionuclide contributing to dose from ingestion is Po-210.

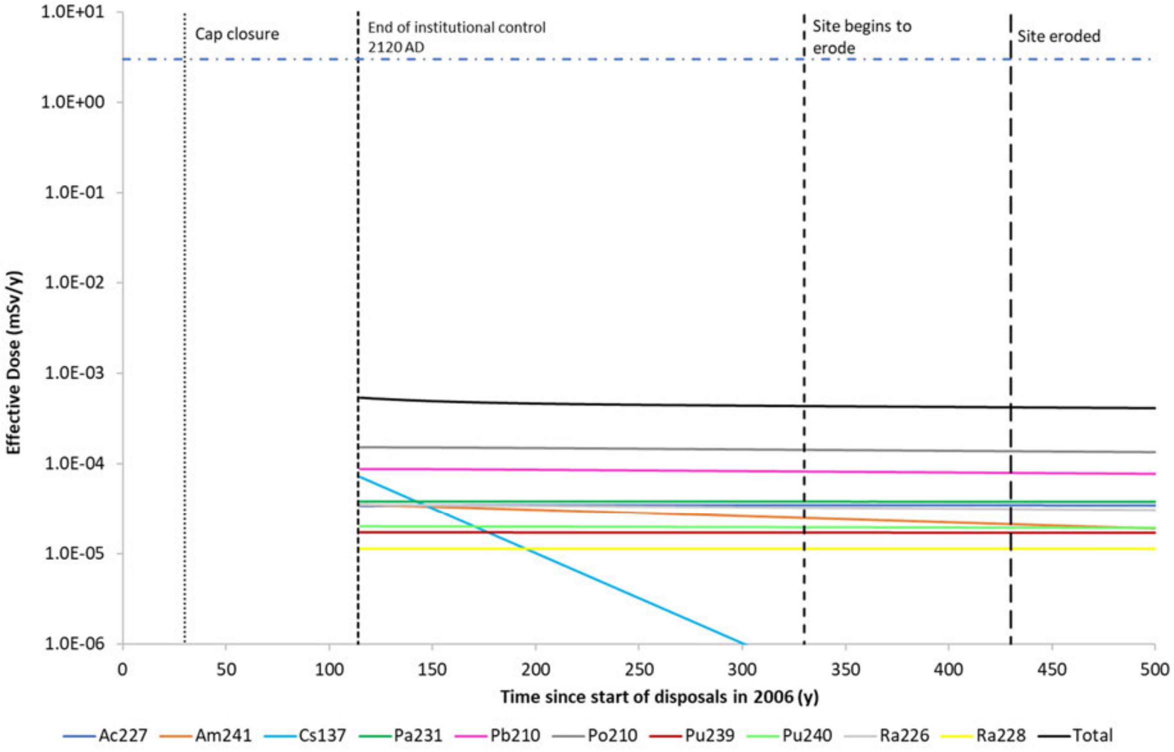

Figure 35. Doses from construction of a house due to ingestion, compared with the GRA dose guidance level for short-term exposures of 20 mSv (only the top 10 radionuclides contributing to dose are shown)

6.2.2.4. Total Dose

The calculated peak total dose to a construction worker involved in landscaping works and house building is 0.12 mSv, occurring immediately following the end of the PoA (Figure 36). Cs-137 provides the largest contribution to dose, followed by Ra-226. The dose is dominated by the external irradiation pathway. The peak dose is significantly below the dose guidance level of 20 mSv for short-term exposures.

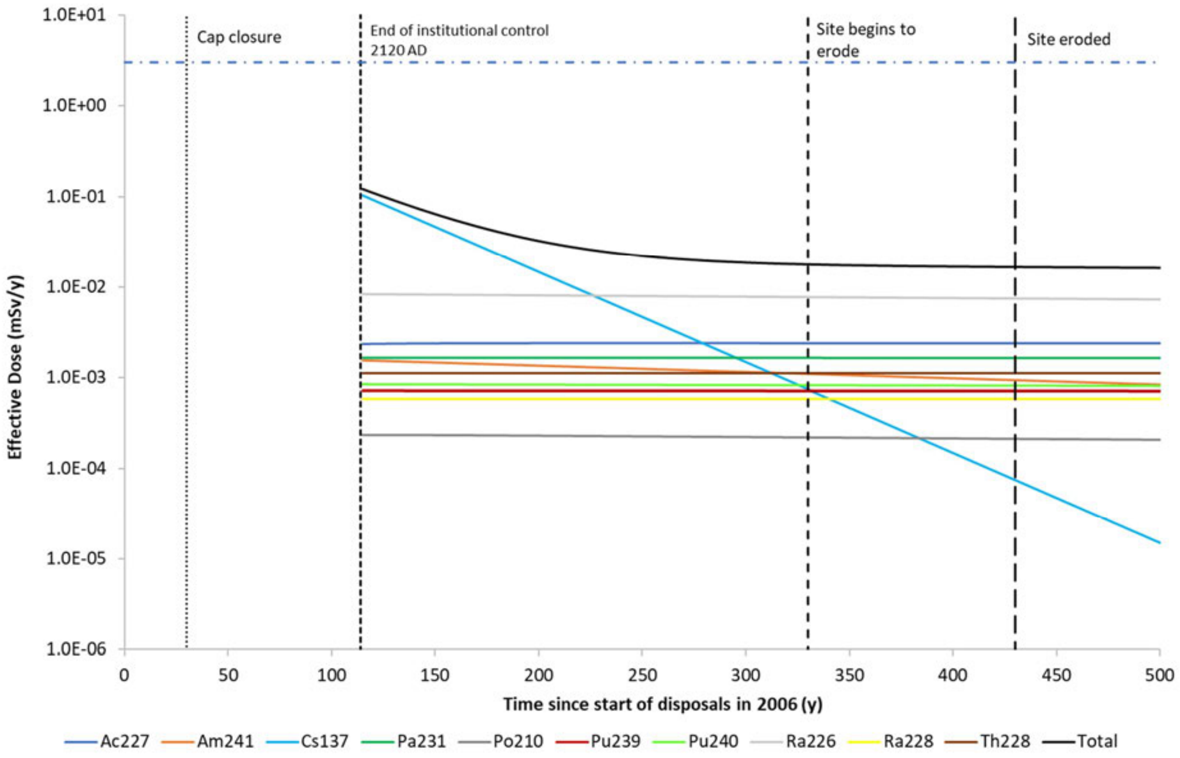

Figure 36. Doses from construction of a house compared with the GRA dose guidance level for short-term exposures of 20 mSv (only the top 10 radionuclides contributing to dose are shown)

6.2.3. Reference Case - Borehole Driller

Calculated doses are presented for each exposure pathway, followed by the total dose to a person drilling five site investigation boreholes into the existing disposal area and two (shorter) boreholes into the valley area.

6.2.3.1. External Irradiation Pathway

Figure 37 shows the dose to the borehole driller due to external irradiation. The peak dose is 9E-04 mSv and occurs immediately following the end of the PoA. The key radionuclides contributing to dose from external irradiation are Cs-137 (in the period up to 100 years following the end of the PoA) and Ra-226.

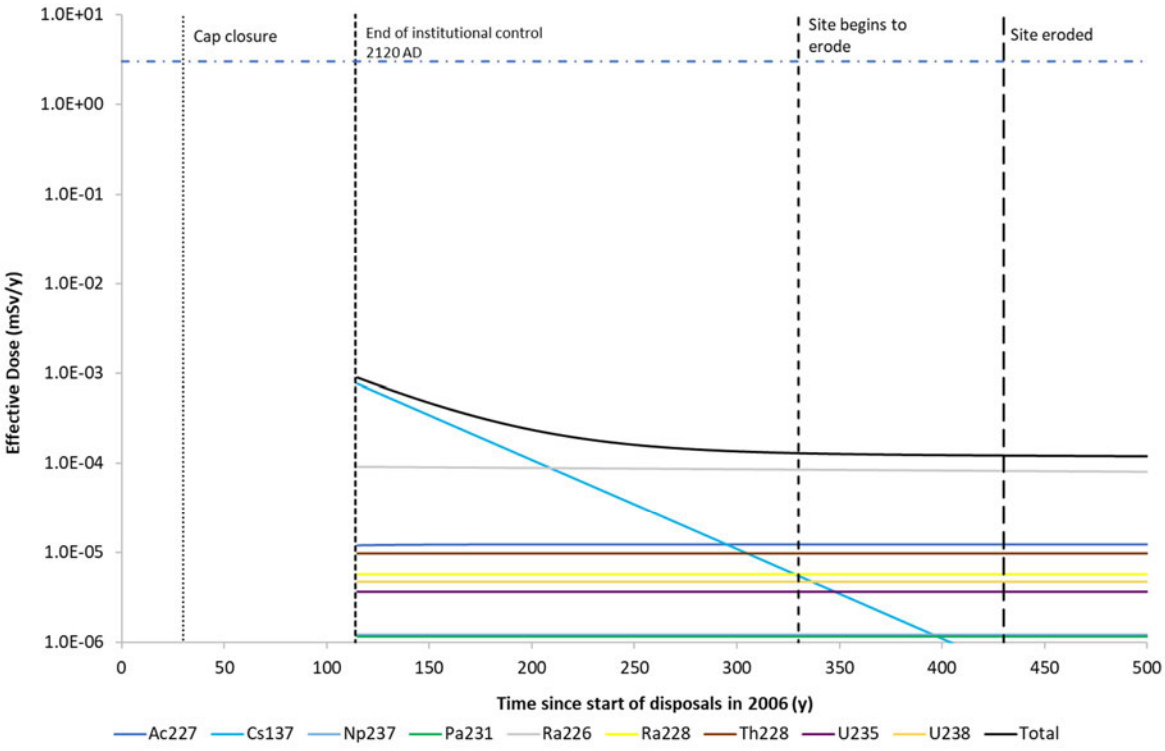

Figure 37. Doses from drilling site investigation boreholes into the existing disposal area and valley area, due to external irradiation, compared with the GRA dose guidance level for short-term exposures of 20 mSv

6.2.3.2. Inhalation Pathway

Figure 38 shows the dose to the borehole driller due to inhalation. The peak dose is 9E-04 mSv and is mostly insensitive to the timing of the borehole drilling after the end of the PoA. The key radionuclides contributing to dose from inhalation are Pa-231 and Ac-227.

