Environmental Safety Case 2025: Disposal of Low-level Radioactive Waste at the Port Clarence Landfill Sites

Reference: ENE-0154/F3/001

Issue: 1

To : [redacted]

Augean Limited

4 Rudgate Court, Walton, Near Wetherby

From: Eden Nuclear and Environment Ltd

March 2025

Eden Nuclear and Environment Ltd
Unit 1 Mereside, Greenbank Road, Eden Business Park, Penrith, Cumbria. CA11 9FB

Tel: **+44 (0) 1768 868985**
Email: **info@eden-ne.co.uk**
Web: **www.eden-ne.co.uk**

Eden Nuclear and Environment

DOCUMENT ISSUE RECORD					
Document Title:	Environmental Safety Case 2025: Disposal of Low-level Radioactive Waste at the Port Clarence Landfill Sites				
Project	Assessment of LLW disposal at Port Clarence Landfills				
Reference:	ENE-0154/F3/001				
Project Manager:	Eden Nuclear and Environment Ltd				
Document Status					
Issue	Description	Author(s)	Review	Approver	Date
01	Technical Report	[redacted]	[redacted]	[redacted]	28/03/25

Document Restrictions and Accessibility
You can apply restrictions on access and security for the document using permissions and security in MS or Acrobat. Further, you can set the document so that it is shared with other users. Details of any restrictions if the document is to be provided digitally should be highlighted here. **Any previous versions must be destroyed or marked superseded.**

Distribution			
Issue	Copies	Name	Organisation
1			

Environmental Safety Case for the Disposal of Low Level Radioactive Waste at the Port Clarence Landfill Site: Non-technical Summary

This is the 'Non-technical Summary' of the Environmental Safety Case (ESC) for the disposal of low level radioactive waste (LLW) at the Port Clarence Landfill Site. The disposal of radioactive waste in England and Wales is regulated by the Environment Agency under the Environmental Permitting (England and Wales) Regulations 2016. The Environment Agency commented on an ESC published in August 2019 and subsequent dialogue has resulted in a revised ESC that takes note of the feedback provided to Augean. This ESC supports an application to the Environment Agency for a Permit to dispose of LLW in the Port Clarence Landfills.

The application is for the disposal of radioactive wastes that would be classified as inert, non-hazardous or hazardous wastes in terms of their content of non-radioactive materials. The radioactive waste disposals do not need to be segregated from other, non-radioactive wastes disposed in the landfills.

The Port Clarence Landfills

Augean is the operator of the Port Clarence site, which comprises a non-hazardous and hazardous waste treatment facility at which materials are recycled, recovered and hazardous properties reduced, and two landfills at which a range of hazardous wastes and non-hazardous wastes are disposed in adjacent but separately engineered landfill sites. The site comprises land that was reclaimed from salt marshes and mudflats using waste from iron, steel and coke works and a tar distillation plant (from the 1800s to the 1960s). The site is close to the River Tees.

The Port Clarence landfill sites were granted planning permission in September 1996 (planning application reference TDC/94/065) for use as a waste disposal site (see planning reference 94/1049) and the most recent planning variation (planning reference 14/3135/VARY) for the site was granted by Stockton-on-Tees Borough Council in June 2015. This extended the operational life of the non-hazardous and hazardous waste landfill sites beyond 2016 with no fixed completion date. The two landfill sites are the subject of separate Environmental Permits which are regulated by the Environment Agency and control the engineering of the containment systems as well as the waste acceptance and management procedures (EPR/BV1399IT - hazardous waste, EPR/BV1402IC - non-hazardous waste). Further Environmental Permits are in place for the waste treatment facility located to the south of the landfill sites (EPR/YP3234XR, EPR/UB3694DU).

The radioactive waste permit application this document supports is to allow for LLW disposal to the hazardous and non-hazardous waste landfills.

Low Level Waste

Low level radioactive wastes form the bulk of all the radioactive wastes in the United Kingdom. About 89 per cent of the total physical volume of radioactive wastes comprises LLW and VLLW; however, LLW and VLLW combined only contains a small fraction of the total radioactivity in all the wastes, much less than one per cent of the total (0.0009%). LLW comprises a wide range of materials. The major components of LLW are building rubble, soil and steel items. The LLW can include framework, pipework and reinforcement from the dismantling and demolition of nuclear reactors and other nuclear facilities and the clean-up of nuclear sites. LLW also comprises miscellaneous contaminated wastes from the operation of nuclear facilities which is mainly scrap metal items, plastics and paper. It includes radioactive wastes from other sources including the oil industry, research facilities, remediation of contaminated sites and hospitals.