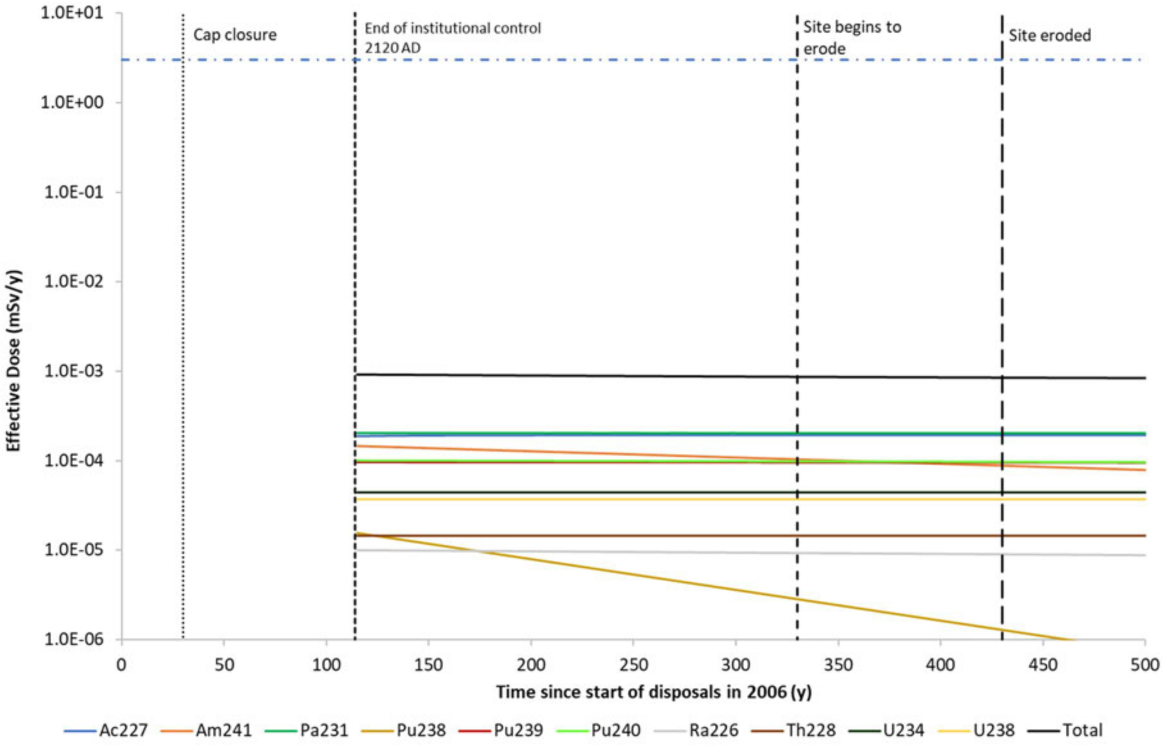

Figure 38. Doses from drilling site investigation boreholes into the existing disposal area and valley area, due to inhalation, compared with the GRA dose guidance level for short-term exposures of 20 mSv (only the top 10 radionuclides contributing to dose are shown)

6.2.3.3. Ingestion Pathway

Figure 39 shows the dose to the borehole driller due to ingestion. The peak dose is 7E-05 mSv and is mostly insensitive to the timing of the borehole drilling after the end of the PoA. The key radionuclides contributing to dose from ingestion are Po-210 and Pb-210.

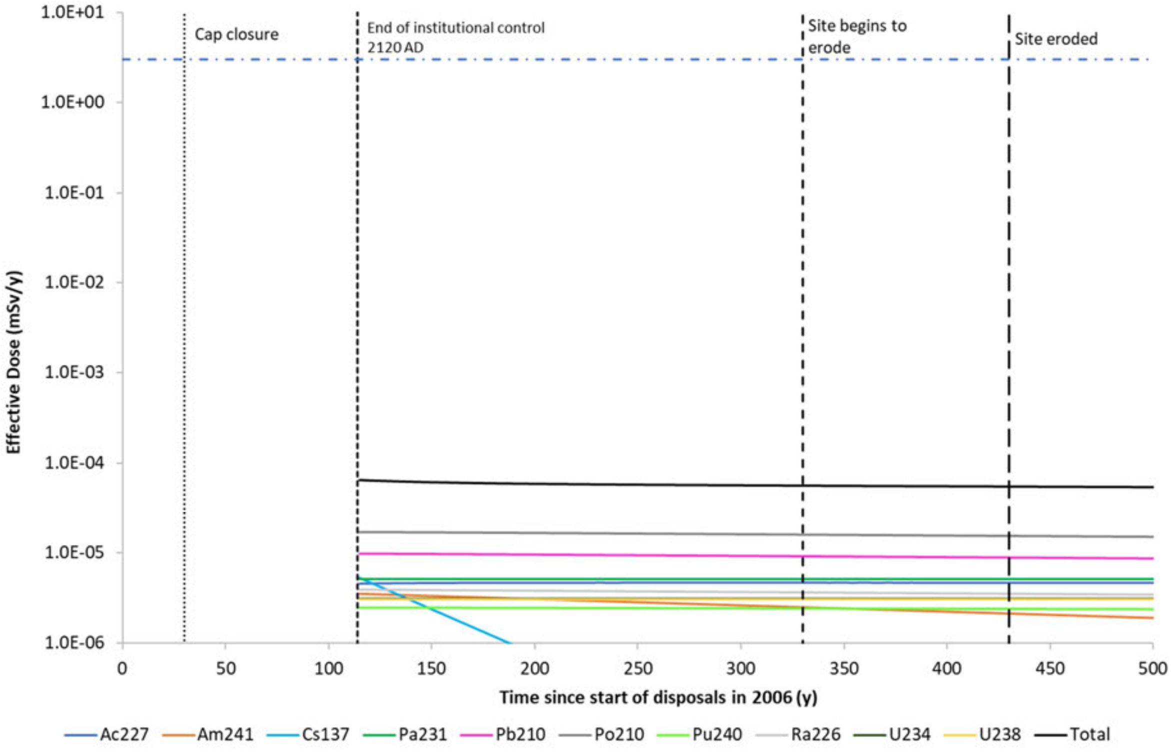

Figure 39. Doses from drilling site investigation boreholes into the existing disposal area and valley area, due to inadvertent ingestion, compared with the GRA dose guidance level for short-term exposures of 20 mSv (only the top 10 radionuclides contributing to dose are shown)

6.2.3.4. Total Dose

The calculated peak total dose to the borehole driller is 1.9E-03 mSv (Figure 40). The highest doses occur immediately following the end of the PoA, while Cs-137 still provides the largest contribution to dose. The peak dose is significantly below the dose guidance level of 20 mSv for short-term exposures.

The peak total dose is a little lower than calculated in the 2017 PCRSA (5E-03 mSv). The 2017 PCRSA cautiously assumed all the excavated waste has an average activity of 37 Bq/g with the PCRSA fingerprint. This updated assessment uses a more realistic estimate of the excavated waste activity and fingerprint, based on the disposal records and an updated fingerprint for future disposals (Table 2). The more realistic radionuclide inventory results in a lower average concentration of Cs-137 in waste excavated from the existing disposal area and a reduction in total dose compared with the 2017 PCRSA.

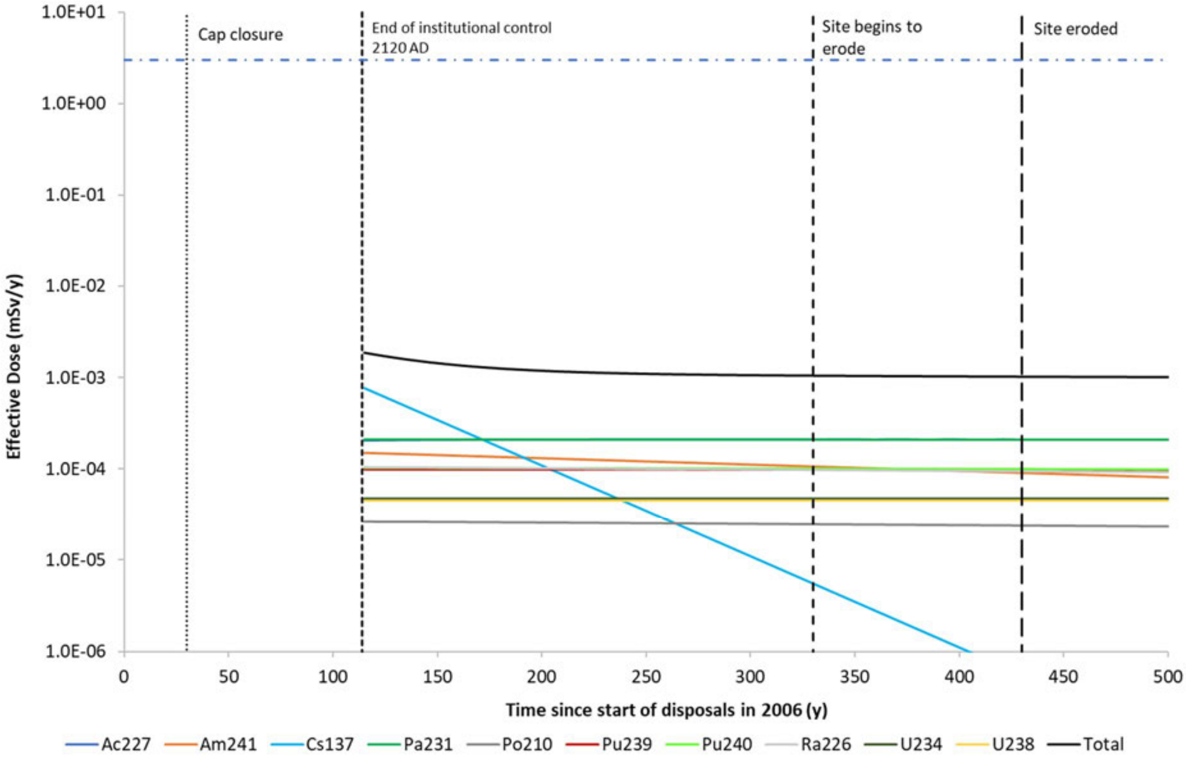

Figure 40. Doses from drilling site investigation boreholes into the existing disposal area and valley area, compared with the GRA dose guidance level for short-term exposures of 20 mSv

6.3. Earlier than Expected Cap Failure AES Calculation Cases

6.3.1. Reference Case

Risks from earlier than expected cap failure are dominated by Ra-226, which is leached from the facility (due to ‘bathtubbing’) and then sorbs onto soils around the cap perimeter (Figure 41). The calculated peak risk before the facility begins to erode is 1.4E-07 y^{-1}, approximately a factor of two higher than the peak risk calculated for the 2017 PCRSA (6.0E-08 y^{-1}). The increase is caused by the updated geometry of the affected area around the cap perimeter (Figure 19), resulting in a smaller and more concentrated contaminated soil area, and updates to the assumed fingerprint of future disposals. The peak risk remains below the risk guidance level.

Doses to terrestrial non-human biota (Table 17) are also dominated by Ra-226. Ra-226 concentrations in the discharge area are at their maximum at 300 years post-closure, when the facility starts to be disrupted by coastal erosion. (Ra-226 concentrations would continue to increase beyond 300 years post-closure if disruption by coastal erosion did not happen at this time, and therefore so would dose rates to non-human biota in the discharge area.)

The peak Ra-226 concentration in soil of 1.34 Bq g^{-1} is higher than the concentration of Ra-226 in the updated fingerprint assumed for future waste disposals (0.04 Bq g^{-1}, see Table 2).This phenomenon occurs because the assumed sorption of radium in the wastes is around 100 times lower than that assumed for the soil into which the overtopping water flows in this scenario. The relatively high flow rate (through all of the waste but a relatively small volume of soil at the perimeter of CLESA) results in Ra-226 selectively concentrating in the perimeter soils due to the very different sorption coefficients. It should be noted that sorption coefficients are generally regarded as being significantly uncertain. In this case, because much of the waste would in practice be the same material as the surrounding soil, such a large disparity would not be expected in practice.

As a result of this phenomenon, dose rates to all biota that have been assessed, except molluscs, are higher than the dose rate criterion of 10 µSv/hr presented in the GRR (SEPA et al., 2018). This criterion, however, applies specifically to designated conservation sites; the area that could become contaminated is not subject to any such classification. For an alternative point of comparison, dose rates to amphibians, arthropods – detritivorous, annelids and reptiles are at or just exceed the screening criteria recommended by IAEA (1992), USDOE (2002) and UNSCEAR (1996), which are consistent with those previously referred to by the EA (2009) (also applying to designated conservation sites). More pertinently, the area that is contaminated is quite small (only 10 m wide). For many of the assessed species this is unlikely to be sufficient to support a population (the dose criteria for non-human species relate to exposures of populations in a designated conservation habitat).

It is noted that, as described in the 2017 PCRSA (AECOM, 2017a), some of the radionuclides in the CLESA inventory are not included in the ERICA assessment tool. However, the excluded radionuclides only provide a small contribution to the calculated activity in the cap perimeter soils compared with Ra-226, so they are only expected to result in a relatively small additional dose to non-human biota.

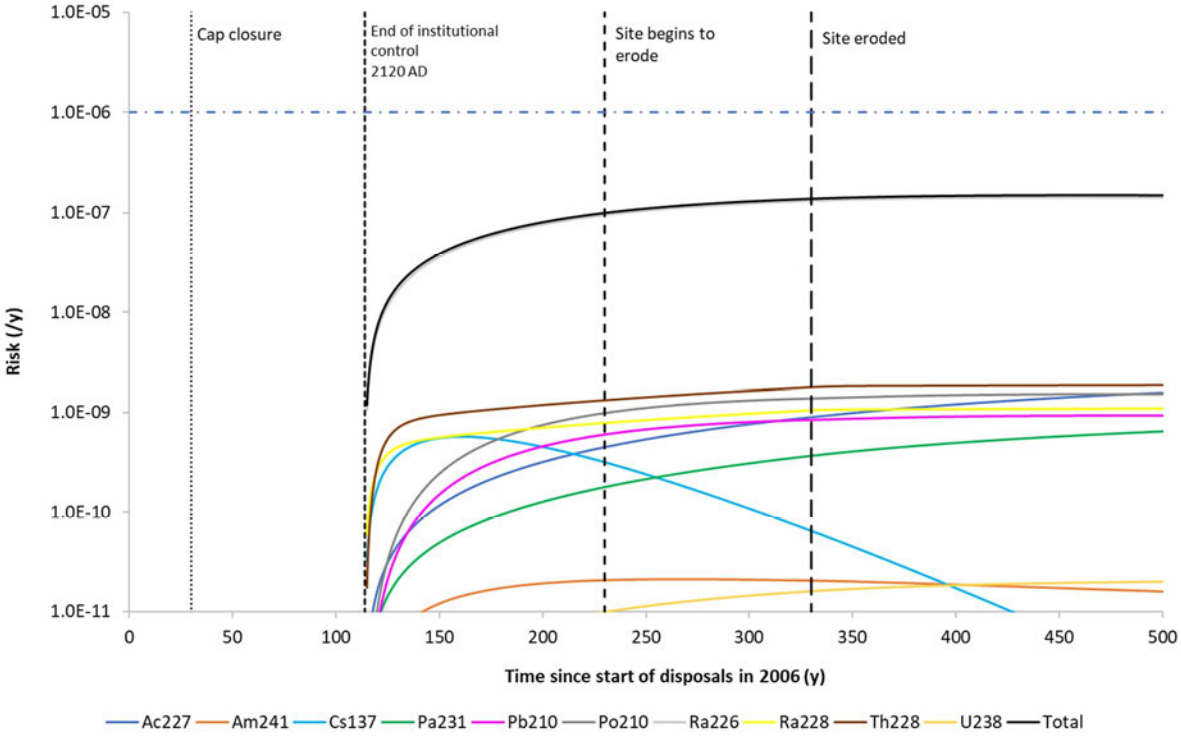

Figure 41. Risks to the recreational PEG during earlier than expected cap failure and bathtubbing of CLESA, compared with the GRA risk guidance level of 1E-06 y^{-1} (only the top 10 radionuclides contributing to risk are shown)

Table 17. Dose rates to terrestrial non-human biota

	Total Dose Rate per Organism	**Screening Value**	**Risk Quotient**
Organism	**µGy/hr**	**µGy/hr**	**-**
Amphibian	4.1E+01	40	1.0E+00
Arthropod - detritivorous	5.0E+01	40	1.3E+00
Flying insects	1.2E+01	40	3.1E-01
Mollusc - gastropod	7.5E+00	40	1.9E-01
Grasses & Herbs	4.0E+01	400	1.0E-01
Lichen & Bryophytes	2.2E+02	400	5.5E-01
Shrub	7.5E+01	400	1.9E-01
Annelid	4.7E+01	40	1.2E+00
Mammal - small-burrowing	2.0E+01	40	5.0E-01
Reptile	4.1E+01	40	1.0E+00

6.3.2. Variant Case 1 – Radium Sorption

This variant case assumes a higher, and arguably more realistic, parameter value for sorption of radium onto the waste. This reduces the concentration of Ra-226 in water discharging from the waste to adjacent surface soils. The peak Ra-226 concentration in the surface soils is reduced by a factor of 74 from 1.34 Bq/g to 0.018 Bq/g. The peak Ra-226 concentration in the surface soils is approximately half the concentration in the assumed future waste fingerprint.

Peak risk to the recreational PEG is reduced to 3.6E-09 y^{-1} and peak dose rates to non-human biota are also significantly reduced (Table 18). Doses rates to non-human biota are less than 10 µGy/hr for all organisms. However, it is noted that there would be some additional doses from radionuclides that are not included in ERICA, and these additional doses would be more significant for this case than the reference case described in the previous section.

Table 18. Dose rates to terrestrial non-human biota with variant waste Ra sorption distribution coefficient

	Total Dose Rate per Organism	Screening Value	Risk Quotient
Organism	**µGy/hr**	**µGy/hr**	**-**
Amphibian	7.9E-01	40	2.0E-02
Arthropod - detritivorous	1.1E+00	40	2.7E-02
Flying insects	4.3E-01	40	1.1E-02
Mollusc - gastropod	5.0E-01	40	1.3E-02
Grasses & Herbs	1.0E+00	400	2.5E-03
Lichen & Bryophytes	6.7E+00	400	1.7E-02
Shrub	1.3E+00	400	3.1E-03
Annelid	9.7E-01	40	2.4E-02
Mammal - small-burrowing	3.5E-01	40	8.8E-03
Reptile	7.2E-01	40	1.8E-02

6.4. Riverine Erosion AES Calculation Cases

6.4.1. Reference Case

The calculated peak risk due to riverine erosion is 1.3E-07 y^{-1}, which is an order of magnitude higher than the peak risk from coastal erosion, but still nearly an order of magnitude below the risk guidance level (Figure 42). As for coastal erosion, the risks are dominated by Ra-226 and other actinides. However, Cs-137 is a larger contributor to the peak risk due to the earlier time of erosion (there is around three half-lives less decay of Cs-137, a factor of ~8). Risks from other radionuclides are also increased compared with coastal erosion, due to the greater time of exposure to undiluted wastes.

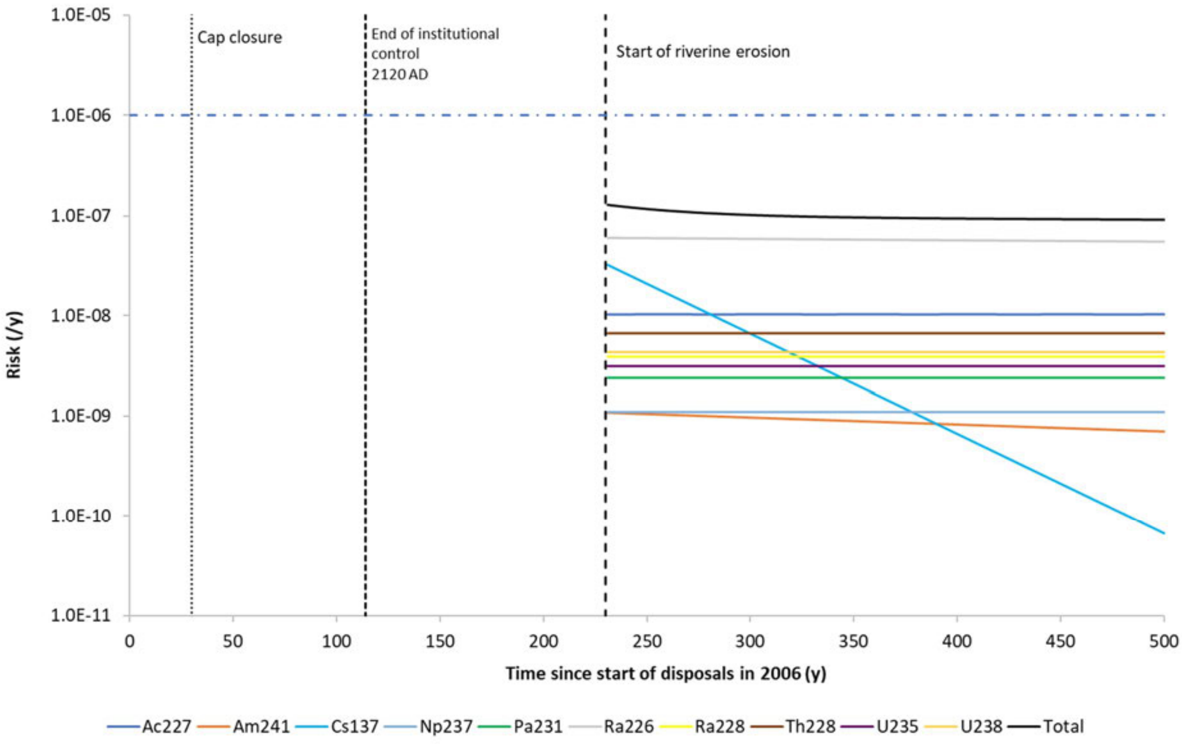

Figure 42. Risks to the angler PEG during riverine erosion of the facility compared with the GRA risk guidance level of 1E-06 y^{-1} (only the top 10 radionuclides contributing to dose are shown)

6.5. Headland Formation AES Calculation Cases

6.5.1. Reference Case

This case assumes that after 50 years of erosion, enough blocks have been exposed to form a headland that is suitable for fishing. Calculated risks are presented for each exposure pathway, followed by the total peak risk to an angler PEG.