Some types of LLW pose little risk to health or the environment. Some VLLW is suitable for disposal in landfill sites that do not have a permit for radioactive substance activities. Other VLLW and LLW is disposed of at permitted disposal sites provided by commercial operators. The UK Government's and devolved administrations' preference is for commercial operators to continue to provide sufficient capacity for disposal of both low and high volumes of VLLW and low risk LLW that is likely to arise over coming decades.

Augean's proposal for an LLW permit involves the disposal of non-recoverable low activity radioactive waste that poses a relatively low risk to people and the environment. The specific activity (radionuclide activity concentration in a consignment) of each radionuclide present in the waste and the total activity of each radionuclide disposed of in the site will be limited to ensure that the waste poses a relatively low risk.

Naturally Occurring Radioactive Material

Waste naturally occurring radioactive material (NORM) has been disposed at the Port Clarence site since 2016 under an exemption from the need for a Permit. Augean completed a radiological assessment of the exposure to the public and workers before disposals of waste NORM started and used this to calculate the tonnage that could be buried in accordance with the specified dose limit for these wastes. Augean will continue to accept waste NORM at the Port Clarence site in compliance with this exemption.

Protecting the Environment

When the Port Clarence Landfills are full and site restoration has been completed, the design minimises contact between infiltrating water and the waste; limiting any releases to the environment. However, it is recognised that over long timescales and the natural evolution of the estuary, small quantities of radioactivity may migrate to the environment. The objective of the ESC is to show that the public and the environment are adequately protected from such releases. The approach follows guidance for assessing disposal sites prepared by the Environment Agency who regulate radioactive waste disposal in England (Environment Agencies, 2009). The amount of LLW that can be safely accepted at the Port Clarence landfills has been determined using cautious assumptions. The ESC demonstrates that for all reasonably foreseeable circumstances, doses or risks remain below the relevant dose and risk guidance levels that have been defined for England and Wales by the Environment Agency based on International criteria, both for humans and for biota. For humans, in the long term and for events that are expected to occur the Environment Agency requires that a radiation dose of no more than 20 micro Sievert per annum (µSv y^{-1}) arises to members of the most exposed group. This dose is less than 1% of average natural background levels of radiation present in the UK.

Design and Management

Modern landfills are engineered facilities that are designed, built, managed and monitored in order to protect the environment from risks associated with the disposed wastes. Environment Agency design requirements consider: the stability of the lining and capping system, wastes and underlying geological strata; the leachate collection system; operational and management control of the leachate and groundwater systems; collection of landfill gas and preventing migration of gas; and, environmental monitoring. The design will contain the disposed radionuclides for as long as reasonably practicable and thereafter limit the rate at which any radionuclides are released to the accessible environment.

Port Clarence landfills have been operational for twenty four years. The landfill sites are designed and operated based on the principle of engineered containment with low permeability basal, perimeter and capping seals constructed to an engineering specification which is the subject of approval by the Environment Agency under the Environmental Permit for hazardous waste disposal and non-hazardous waste disposal and the Landfill Directive (European Commission, 1999).

The Port Clarence designs are consistent with best practice for hazardous landfills and non-hazardous landfills and these designs aspects are relevant to the disposal of LLW. The designs:

- are based on well tried and tested technologies;
- are robust and incorporate multiple engineered barriers and safety functions (waste cells are formed of a low permeability mineral liner such as clay, an artificial liner such as a geomembrane and a capping layer comprising a low permeability liner and 1 m of restoration soil) subject to a Construction Quality Assurance Plan;
- are regularly reviewed for compliance with current standards as subsequent phases for developing disposal cells are planned;
- are subject to active management control (specific procedures for receipt and disposal of LLW, and environmental monitoring) and security measures; and,
- maximise the use of passive safety features.

The landfill design provides confidence that any impacts of LLW from the facility during both the operational period and post-closure period will be below regulatory criteria and will be as low as reasonably achievable.

Augean recognises the importance of an effective management culture and safety procedures to ensure that wastes are transported and handled safely reducing the potential for dose impacts on the workforce and the risk of accidents. Augean has a sound independently certified Management System, a positive safety culture and is committed to high standards of environmental safety and quality.

Environmental Monitoring

Environmental monitoring will be undertaken by Augean during the period over which the site is managed. Baseline conditions have already been established. Environmental samples will be taken on a regular basis and results will be reported to the Environment Agency, who may also undertake an independent sampling programme. An agreed programme is specified and follows protocols set by the Environment Agency. Monitoring information will be published on the Augean website for review by the public.

The environmental monitoring provides a check that levels of radioactivity in environmental media do not result in exposure that exceeds the design criteria set for the site and confirm that it is operating in compliance with all appropriate International and national health and safety standards. Environmental monitoring will check the levels of radiation in a range of environmental media such as leachate, surface water, groundwater, landfill gas and dust and will also measure direct exposure at the site perimeter. The monitoring regime provides reassurance that the site is performing as expected and that the sites' design, construction and operating standards are effective in eliminating or controlling any exposure risks.

Summary of the Assessment

Following comments from, and dialogue with, the Environment Agency (2020) a revised ESC has been produced to support the application for a permit, made in August 2019, that would enable low level radioactive waste disposal in the Port Clarence Landfills.

The ESC contains a detailed radiological assessment of the potential dose to the public from disposals of low activity radioactive waste to the hazardous and non-hazardous landfills. This radiological assessment looks at the behaviour of radionuclides in the landfills, considers ways that radionuclides can enter the local environment and has looked at the timescale over which this may occur. The radiological assessment also takes into account the future of the site once it has been closed, examining different site uses and also potential situations that could arise in the future when active control of the site has ceased, even the possibility of people digging into the waste, living on top of the site or erosion of waste into the estuary.

The results of the calculations are used to determine the quantity (total activity) of each radionuclide that would meet the health protection standards specified by the Environment Agency if it was disposed of at Port Clarence. These quantities are used to limit the disposal of radioactive waste, and they will be specified in the Permit. The assessment approach is very conservative and inevitably overestimates the doses that may occur from the disposal of each radionuclide. This means that, by using conservative assumptions and calculations, a lower limiting quantity for the LLW that can be disposed is set, compared with calculations based on more realistic assumptions.

Low risk radioactive wastes can contain different mixtures of radionuclides. It is not possible to know now the exact mixture of radionuclides that will be contained in future radioactive wastes received at the landfills: this will only be known when the wastes are generated, analysed and sent for disposal. In order to maintain the flexibility to respond to future mixtures of radionuclides, an approach is used by which the total quantity that can be received is under continual review within the framework of an agreed set of limits specified by the calculations in the ESC. The limits ensure that the radiological impact of disposals does not exceed regulatory guidance. The approach is referred to as the "sum of fractions" approach and is controlled through a clear condition of the permit.

Each waste consignment will be evaluated to check that it meets the criteria set through the sum of fractions approach. The sum of fractions approach is applied both to the activity concentration (Bq g^{-1}) and to the total activity disposed (MBq) using radionuclide specific values that will be specified in the Permit. The total activity of a consignment is capped at 2000 Bq g^{-1}. The amount of LLW that is accepted will also be limited to just 5% of the remaining landfill volume. Each waste consignment will also be evaluated to check that it meets the limits on the total number of tonnes of radioactive waste for the site. This limit on the total number of tonnes accepted for disposal may be more restrictive than the 'sum of fractions' limit on the total activity for some radionuclides and some wastes.

A record will be maintained showing the combined dose impacts from LLW and exempt NORM waste streams for relevant exposure scenarios. The combined impacts to members of the public during the period of authorisation will not exceed a maximum 300 μSv y^{-1}. After the period of authorisation, we will use a cautious dose criterion of 300 μSv y^{-1} for the NORM disposals

The ESC takes the following approaches:

- Waste acceptance criteria are developed to ensure that wastes received at the Port Clarence Landfills are handled and disposed of safely;

- The capacity of the site is given in terms of the total quantity of each radionuclide that would meet the Environment Agency standards for the protection of health and the environment;
- A sum of fractions approach limits the final inventory and the radionuclide activity concentrations that can be disposed;
- The models used in the radiological assessment are based on those used in other assessments of similar facilities;
- Detailed modelling has been carried out of the movement of radionuclides to surrounding features in groundwater (including calculations for flooding and nearby ponds);
- Updated versions of Erica and the Environment Agency's Initial Radiological Assessment Tool 2 are used;
- Explicit consideration is given to wastes that contain an uneven distribution of activity;
- Sensitivity analyses are undertaken;
- A detailed discussion and tabulation of major uncertainties is included;
- Waste acceptance criteria for Ra-226 specify that wastes containing above 5 Bq g^{-1} of Ra-226 should be buried at least 5 m below the restored land surface; and,
- The supporting databases for models have been updated (transfer factors, Kd values, sub-soil to top soil transfer, external dose coefficients) and habits data have been reviewed and are fully referenced.