Note that headland formation is considered a low likelihood situation, but the probability of it occurring cannot be quantified. The calculated risks are conditional on headland formation occurring (probability of 1). Therefore, the actual risks should be significantly lower than the calculated risks.

6.5.1.1. External Irradiation Pathway

For the case where a headland is formed of blocks with the same fingerprint as recent disposals but a total activity of 50 Bq/g (Table 2), the peak risk to the angler PEG from external irradiation is 1.6E-06 y^{-1} (Figure 43). The dose is dominated by Ra-226 and other long-lived radionuclides, so it is not very sensitive to the timing of erosion and headland formation.

For the case where a headland is formed of blocks with the Pile chimney fingerprint with a total activity of 50 Bq/g, the peak risk is significantly lower at 5.1E-08 y^{-1} (Figure 44). Cs-137 is the peak contributor to risk.

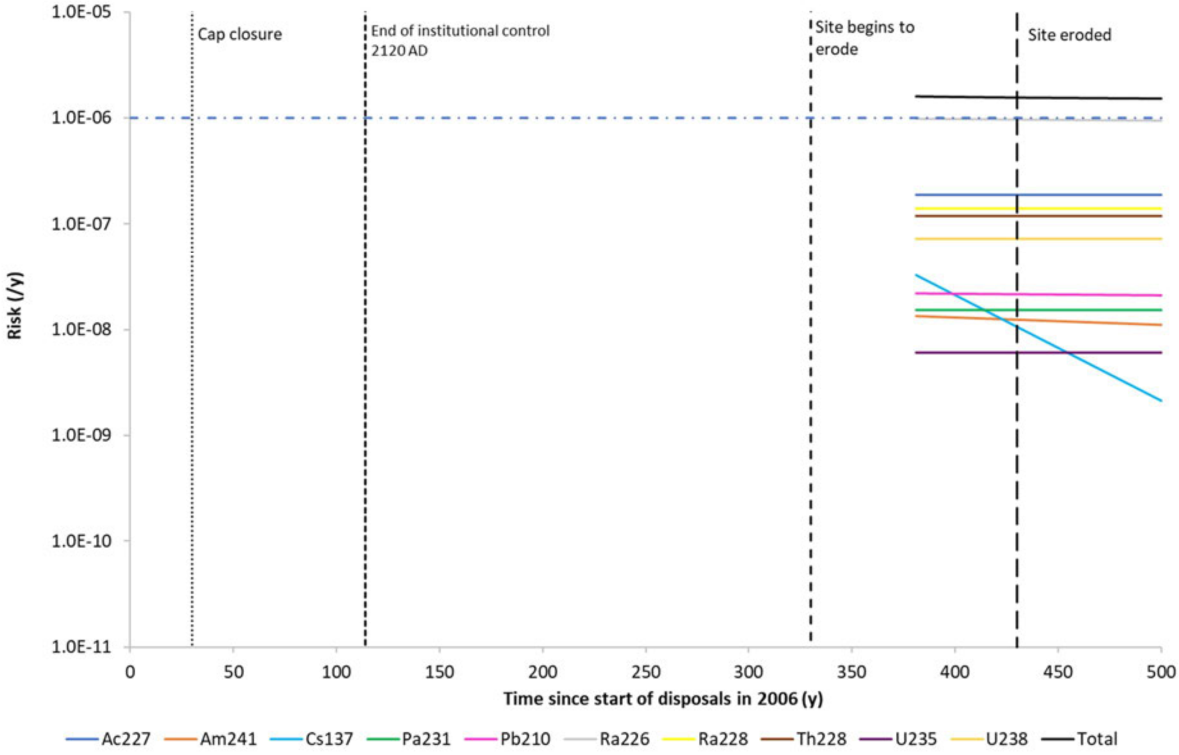

Figure 43. Conditional risks to the angler PEG from a headland formed from contaminated blocks with an average activity of 50 Bq/g and the fingerprint of recent disposals, due to external irradiation, compared with the GRA risk guidance level 1E-06 y^{-1} (only the top 10 radionuclides contributing to risks are shown)

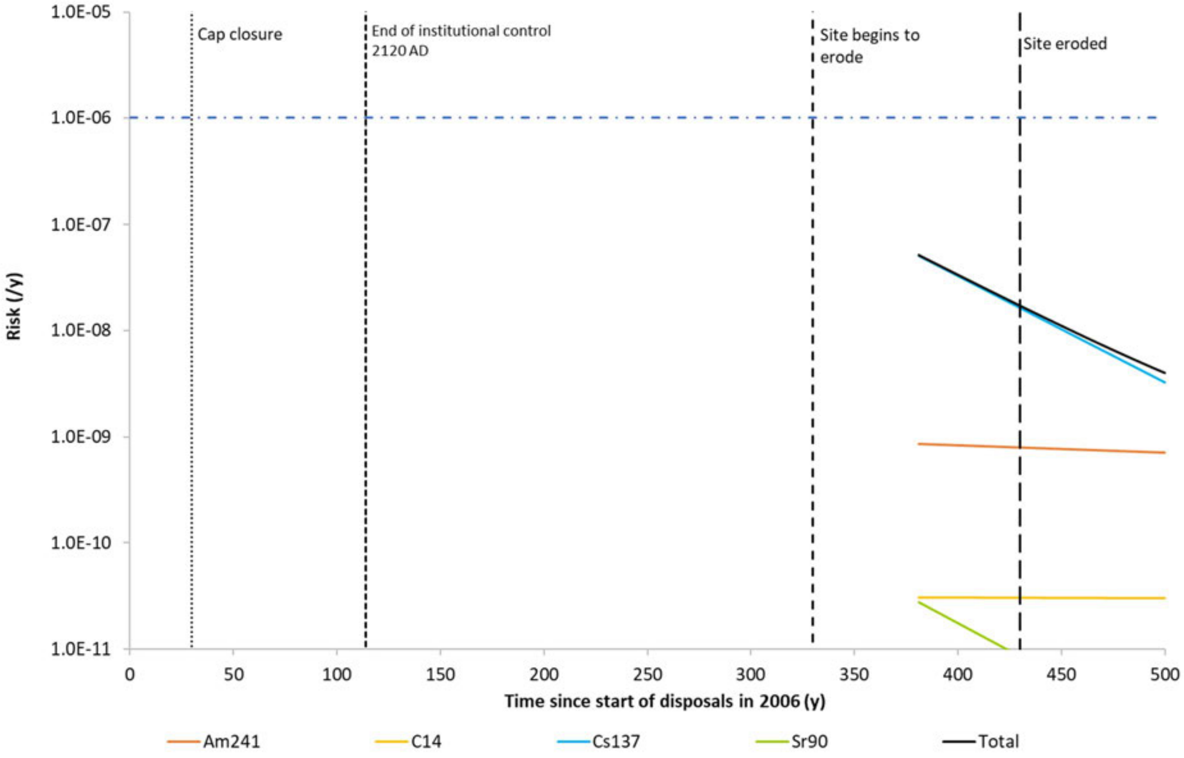

Figure 44. Conditional risks to the angler PEG from a headland formed from contaminated blocks with an average activity of 50 Bq/g and the Pile chimney fingerprint, due to external irradiation, compared with the GRA risk guidance level 1E-6 y^{-1}

6.5.1.2. Ingestion Pathway

Figure 45 shows the conditional risks to the angler PEG from inadvertent ingestion of contaminated material, with the fingerprint of future disposals. The peak risk is 6.0E-07 y^{-1} and primarily due to ingestion of Po-210 and Pb-210.

Figure 46 shows the equivalent risks for the blocks with the Pile chimney fingerprint. The peak risk is 2.8E-09 y^{-1} and primarily due to ingestion of Am-241.