Overall Safety Strategy

The overall safety strategy for the disposal of LLW at Port Clarence involves both active (operational) management and the construction of passive barriers ensuring that waste disposal will give rise to a low risk of impacts in the future, within the dose and risk guidance levels laid down by the Environment Agency. The safety strategy takes the following approach:

- limits will be set on the specific activity in each consignment and the total activity to be disposed (the total tonnage of LLW that can be accepted will also be limited to just 5% of the remaining landfill volume);
- the maximum activity measured at 1 m from each package face must not exceed 10 μSv h^{-1};
- Conditions for Acceptance (CfA) will be specified, covering radiological and non-radiological properties of the wastes, and a written specification of acceptable waste types will be provided to any person seeking to dispose waste at the Port Clarence Landfills;
- waste inventory is regulated using a sum of fractions approach;
- landfill design with fit-for-purpose disposal cells with basal and wall liners, as well as a low permeability capping layer, provide an engineered barrier, controlling leachate generation over periods of many decades or centuries;
- work management culture and safety procedures ensure that wastes are transported and handled safely reducing the potential for dose impact to the

workforce and the risk of accidents leading to unplanned impacts on the environment;

- active collection of leachate reduces the risk of contamination of groundwater in the vicinity of the disposal site;
- any LLW delivered to Port Clarence will be deposited in the landfill within 24 hours of arrival at the site;
- the wastes will be covered on the same working day as their placement in the landfill to reduce the risk of impacts during the operational period;
- the location of LLW consignments will be recorded by GPS and LLW will not be placed near the sides or base of a cell;
- there will be no double handling of waste on-site;
- cell caps will be constructed once disposal cells are full, eliminating dust resuspension and reducing water ingress, and hence reducing potential leachate generation;
- loose tipping is permitted for waste up to defined specific activities in a consignment, above which Environment Agency permission will be sought for specified consignments;
- environmental monitoring during the period of authorisation will check the integrity of barriers and safety plans;
- scenarios involving exposure to waste during normal operations and expected site evolution have been considered ensuring doses or risks will remain below the relevant dose and risk guidance levels;
- radiological assessments use cautious assumptions that overestimate the potential doses to workers and members of the public consequently resulting in a cautious radiological capacity;
- a full range of scenarios involving unplanned exposure to waste have been considered in order to ensure that for all reasonably foreseeable circumstances, doses or risks remain below the relevant dose and risk guidance levels; and,
- the impact of uncertainty in estimated doses and risks has been considered to demonstrate that the ESC is robust in meeting all relevant dose and risk guidance levels.

Dialogue with Stakeholders

The ESC will be communicated to interested parties in the vicinity of the site and their elected representatives. Evidence is presented in the ESC to show careful control of the activity and quantities of waste disposed, use of best practice design, the existence of a sound environmental management culture, and ongoing environmental monitoring. The ESC provides confidence that any radioactive emissions will be low and consistent with the health protection standards specified by the Environment Agency.

Augean is committed to continuous engagement with the local community through annual open days, a twice yearly newsletter and any other initiative that they consider beneficial, like the formation of a liaison group, to provide reassurance about site operations for the lifetime of the site.

Contents

ENVIRONMENTAL SAFETY CASE FOR THE DISPOSAL OF LOW LEVEL RADIOACTIVE WASTE AT THE PORT CLARENCE LANDFILL SITE: NON-TECHNICAL SUMMARY 2

1 INTRODUCTION 16

1.1 BACKGROUND 17
1.2 EXISTING SITE STATUS 20
1.3 SITE DEVELOPMENT PLANS 26
1.4 THE PROPOSAL 27
1.5 THE SUM OF FRACTIONS APPROACH 29
1.6 ENVIRONMENTAL SAFETY STRATEGY 32

2 SITE CHARACTERISTICS 35

2.1 INTRODUCTION 35
2.2 LOCATION 35
2.3 DEVELOPMENT OF THE TEES ESTUARY 38
2.4 LANDFILL HISTORY, DESIGN AND USE 39
2.4.1 Landfill History 39
2.4.2 Design and Construction 40
2.4.3 Leachate Management 41
2.4.4 Landfill Gas Management 42
2.4.5 Surface Water Management 43
2.5 RESTORATION AND AFTER-USE 43
2.6 LOCAL ENVIRONMENT 46
2.6.1 Site Access 46
2.6.2 Settlements and Activities 46
2.6.3 Flora and Fauna 47
2.7 GEOLOGY AND HYDROGEOLOGY 52
2.8 GEOMORPHOLOGY AND COASTAL AND ESTUARINE PROCESSES 52
2.9 SITE SECURITY 54
2.10 FACTORS INFLUENCING THE NATURAL EVOLUTION OF THE SITE 54
2.10.1 Sea level rise 56
2.10.2 Tidal flooding 57
2.10.3 Tidal erosion 58

3 WASTE CHARACTERISTICS 61

3.1 INTRODUCTION 61
3.2 RADIOACTIVE WASTE INVENTORY 61

4 AUTHORISATION OF DISPOSAL 69

4.1 PROCESS BY AGREEMENT {R1} 69
4.2 DIALOGUE WITH LOCAL COMMUNITIES AND OTHERS {R2} 69

5 MANAGEMENT REQUIREMENTS 73

5.1 ENVIRONMENTAL SAFETY CASE {R3} 73
5.2 ENVIRONMENTAL SAFETY CULTURE AND MANAGEMENT SYSTEM {R4} 73
5.2.1 The Augean Business and Culture 74
5.2.2 Management systems 77
5.2.3 Corporate Reporting and Communication 77
5.2.4 Site organisation 78
5.2.5 Arrangements Specific to LLW Disposal Operations 79
5.2.6 Principles that would be applied to waste retrieval 80

6 RADIOLOGICAL REQUIREMENTS 82

6.1 DOSE CONSTRAINTS DURING THE PERIOD OF AUTHORISATION {R5} 83
6.1.1 Dose assessments for the period of authorisation: likely to occur 84
6.1.2 Dose assessments for the period of authorisation: unlikely to occur 93
6.2 RISK GUIDANCE LEVEL AFTER THE PERIOD OF AUTHORISATION {R6} 97

6.2.1 Dose assessments after the period of authorisation – expected to occur 98
6.2.2 After the Period of Authorisation – unlikely to occur 104
6.3 HUMAN INTRUSION AFTER THE PERIOD OF AUTHORISATION {R7} 108
6.3.1 Dose assessments following intrusion after the period of authorisation 108
6.3.2 Dose to workers excavating the site 109
6.3.3 Doses to site residents at 60 years (intact cap) 110
6.3.4 Doses to site occupants at 60 years (cap excavated) 111
6.3.5 Dose to site occupant from Radium when building on waste/spoil mix 112
6.4 HETEROGENEITY OF WASTE 113
6.4.1 Discrete items 116
6.4.2 Particles 118
6.5 OPTIMISATION {R8} 120
6.5.1 Introduction 120
6.5.2 Design considerations 121
6.5.3 Waste location considerations 123
6.5.4 Operational considerations 124
6.5.5 Waste form considerations 125
6.6 ENVIRONMENTAL RADIOACTIVITY {R9} 126
6.6.1 Marine ecosystem 128
6.6.2 Freshwater ecosystem 128
6.6.3 Terrestrial ecosystem 129
6.6.4 Animals burrowing into landfill 129

7 TECHNICAL REQUIREMENTS 131

7.1 PROTECTION AGAINST NON-RADIOLOGICAL HAZARDS {R10} 131
7.2 SITE INVESTIGATION {R11} 133
7.3 USE OF SITE AND FACILITY DESIGN, CONSTRUCTION, OPERATION AND CLOSURE {R12} 133
7.3.1 LLW operations 134
7.3.2 Leachate management 136
7.4 WASTE ACCEPTANCE CRITERIA {R13} 140
7.4.1 Introduction 140
7.4.2 Conditions for acceptance of LLW 159
7.4.3 Radioactive waste disposal proposed permit conditions 164
7.5 MONITORING {R14} 173
7.5.1 Existing monitoring programme 173
7.5.2 Proposed monitoring programme in relation to the LLW permit 173
7.5.3 Reassurance 176
7.5.4 Groundwater monitoring programme 176

8 SUMMARY OF THE ENVIRONMENTAL SAFETY CASE 178

8.1 PROTECTION AGAINST RADIOLOGICAL HAZARDS 178
8.2 OPTIMISATION 182
8.3 PROTECTION AGAINST NON-RADIOLOGICAL HAZARDS 184
8.4 RELIANCE ON HUMAN ACTION 184
8.5 OPENNESS AND INCLUSIVITY 185
8.6 CONCLUSION 185