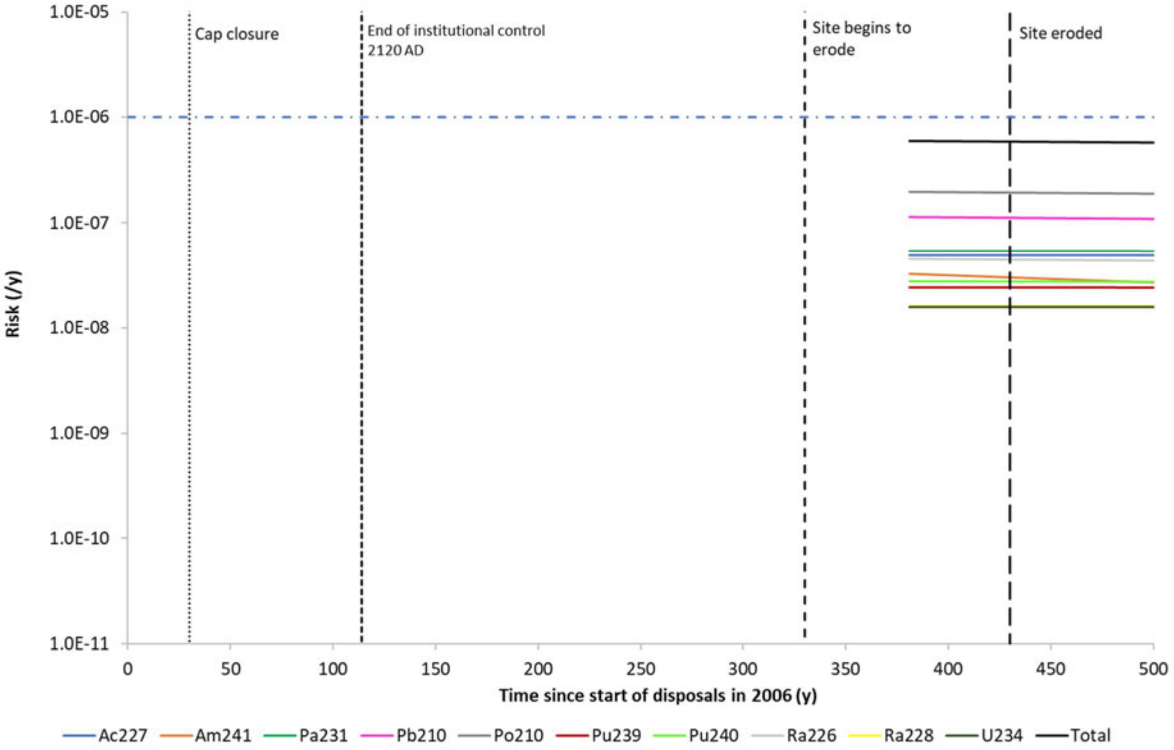

Figure 45. Conditional risks to the angler PEG from a headland formed from contaminated blocks with an average activity of 50 Bq/g and the fingerprint of recent disposals, due to ingestion, compared with the GRA risk guidance level 1E-06 y^{-1} (only the top 10 radionuclides contributing to risks are shown)

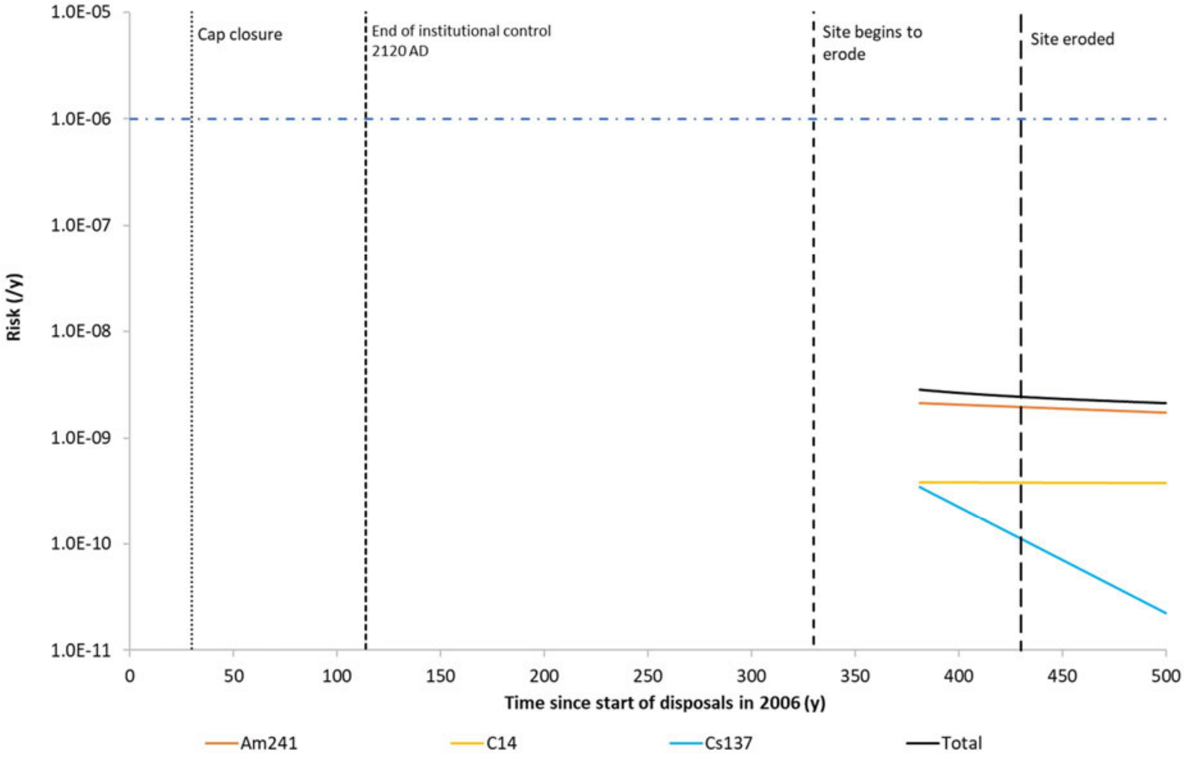

Figure 46. Conditional risks to the angler PEG from a headland formed from contaminated blocks with an average activity of 50 Bq/g and the Pile chimney fingerprint, due to ingestion, compared with the GRA risk guidance level 1E-06 y^{-1}

6.5.1.3. Total Risk

Figure 47 shows the peak total risk to the angler PEG from a headland formed from contaminated blocks with the fingerprint of recent disposals. The peak conditional risk is 2.2E-06 y^{-1} and is dominated by Ra-226.

Figure 48 shows the peak total risk to the angler PEG from a headland formed from contaminated blocks with the Pile chimney fingerprint. The peak conditional risk is 5.4E-08 y^{-1} and is dominated by Cs-137.

The probability of this scenario cannot be quantified but is expected to be low. Assuming this scenario occurs, the calculated risks range from below the GRA risk guidance level, to slightly above. Therefore, if the probability of this scenario could be quantified it is expected the calculated total risks would be below the GRA risk guidance level.

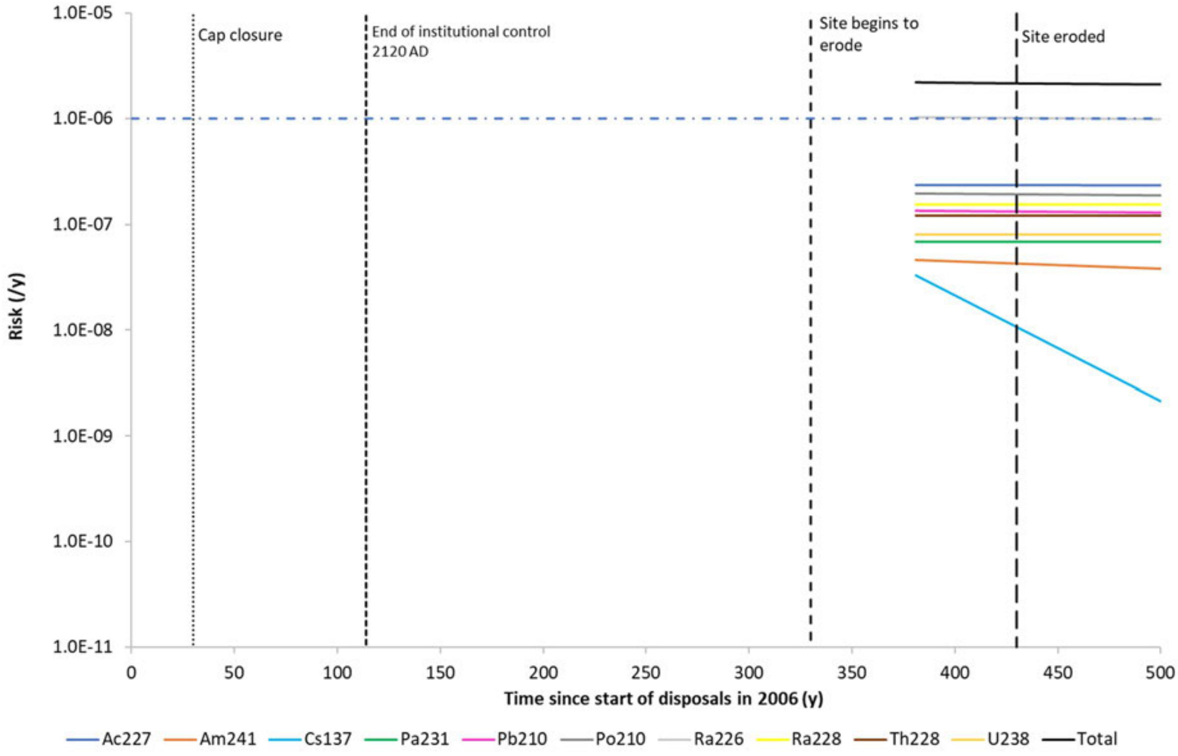

Figure 47. Conditional risks to the angler PEG from a headland formed from contaminated blocks with an average activity of 50 Bq/g and the fingerprint of recent disposals, compared with the GRA risk guidance level 1E-06 y^{-1} (only the top 10 radionuclides contributing to risks are shown)

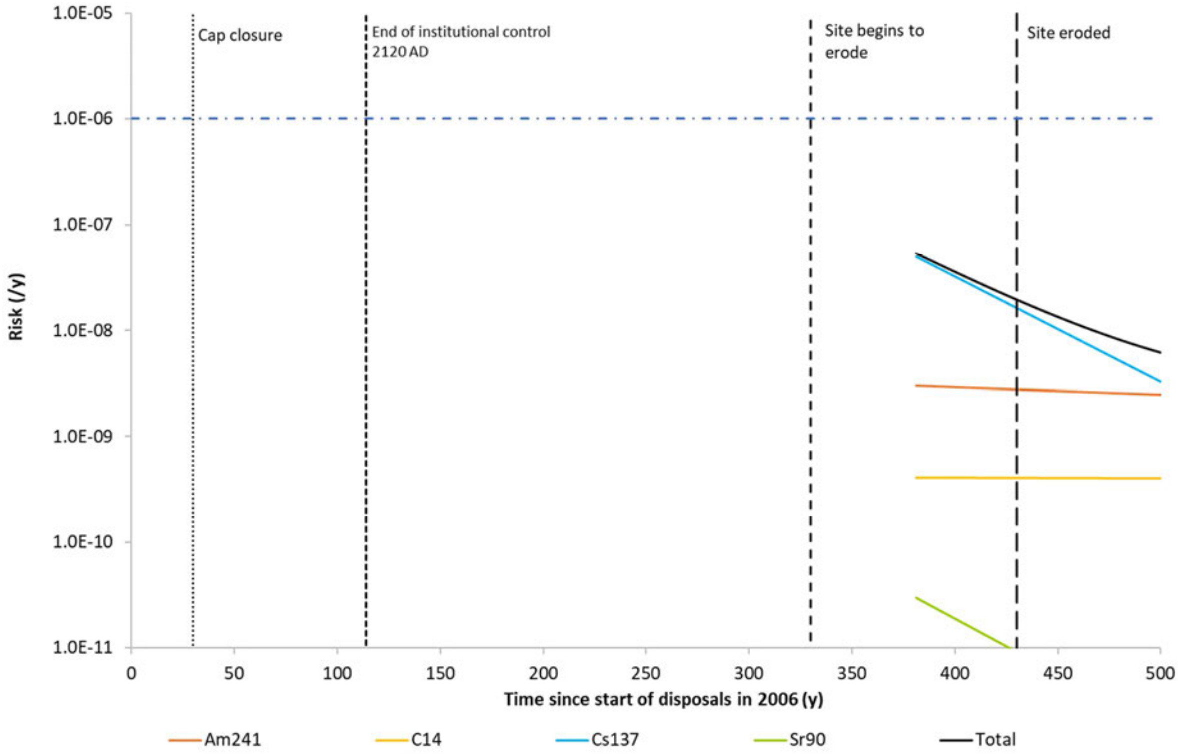

Figure 48. Conditional risks to the angler PEG from a headland formed from contaminated blocks with an average activity of 50 Bq/g and the Pile chimney fingerprint, compared with the GRA risk guidance level 1E-06 y^{-1}