9 REFERENCES 187

APPENDIX A. GLOSSARY 197

APPENDIX B. BASELINE MONITORING 211

APPENDIX C. POLICY STATEMENT AND INTEGRATED MANAGEMENT SYSTEM 217

APPENDIX D. IMPACT OF WASTE DISPOSAL USING ILLUSTRATIVE WASTE STREAMS 222

APPENDIX E. ENVIRONMENTAL SAFETY CASE – TECHNICAL BASIS {R3} 236

APPENDIX F. DESCRIPTION OF THE GNU OCTAVE MODEL 565

APPENDIX G. MAJOR UNCERTAINTIES IN THE ESC 577

APPENDIX H. ASSESSMENT OF TRANSBOUNDARY RADIOACTIVE CONTAMINATION 586

Tables and Figures

Figure 1 The Waste Hierarchy 18
Figure 2 Approximate locations of the facilities at which the majority of LLW is produced 22
Figure 3 Consented site layout 23
Figure 4 Design of separation bund between non-hazardous and hazardous waste landfills 25
Figure 5 The site location 36
Figure 6 Aerial view of the site showing approximate location of planning consent boundary 37
Figure 7 Landform and landscaping of the restored site 45
Figure 8 Site constraints 48
Figure 9 Flood zones 49
Figure 10 Illustrative cross section of the Port Clarence Landfill Site profile 50
Figure 11 Decay system for Cm-248 and Cm-244 65
Figure 12 Decay system for Cm-246 and Am-242m 65
Figure 13 Decay system for Cm-245 65
Figure 14 Decay system for Cm-243 66
Figure 15 Augean Management Board 76
Figure 16 Timeline for the Port Clarence site 241
Figure 17 Compartments as modelled in GoldSim 341
Figure 18 Water flux through the waste cells for the combined landfill (without considering the effects of climate change) 349
Figure 19 Area between landfill and River Tees affected by bathtubbing 360
Figure 20 Layout of the aquifer, landfill, overflow zone and abstraction point 362
Figure 21 Simplified conceptual model of aquifer used by GoldSim (plan view) 363
Figure 22 Estuary local compartment 391
Figure 23 Contaminated concrete block 468
Figure 24 Time-dependent dose to site occupant from contaminated concrete demolition slabs .. 471
Figure 25 Time-dependent dose to site investigator from contaminated concrete demolition slabs 473
Figure 26 Time-dependent dose to site occupant from activated concrete shielding blocks 474
Figure 27 Time-dependent dose to site investigator from activated shielding blocks 475
Figure 28 Time-dependent dose to site occupant from crushed concrete 476
Figure 29 Time-dependent dose to site occupant from contaminated reinforced concrete 477
Figure 30 Time-dependent dose to site investigator from contaminated reinforced concrete 478
Figure 31 Doses at 60 years after closure from encounter with a 1 tonne sphere contaminated with 1 GBq of radionuclide at consignment 489
Figure 32 Activity required to give an effective dose of 20 µSv y^{-1} from a 1 hour exposure to a 1 tonne contaminated sphere at 60 years after closure 495
Figure 33 Item activity leading to a dose of 20 µSv y^{-1} for Ra-226 498
Figure 34 Item activity leading to a dose of 20 µSv y^{-1} for Pb-210 499
Figure 35 Item activity leading to a dose of 20 µSv y^{-1} for U-233 500
Figure 36 Item activity leading to a dose of 20 µSv y^{-1} for Mo-93 501
Figure 37 Item activity leading to a dose of 20 µSv y^{-1} for Ni-63 502
Figure 38 Comparison of Port Clarence Discrete Item Limits with those for individual consignments and waste packages 503
Figure 39 Impact of delayed onset of erosion on scenario radiological capacity due to in-growth . 540
Figure 40 Comparison of GNU Octave (solid) and GoldSim (dashed) estimations of Cl-36 activity concentration in the saturated zone (per MBq disposed Cl-36) 570
Figure 41 Comparison of GNU Octave (solid) and GoldSim (dashed) estimates of Ra-226 (black) and daughter Pb-210 (red) activity concentrations in the aquifer zone (per MBq disposed Ra-226) 575
Figure 42 Comparison of GNU Octave (solid, black) and GoldSim (dashed, red) estimates of Th-232 (top) and daughter Ra-228 (bottom) activity concentrations in the aquifer zone (per MBq disposed Th-232) 576
Figure 43 Current boundary of Port Clarence and design 589
Figure 44 Restored profile of Port Clarence site 590
Figure 45 Location of Port Clarence in relation to other notifiable countries 596