7. Radiological Capacities and Activity Limits

Radiological capacity values and activity limits can be derived for an appropriate range of assessment cases. The 2017 PCRSA argued that the relevant cases for consideration in establishing limits are those assessment cases that are the most representative of each pathway and PEG relevant to that pathway. It is considered unreasonable to derive limits on the basis of assessment cases that are unlikely to occur, even though such cases might be explored within the assessments. This mirrors the approaches applied at the LLWR, Clifton Marsh landfill and Kings Cliffe landfill.

7.1. Radiological Capacities

The 2017 PCRSA used NES reference case risks from consumption of beach seeps and erosion of the facility, to calculate the maximum amount of each radionuclide that can safety be disposed, i.e. the radiological capacity for each radionuclide. The radiological capacity for each radionuclide was calculated by:

- calculating the risk per unit inventory (including the risk arising from daughter radionuclides); and then
- dividing the regulatory risk guidance level (1E-06 y^{-1}) by the peak risk per unit inventory.

The same approach has been used to calculate an updated radiological capacity using the updated assessment results presented in Section 6.1. Note the beach seeps pathway is only considered to be relevant until the start of disruption of CLESA by coastal erosion. Capacities for the beech seeps pathway are now calculated for the current coastline and future eroded coastline.

Calculating two sets of capacities for the beech seeps pathway is a justifiable simplification, because the peak risks for the key radionuclides for this pathway are not sensitive to the assumed coastal position.

The resultant capacities are shown in Table 19, with the potential final inventory for comparison. Where no radiological capacity is given, the calculated peak risk for that radionuclide and its progeny is zero[12]. Therefore, the associated pathway does not limit on the inventory of that radionuclide that can safely be disposed.

A sum of fractions (SoF) approach is used to calculate the fraction of the radiological capacity that may be used when CLESA is full (shown at the bottom of Table 19). This is calculated by dividing the radiological capacity for each radionuclide by the potential final inventory for each radionuclide, then summing the fractional contributions over all radionuclides. For the beach seeps pathway, around 3% of CLESA's radiological capacity could be used when the site is full (including valley development), and for the coastal erosion pathway around 2% could be used (also including valley development).

(Note the 2017 PCRSA used a slightly different approach and calculated remaining capacities, rather than total capacities, to explore the potential to increase activity limits. Therefore, the two sets of capacities are not compared. However, disposals pre-2017 only used a very small fraction of the radiological capacities, so the error in any comparison of the new capacities and the remaining capacities calculated in the 2017 PCRSA is expected to be small.)

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[12] Note that strictly the risk can never fall to zero, only a very small value which would lead to a very large radiological capacity. However, once the risk falls to a very small number GoldSim may report a risk of zero.

Table 19. Updated radiological capacities and SoF

Radionuclide	Potential final inventory including the valley area (TBq)	Radiological capacities (TBq)		
		Beach seeps (current coastline)	Beach seeps (eroded coastline)	Coastal erosion (bulk wastes)
Am-241	1.12E-02	1.18E+08	1.21E+06	7.41E+01
C-14	3.29E-02	5.40E+02	7.50E+01	9.14E+04
Ce-144	1.35E-03	-	-	9.25E+15
Cl-36	4.28E-03	4.90E+00	4.70E+00	3.31E+03
Cm-242	6.59E-05	-	2.68E+19	1.95E+05
Cm-244	8.31E-04	3.40E+26	3.02E+18	1.47E+04
Co-60	5.69E-03	-	3.40E+26	2.46E+15
Cs-134	2.03E-03	-	-	-
Cs-137	3.60E+00	-	3.40E+26	1.31E+04
H-3	2.53E+00	5.50E+03	2.85E+03	6.06E+14
I-129	1.17E-03	4.13E-02	3.94E-02	3.61E+02
Nb-95	7.34E-07	-	-	2.72E+10
Ni-63	6.50E-03	1.63E+07	1.07E+05	6.25E+06
Np-237	1.17E-03	1.08E+03	1.53E+01	7.91E+00
Pa-231	6.77E-03	-	1.96E+21	3.05E+00
Pb-210	6.77E-03	-	4.01E+20	3.01E+06
Pm-147	2.62E-03	-	-	2.85E+20
Pu-238	2.55E-03	3.40E+26	1.79E+17	9.93E+02
Pu-239	6.00E-03	1.37E+26	1.41E+16	3.90E+01
Pu-240	6.34E-03	1.54E+26	1.59E+16	4.02E+01
Pu-241	6.19E-02	4.20E+09	3.98E+07	2.16E+03
Pu-242	1.17E-04	8.23E+25	8.48E+15	4.12E+01
Ra-226	9.27E-03	3.40E+26	6.97E+15	9.38E-01
Ru-106	2.33E-03	-	-	4.79E+15
Sr-90	9.28E-02	9.65E+14	8.17E+09	1.42E+06
Tc-99	3.83E-03	8.05E+01	7.66E+01	4.14E+04
Th-229	4.23E-07	-	-	4.69E+00
Th-230	1.86E-03	-	1.70E+17	4.67E+00
Th-232	1.05E-03	-	7.54E+24	5.45E-01
U-233	5.59E-03	-	8.36E+22	9.45E+01
U-234	3.83E-02	-	2.35E+20	3.63E+02
U-235	5.16E-03	3.40E+26	7.44E+22	1.20E+01
U-236	3.37E-03	-	8.99E+22	4.67E+02
U-238	3.87E-02	3.40E+26	8.02E+22	6.38E+01
Zr-95	1.74E-06	-	-	1.35E+11
SoF	**-**	**2.99E-02**	**3.22E-02**	**1.66E-02**

7.2. Activity Limits

7.2.1. Consignment Activity Limits

The consignment activity limits (Table 20) are used to:

- Build confidence CLESA’s radiological capacity would not be exceeded without needing to fully characterise the activity of each radionuclide in each consignment.
- Control the potential doses from inadvertent human intrusion events and radon gas.
- Control the potential doses from blocks, when applied in combination with surface / hotspot activity limits.

The first two bullets are discussed below. Blocks are discussed in the next sub-section.

The 2017 PCRSA used potential doses from borehole intrusion and radon gas to inform consignment activity limits. These two pathways are still relevant to consignment activity limits, but with valley development potential doses from house construction and site occupancy are also relevant. Doses to a site occupant include doses from radon gas.

With the cautiously realistic assumption that all future disposals have an average activity of 37 Bq/g and the fingerprint of recent disposals, the SoFs for beach seeps and coastal erosion (bulk wastes) indicate that with valley development around 3% and 2% of the respective radiological capacities would be used when CLESA is closed (Table 19). Even though the fingerprints of future disposals are uncertain, there is sufficient spare radiological capacity to be confident that with the current activity limit of 200 Bq/g the SoF for the final inventory would be less than one, and radiological risks would be below the GRA risk guidance level.

Table 20. Consignment activity limits

Radionuclide	Consignment activity limits (Bq/g)			
	Human intrusion (borehole)	Human intrusion (House builder)	Human intrusion (Site occupant)	Human intrusion (Site occupant – Radon gas pathway)
Am-241	6.09E+03	8.40E+02	3.42E+03	-
C-14	4.51E+07	5.96E+06	2.86E+05	-
Ce-144	2.26E+22	2.49E+20	1.27E+20	-
Cl-36	1.10E+07	3.52E+05	1.27E+01	-
Cm-242	2.18E+06	3.13E+05	1.61E+06	8.15E+08
Cm-244	4.44E+05	6.41E+04	3.24E+05	-
Co-60	1.58E+10	2.25E+08	1.14E+08	-
Cs-134	3.64E+20	5.16E+18	2.62E+18	-
Cs-137	3.12E+05	4.40E+03	2.15E+03	-
H-3	5.43E+11	7.66E+10	2.61E+06	-
I-129	3.63E+05	3.62E+04	4.18E+03	-
Nb-95	9.41E+16	-	-	-
Ni-63	3.90E+08	5.56E+07	3.84E+05	-
Np-237	8.08E+03	5.70E+02	3.68E+02	-
Pa-231	1.12E+03	1.24E+02	1.28E+02	-
Pb-210	5.50E+05	7.70E+04	2.39E+03	-
Pm-147	5.77E+20	6.63E+19	8.54E+19	-
Pu-238	1.12E+04	1.60E+03	8.20E+03	4.12E+06
Pu-239	4.21E+03	5.98E+02	3.06E+03	-
Pu-240	4.25E+03	6.03E+02	3.09E+03	-
Pu-241	1.77E+05	2.45E+04	9.98E+04	-
Pu-242	4.35E+03	6.28E+02	3.22E+03	1.85E+14
Ra-226	4.51E+03	9.50E+01	1.62E-01	1.63E-01
Ru-106	1.01E+22	2.13E+20	1.08E+20	-
Sr-90	1.10E+07	3.40E+05	2.71E+03	-
Tc-99	2.83E+07	2.93E+06	2.76E+02	-
Th-229	2.33E+03	2.29E+02	1.43E+02	-
Th-230	1.00E+04	5.11E+02	1.16E+00	1.17E+00
Th-232	1.77E+03	5.68E+01	2.96E+01	-
U-233	3.15E+04	3.84E+03	2.90E+03	-
U-234	5.66E+04	7.97E+03	6.82E+02	7.50E+02
U-235	3.17E+04	1.19E+03	6.63E+02	-
U-236	6.17E+04	8.89E+03	8.67E+03	-
U-238	6.13E+04	4.55E+03	2.87E+03	2.39E+06
Zr-95	3.60E+17	2.46E+15	1.25E+15	-

The SoF for borehole intrusion is very low (0.01 %,Table 21) indicating that consignment activity limits are more important to build confidence that CLESA's radiological capacity would not be exceeded than to control potential doses from borehole intrusion.