Table 1 Annual waste disposal limits specified in the permits ... 20
Table 2 Void space at Port Clarence, June 2024 ... 26
Table 3 Construction design of the hazardous and non-hazardous waste cells ... 26
Table 4 Radioactivity concentration limits for the application of the Paris Convention on Third Party Liability ... 28
Table 5 Allocation of void space at Port Clarence landfill sites ... 40
Table 6 Radionuclides included in the radiological assessments ... 62
Table 7 Types of solid NORM waste produced in the UK requiring specialist disposal ... 67
Table 8 Summary of radiological assessment scenarios during the period of authorisation ... 84
Table 9 Limiting concentrations for loose tipping based on worker exposure ... 88
Table 10 Dose estimated for exposure from the treatment of leachate ... 90
Table 12 Dose estimated for exposure from gas released during operations ... 92
Table 13 Doses from a dropped bag containing 200 Bq g^{-1} ... 93
Table 14 Doses from a leachate spillage ... 96
Table 16 Summary of radiological assessment scenarios considered after the period of authorisation (excluding intrusion scenarios and non-human biota) ... 98
Table 17 Doses to recreational users of the restored site at the time of closure and 60 years after closure ... 99
Table 18 Radiological capacity limited by doses to a walker due to erosion of landfill ... 100
Table 19 Peak doses due to erosion of landfill to sea ... 102
Table 21 Peak doses due to an inundation event after the period of authorisation. ... 104
Table 22 Peak doses due to groundwater abstraction after the period of authorisation ... 105
Table 23 Peak doses due to bathtubbing after the period of authorisation. ... 107
Table 24 Summary of radiological assessment scenarios following intrusion after the period of authorisation ... 109
Table 25 Highest doses to workers excavating at the site ... 110
Table 26 Site resident exposure – cap intact ... 111
Table 27 Doses to site residents or smallholders after 60 years ... 112
Table 28 Summary of radiological assessment scenarios for different waste forms ... 113
Table 30 Radionuclide groups for Discrete Item Limits at Port Clarence ... 117
Table 31 Discrete Item Limits for Port Clarence ... 117
Table 32 Wildlife groups considered in the ERICA tool ... 127
Table 33 Radiological capacity producing leachate activity concentrations above the relevant exemption level (ELL) ... 138
Table 34 Scenario radiological capacity calculations for WRP workers, leachate spillage and recreational use ... 143
Table 35 Scenario radiological capacity calculations for site erosion and bathtubbing ... 145
Table 36 Scenario radiological capacity calculated for inundation (flooding), landfill fire (non-hazardous landfill only) and for burrowing mammals ... 148
Table 37 Port Clarence radiological capacities (MBq) ... 150
Table 38 Activity concentrations used to limit disposal of packaged LLW at Port Clarence ... 155
Table 39 Activity concentrations used to limit disposal of LLW at Port Clarence by loose tipping 155
Table 40 Radionuclides where maximum inventory is more limiting than the radiological capacity 156
Table 41 Suggested Schedule 3 – Disposals of radioactive waste in hazardous landfill (Permit Table 3.1) ... 165
Table 42 Suggested Schedule 3 – Disposals of radioactive waste in non-hazardous landfill (Permit Table 3.1) ... 168
Table 43 Suggested Schedule 3 – Disposals of radioactive waste at Port Clarence (Permit Table 3.2) ... 171
Table 45 Peak groundwater concentrations at the site boundary, analytical detection limits and water concentrations producing a dose of 20 µSv ... 177
Table 46 Summary of modelling approaches ... 180
Table 47 Analysis of radioactivity in groundwater samples from various locations on 03/06/2019 212
Table 48 Analysis of radioactivity in surface water samples from various locations on 03/06/2019 213
Table 49 Analysis of radioactivity in leachate samples from various locations on 05/06/2019 ... 214
Table 50 Analysis of radioactivity in leachate collection tanks on 05/06/2019 ... 215
Table 51 Analysis of radioactivity in dust samples (Bq/filter) from two locations on 30/04/2019 ... 216
Table 52 Analysis of radioactivity in soil samples from four locations on 04/06/2019 ... 220