Overall, the current consignment activity limit of 200 Bq/g for the main body of the site is still appropriate with valley development.

In addition, valley development does not impact the H-3 activity limit of 12,000 Bq/g for the main body of the site. This activity limit uses 12,000 Bq/g / 5.43E+11 Bq/g = 2.2E-06 % of the H-3 activity limit for borehole intrusion. This is a very small proportion. Even if all future H-3 disposals were at the activity limit of 12,000 Bq/g, 37% of the radiological capacity for H-3 would remain unused (Table 22). This is not a realistic situation but illustrates that with the current H-3 activity limit the radiological capacity for H-3 could not be exceeded.

The 2017 PCRSA proposed a Ra-226 activity limit of 0.35 Bq/g in the top 3 metres of disposals in the top plane of the facility. This limits potential doses from Rn-222 gas to the GRA dose guidance level of 3 mSv if a house is built on the top of the facility. Subsequent to the 2017 PCRSA the ICRP have recommended a new dose factor for Rn-222 gas. This results in a lower Ra-226 activity limit of 0.16 Bq/g (Table 20). The Ra-226 limit is not significantly further reduced when additional Ra-226 exposure pathways are also considered for a site occupant (Table 20).

Valley development increases the potential for intrusion into CLESA wastes during construction of a house on the crest of the cap and subsequent occupancy of a contaminated site, because a larger area of CLESA waste underlies the relatively flat crestal area of the cap. Intrusion could be up to 2 m into the wastes (Figure 12). Doses from house construction are significantly below the GRA dose guidance level. However, the doses from site occupancy are more significant. The SoF for site occupancy is 0.27 assuming the shallowest wastes have a total activity of 37 Bq/g and the fingerprint of recent disposals (Table 21). This indicates that the activity in the shallowest disposals might need to be limited to less than 200 Bq/g.

Ra-226 contributes 0.25 to the SoF of 0.27, and other radionuclides contribute 0.02 to the SoF of 0.27. (Note that doses from Ra-226 mainly occur due to inhalation of Rn-222 gas in the house). This implies that activities in the top 2 m of disposals in the top plane of the facility should be limited to:

$C_{Ra\text{-}226}$ (Bq/g) / 0.16 (Bq/g) + C_{Others} (Bq/g) / C_{Others_max} (Bq/g) ≤ 1

Where,

$C_{Ra\text{-}226}$ is the concentration of Ra-226 (Bq/g)

C_{Others} is the concentration of all other radionuclides (Bq/g)

C_{Others_max} is the maximum concentration of all other radionuclides (Bq/g)

The maximum concentration of all other radionuclides, C_{Others_max}, is calculated from the activity of other radionuclides of 36.8 Bq/g and the associated SoF fraction of 0.02, i.e. 36.8 Bq/g * 1/0.02 = 2090 Bq/g.

Table 21. SoF for an average bulk activity of 37 Bq/g with the fingerprint of recent disposals

Radionuclide	Assumed fingerprint of future disposals (Bq/g)	Sum of Fractions			
		Human intrusion (borehole)	Human intrusion (House builder)	Human intrusion (Site occupant)	Human intrusion (Site occupant – Radon gas pathway)
Am-241	5.52E-02	9.06E-06	6.57E-05	1.61E-05	-
C-14	1.99E-01	4.41E-09	3.34E-08	6.96E-07	-
Ce-144	3.55E-03	1.57E-25	1.43E-23	2.80E-23	-
Cl-36	6.98E-03	6.34E-10	1.98E-08	5.49E-04	-
Cm-242	8.70E-05	3.99E-11	2.78E-10	5.42E-11	1.07E-13
Cm-244	5.25E-04	1.18E-09	8.19E-09	1.62E-09	-
Co-60	1.78E-02	1.13E-12	7.91E-11	1.56E-10	-
Cs-134	9.62E-03	2.64E-23	1.86E-21	3.67E-21	-
Cs-137	2.30E+01	7.37E-05	5.23E-03	1.07E-02	-
H-3	1.27E+01	2.34E-11	1.66E-10	4.87E-06	-
I-129	6.73E-04	1.85E-09	1.86E-08	1.61E-07	-
Nb-95	0.00E+00	0.00E+00	-	-	-
Ni-63	2.13E-02	5.46E-11	3.83E-10	5.55E-08	-
Np-237	6.94E-04	8.59E-08	1.22E-06	1.89E-06	-
Pa-231	2.50E-02	2.22E-05	2.02E-04	1.96E-04	-
Pb-210	2.50E-02	4.55E-08	3.25E-07	1.05E-05	-
Pm-147	8.32E-03	1.44E-23	1.25E-22	9.75E-23	-
Pu-238	7.82E-03	6.96E-07	4.89E-06	9.53E-07	1.90E-09
Pu-239	2.15E-02	5.11E-06	3.59E-05	7.03E-06	-
Pu-240	2.53E-02	5.95E-06	4.20E-05	8.20E-06	-
Pu-241	2.82E-01	1.59E-06	1.15E-05	2.82E-06	-
Pu-242	1.69E-05	3.89E-09	2.69E-08	5.25E-09	9.13E-20
Ra-226	4.08E-02	9.05E-06	4.29E-04	2.52E-01	2.50E-01
Ru-106	1.16E-02	1.15E-24	5.45E-23	1.07E-22	-
Sr-90	4.23E-01	3.83E-08	1.24E-06	1.56E-04	-
Tc-99	2.38E-03	8.41E-11	8.12E-10	8.63E-06	-
Th-229	2.72E-06	1.17E-09	1.19E-08	1.90E-08	-
Th-230	6.98E-03	6.98E-07	1.37E-05	6.03E-03	5.99E-03
Th-232	5.07E-03	2.86E-06	8.93E-05	1.71E-04	-
U-233	5.79E-06	1.84E-10	1.51E-09	2.00E-09	-
U-234	7.01E-02	1.24E-06	8.80E-06	1.03E-04	9.34E-05
U-235	2.38E-03	7.50E-08	2.01E-06	3.59E-06	-
U-236	1.11E-03	1.80E-08	1.25E-07	1.28E-07	-
U-238	3.83E-02	6.25E-07	8.42E-06	1.34E-05	1.61E-08
Zr-95	3.00E-06	8.34E-24	1.22E-21	2.40E-21	-
SoF	**-**	1.33E-04	6.14E-03	2.70E-01	2.56E-01

Table 22. Maximum mathematically possible H-3 inventory in future disposals and use of the radiological capacity for H-3

Volumetric capacity remaining based on December 2021 topographic survey	120,000 m^3 – 72,398 m^3 = 47,602 m^3
Volumetric capacity of the valley area	28,000 m^3
Total volume available for future disposals	47,602 m^3 + 28,000 m^3 = 75,602 m^3
Mass of future disposals at a density of 2030 kg/m^3	1.5E+11 g
Maximum mathematically possible H-3 inventory at 12,000 Bq/g	1.8E+15 Bq
H-3 total radiological capacity for beach seeps (eroded coastline, Table 19*)	2.85E+15 Bq
Fractional use of H-3 radiological capacity*	63%

* Note the radiological capacity for H-3 with the current coastline is around a factor of two higher, which would lead to a smaller fractional use of the radiological capacity (33%).

The maximum concentration for all other radionuclides, C_{Others_max}, could be lower or higher for different fingerprints. The key radionuclides are alpha radionuclides. The 2Y57 fingerprint has much higher alpha fraction than the higher activity fingerprints, i.e. the PCRSA fingerprint, Pile chimney fingerprint and the fingerprint of recent disposals. Therefore, it is cautious to assume that disposals to the top plane of the facility, below the valley area, have a higher activity (bulk average activity of 37 Bq/g) and the 2Y57 fingerprint (i.e. disposals with an average activity of 37 Bq/g would be expected to have much lower proportion of alpha activity than the 2Y57 fingerprint).

The SoF for wastes with a bulk average activity of 37 Bq/g and the 2Y57 fingerprint is 2.83 (Table 23). Ra-226 contributes 2.73 to the SoF of 2.83, and other radionuclides contribute 0.1 to the SoF of 2.83. Wastes with a bulk average activity of 37 Bq/g and the 2Y57 fingerprint would not be accepted because the concentration of Ra-226 exceeds the limit for the top 3 m in the top plane of the facility, and the dose to a site occupant would exceed the dose guidance level (SoF greater than one). However, if the concentration of Ra-226 is limited to 0.16 Bq/g in the top 3 m in the top plane of the facility, for the 2Y57 fingerprint, maximum concentration for all other radionuclides, C_{Others_max}, would be 36.8 Bq/g * 1/0.1 = 368 Bq/g. (As expected, this is lower than the value of 2090 Bq/g calculated above based on the fingerprint of recent disposals.)

Table 23. SoF for an average bulk activity of 37 Bq/g with the 2Y57 fingerprint

Radionuclide	2Y57 fingerprint (Bq/g)	Sum of Fractions			
		Human intrusion (borehole)	Human intrusion (House builder)	Human intrusion (Site occupant)	Human intrusion (Site occupant – Radon gas pathway)
Am-241	3.89E-01	6.38E-05	4.63E-04	1.14E-04	-
C-14	2.94E-01	6.51E-09	4.93E-08	1.03E-06	-
Ce-144	1.12E-01	4.96E-24	4.50E-22	8.83E-22	-
Cl-36	4.76E-01	4.32E-08	1.35E-06	3.75E-02	-
Cm-242	3.60E-03	1.65E-09	1.15E-08	2.24E-09	4.42E-12
Cm-244	5.16E-02	1.16E-07	8.06E-07	1.59E-07	-
Co-60	4.43E-01	2.80E-11	1.97E-09	3.88E-09	-
Cs-134	6.48E-02	1.78E-22	1.26E-20	2.47E-20	-
Cs-137	4.41E+00	1.41E-05	1.00E-03	2.05E-03	-
H-3	9.50E+00	1.75E-11	1.24E-10	3.65E-06	-
I-129	1.67E-01	4.61E-07	4.62E-06	4.01E-05	-
Nb-95	5.05E-05	5.37E-22	-	-	-
Ni-63	4.90E-01	1.25E-09	8.81E-09	1.28E-06	-
Np-237	1.57E-01	1.95E-05	2.76E-04	4.28E-04	-
Pa-231	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-
Pb-210	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-
Pm-147	2.11E-01	3.65E-22	3.18E-21	2.47E-21	-
Pu-238	1.95E-01	1.74E-05	1.22E-04	2.38E-05	4.74E-08
Pu-239	4.04E-01	9.61E-05	6.76E-04	1.32E-04	-
Pu-240	3.79E-01	8.92E-05	6.29E-04	1.23E-04	-
Pu-241	2.75E+00	1.55E-05	1.12E-04	2.75E-05	-
Pu-242	7.86E-03	1.81E-06	1.25E-05	2.44E-06	4.25E-17
Ra-226	4.43E-01	9.83E-05	4.66E-03	2.73E+00	2.72E+00
Ru-106	9.18E-02	9.10E-24	4.32E-22	8.48E-22	-
Sr-90	4.15E+00	3.77E-07	1.22E-05	1.53E-03	-
Tc-99	5.18E-01	1.83E-08	1.77E-07	1.88E-03	-
Th-229	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-
Th-230	5.33E-02	5.33E-06	1.04E-04	4.60E-02	4.57E-02
Th-232	3.06E-02	1.73E-05	5.39E-04	1.03E-03	-
U-233	8.42E-01	2.67E-05	2.19E-04	2.90E-04	-
U-234	4.17E+00	7.37E-05	5.23E-04	6.11E-03	5.56E-03
U-235	7.48E-01	2.36E-05	6.31E-04	1.13E-03	-
U-236	4.72E-01	7.65E-06	5.30E-05	5.44E-05	-
U-238	4.97E+00	8.11E-05	1.09E-03	1.73E-03	2.08E-06
Zr-95	8.78E-05	2.44E-22	3.56E-20	7.01E-20	-
Updated SoF	-	6.52E-04	1.11E-02	2.83E+00	2.77E+00

In practice Ra-226 in CLESA waste is typically naturally occurring, with an average concentration of 0.036 Bq/g (SL, 2018). Current and historical activities at the Sellafield site have not involved producing or handling radium rich materials. Paragraph 6.3.39 of the GRA notes that assessment of potential doses from human intrusion after the period of authorisation should not include exposures to naturally occurring radon. Therefore Ra-226 can be excluded from the SoF fractions calculation, and the activity concentration of other radionuclides can be up to the value of C_{others_max}. The values of C_{other_max} calculated for the fingerprint of recent disposals (2090 Bq/g) and the 2Y57 fingerprint (368 Bq/g) are sufficiently greater than the consignment average activity limit of 200 Bq/g, that a more restrictive activity limit is not needed for shallow disposals below the crest of the cap.

Note on Water Content

The fingerprint of recent disposals has been derived from records of disposed activities and masses. The disposed masses are a mix of measured and estimated consignment weights. The waste materials will contain some water (in general they will not be fully saturated), therefore the calculated activities can be described as Bq/g 'wet'. The assessment uses dry bulk density to calculate activity concentrations (Bq/g), which are then used in the dose calculations. The dry bulk density is lower than the 'wet' bulk density, so this leads to higher activity concentrations and calculated doses compared with using 'wet' densities. The difference is small (about 10% based on a 'wet' waste density of 2030 kg/m^3 and a dry bulk density of 1830 kg/m^3), and similar to the variability expected from variations in water content, grain size, mineralogy, compaction, etc.

Where the calculated doses have been used to calculate consignment activity limits these will tend to be sightly cautious. When the fingerprint of recent disposals is used in Sum of Fraction (SoF) calculations, the SoF will be slightly underestimated compared with using a fingerprint derived using dry material masses. However, this will tend of be offset by activity limits that are slightly cautious. Overall, variations in materials dry bulk densities and water content will only have a small impact on calculated risks, doses and activity limits, and are part of the normal range of assessment uncertainties.

7.2.1.1. Summary of Updated Consignment Activity Limits

The proposed updated consignment activity limits are:

- The existing activity limits of 12,000 Bq/g for H-3 and 200 Bq/g for all other radionuclides can be retained.
- The existing activity limit of 0.35 Bq/g for Ra-226 in the top 3 metres of disposals in the top plane of the facility should be reduced to 0.16 Bq/g.

The Ra-226 activity is not expected to constrain disposals or introduce characterisation challenges, because, as noted previously, Ra-226 in CLESA waste is typically naturally occurring and the associated exposures can be excluded from assessment.

7.2.2. Surface and ‘Hotspot’ Activity Limits

Potential bulk activity limits for blocks are given in Table 24. Activity is expected to be dominated by beta-gamma radionuclides (mainly Cs-137), so for small blocks (~2 tonnes) the bulk activity limit of 200 Bq/g will constrain dose rates to less than the acceptance criterion of 20 µSv/hr unless the block has a very unusual fingerprint with more than a trace amount of ‘Alpha 2’ radionuclides (see Table 24). Blocks are unlikely to typically exceed 10 tonnes. At this mass, the bulk activity limit of 200 Bq/g will constrain dose rates to less than the target maximum of 20 µSv/hr unless the block has much higher than expected alpha activity. Bulk activity limits for blocks weighing over 10 tonnes are based on blocks weighing 30 tonnes, as these are likely to be a practicable maximum weight.

Radionuclides have been assigned to groups considering the key radionuclides in the CLESA waste fingerprints, and the similar groups in the LLWR Waste Acceptance Criteria (WAC: LLWR, 2014). It is noted that the groups used in the LLWR WAC assign some beta/gamma radionuclides to the same group as Ra-226, Th-232, etc. These beta/gamma radionuclides include Nb-94, Ag-108m and Sn-126. However, these radionuclides either don’t appear in the CLESA waste fingerprints, or are present in only tiny amounts, therefore it is not considered necessary to differentiate beta/gamma radionuclides into different groups. The alpha activity in CLESA fingerprints is dominated by ‘Alpha 1’ radionuclides, with ‘Alpha 2’ only present in very small quantities.

The radionuclides used to the determine the group activity limits are prominent in the CLESA fingerprints and at the limiting end of their group. The bulk activity limits in Table 24 should be applied as follows:

$BG / BGmax + A1 / A1max + A2 / A2max \leq 1$

Where,

BG, *A1* and *A2* refer to the activity of each radionuclide group in the block (Bq/g).

BGmax, *A1max* and *A2max* refer to the maximum activity of each radionuclide group from Table 24 (Bq/g).

Table 24. Potential bulk activity limits for blocks (Bq/g)

Radionuclide group	**Radionuclides in group**	**Radionuclide used to determine group activity limits**	**Block mass (tonnes)**		
			<2	**2 to 10**	**>10**
Beta / gamma limit, *BGmax* (Bq/g)	All beta / gamma radionuclides	Cs-137	200	200	200
Alpha 1 limit, *A1max* (Bq/g)	All alphas except those listed under Alpha 2	U-238	200	100	50
Alpha 2 limit, *A2max* (Bq/g)	Undefined alpha[#] Pa-231, Ra-226, Th-229, Th-230, Th-232, Np-237	Th-232*	8.5	4	2

* Radionuclide limits slightly more restrictive than Ra-226.

[#] Total alpha if this is the only measurement available.

8. Conclusions

This PCRSA addendum assesses the potential additional radiological impacts of disposals to the valley area as well as updating the assessment of doses and risks from the whole of the CLESA disposal facility.

A feasibility assessment (AECOM, 2022b) concluded the additional radiological impacts from disposals to the valley area would be low. The results of the assessment calculations presented in this PCRSA addendum build further confidence the additional radiological impacts from disposals to the valley area would be low.

Disposal of waste to the valley area increases the potential for occupancy of a contaminated site following inadvertent human intrusion into the waste, compared with the existing disposal area. The limiting situation is an inadvertent human intrusion event which assumes the top of the facility is landscaped, exposing the waste in the process, to allow construction of a house and adjacent garden. The house occupant is then exposed by inhalation of Rn-222, H-3 and C-14 gases, external irradiation in the house and garden, inhalation of dust and inadvertent ingestion in the garden, and consumption of foodstuffs grown in the garden. The potential doses are sufficiently below the GRA dose guidance level of 3 mSv that the current consignment average activity limit of 200 Bq/g can also be applied to shallow disposals in the valley area.

A key underpinning assumption is that following landscaping sufficient thickness of cap soils would remain to prevent the roots of foodstuffs grown in the garden from extending into the wastes. It may be optimal to locally increase the thickness of the restoration soils in the relevant area of the cap to build confidence in this assumption, e.g. increasing the total cap thickness from around 1 m to 1.5 m. This could be considered during the next closure engineering design stage.

The assessment calculations for the existing disposal area have also been updated to capture new information and knowledge in a range of topic areas, including inventory, coastal and riverine erosion, and closure engineering design and performance. Some proportionate improvements have also been made to the assessment calculations, reflecting the small increase in hazard posed by CLESA with valley development. Although many of the calculations include cautious assumptions, results show that the potential impacts from CLESA are low and remain consistent with the relevant regulatory guidance.

In the event of bathtubbing of the facility, dose rates to some non-human biota occupying the discharge zone could be around or just above the dose rate below which populations are unlikely to be significantly harmed. The area affected would, however, be relatively limited and furthermore it is not the subject of any conservation designation. The dose rates are higher than calculated in the 2017 PCRSA due to higher concentration of Ra-226 in the updated fingerprint assumed for future disposals compared with the PCRSA fingerprint assumed in the 2017 PCRSA. However, it is noted that these results are significantly influenced by reference assumptions concerning the sorption of radium in both the wastes and the soil and drift. Alternative parameter assumptions, which are arguably more realistic, would significantly decrease the peak dose rates to all organisms, so they are unlikely to be significantly harmed.

A new Alternative Evolution Scenario has been introduced which considers formation of a rocky headland from concrete blocks during coastal erosion of the facility, and occupancy of the headland by a new angler PEG. The probability of this scenario cannot be quantified but is expected to be low. Assuming this scenario occurs, the calculated risks range from below the GRA risk guidance level, to slightly above. Therefore, if the probability of this scenario could be quantified it is expected the calculated risk would be below the GRA risk guidance level.

CLESA's Permit limits the activity of Ra-226 to 0.35 Bq/g in the top 3 metres of disposals in the top plane of the facility. Updated dose coefficients for Rn-222 gas indicate this should be reduced to 0.16 Bq/g. This limit is not expected to constrain disposals or introduce characterisation challenges, because Ra-226 in CLESA waste is typically naturally occurring and the associated exposures can be excluded from assessment.

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