Table 53 Site perimeter total gamma dose rate (μSv h^{-1}) measurements at the site boundary location (02/07/2019) ... 221
Table 54 Activity disposed at the ENRMF and the composition of the national inventory of low level waste ... 222
Table 55 Activity concentration sum of fractions for illustrative inventories ... 224
Table 56 Quantity of illustrative waste stream that could be disposed of at Port Clarence ... 225
Table 57 Total doses arising during the period of authorisation based on illustrative inventories ... 225
Table 58 Total doses arising after the period of authorisation based on illustrative inventories ... 226
Table 59 Total doses arising from intrusion scenarios based on illustrative inventories ... 226
Table 60 Radiological composition of waste stream A. ... 227
Table 61 Radiological composition of waste stream B. ... 227
Table 62 Illustration of sum of fractions approach to assess the specific activity of waste stream A for normal operations and loose tipping. ... 227
Table 63 Illustration of sum of fractions approach to assess the specific activity of waste stream B for normal operations and loose tipping. ... 228
Table 64 Illustration of sum of fractions approach to assess the total activity of waste stream A (non-hazardous waste landfill) ... 230
Table 65 Dose calculation for waste stream A and total LLW disposal (non-hazardous waste landfill) ... 232
Table 66 Dose calculation for exempt NORM disposals (non-hazardous waste landfill) to September 2024 ... 234
Table 67 Dimensions of the landfills ... 242
Table 68 Summary of radiological assessment scenarios considered in the ESC ... 247
Table 69 Summary of scenarios and exposure pathways during the period of authorisation ... 248
Table 70 Estimated annual dose to landfill workers based on typical dose rates ... 252
Table 71 External doses to workers from wastes at maximum activity concentration ... 253
Table 72 Parameters for inhalation of dust used by the IAEA SR44 model ... 257
Table 73 Worker and public habit data for exposure to dust and gas: applicable during the Period of Authorisation ... 257
Table 74 Doses estimated from loose tipping waste at 200 Bq g^{-1} and the maximum activity concentration for loose tipped waste that meets 1 mSv y^{-1} to a worker ... 258
Table 75 Gas generation parameters ... 261
Table 76 Parameter values used in calculations of doses through the gas pathway during site operations ... 262
Table 77 Wind data from Teeside for 2007 to 2011 ... 263
Table 78 Radon parameters ... 264
Table 79 Inhalation dose coefficient for use in calculation of radon doses ... 265
Table 80 Dose estimated for exposure from gas released during operations ... 265
Table 81 Landfill gas generation and utilisation for the year 2018 CE at Port Clarence ... 266
Table 82 Calculated annual dose for gaseous dispersion following disposal of 1 MBq of H-3 and C-14 and dose at maximum inventory ... 267
Table 83 Parameters for use in calculation of doses from fires ... 269
Table 84 Doses estimated for two fires in a non-hazardous waste cell in one year ... 270
Table 85 Projected leachate activity concentration and input to treatment works ... 273
Table 87 Treatment plant worker characteristics ... 276
Table 88 Dose per unit release factors for effluent treatment workers – leachate to treatment facility scenario (μSv/y per Bq/y of discharge to leachate) calculated using the EA IRAT methodology ... 276
Table 89 Parameters characterising the application of treated sludge to agricultural land: applicable during the Period of Authorisation ... 279
Table 90 Farming family habits data ... 280
Table 91 Dose per unit release factors for adult member of the farming family – leachate release to treatment facility scenario (μSv y^{-1} per Bq y^{-1}) given in the EA IRAT methodology ... 282
Table 92 Dose per unit release factors for child member of the farming family – leachate release to treatment facility scenario (μSv y^{-1} per Bq y^{-1}) given in the EA IRAT methodology ... 285
Table 93 Dose per unit release factors for infant member of the farming family – leachate release to treatment facility scenario (μSv y^{-1} per Bq y^{-1}) given in the EA IRAT methodology ... 288
Table 94 Habit data for the angling family: applicable during the Period of Authorisation ... 292

Table 95 Dose per unit release factors for an adult member of the fishing family – leachate release to treatment facility scenario (µSv/y per Bq/y of discharge to sewer) given in the EA IRAT methodology ... 293
Table 96 Dose per unit release factors for a child member of the fishing family – leachate release to treatment facility scenario (µSv/y per Bq/y of discharge to sewer) given in the EA IRAT methodology ... 295
Table 97 Dose per unit release factors for an infant member of the fishing family – leachate release to treatment facility scenario (µSv/y per Bq/y of discharge to sewer) given in the EA IRAT methodology ... 297
Table 98 Dose for exposure from the off-site treatment of leachate per MBq input to Port Clarence ... 301
Table 99 Dose for exposure from the off-site treatment of leachate for disposal of the maximum inventory at Port Clarence ... 305
Table 100 Dropped container parameters ... 311
Table 101 Doses from a dropped container containing waste with 200 Bq g^{-1} of the radionuclide ... 311
Table 102 Doses from a dropped container containing waste at the consignment average and package limits ... 314
Table 103 Doses from a tipper truck load spillage assuming 200 Bq g^{-1} in the load ... 317
Table 105 Wound doses using package limit ... 322
Table 106 Habit data for the leachate spillage: applicable during the Period of Authorisation ... 323
Table 107 Properties for soil irrigation ... 324
Table 108 Dose to farming family from leachate spillage ... 325
Table 109 Summary of scenarios and exposure pathways after the period of authorisation ... 329
Table 110 Provisions whereby material and packages are excepted from classification as fissile ... 332
Table 111 Habit data for exposure to gas releases: applicable after the Period of Authorisation ... 334
Table 112 Doses to recreational users of restored site at site closure ... 335
Table 113 Doses to recreational users of restored site 60 years after closure ... 337
Table 114 Parameters to calculate the effective rainfall infiltration through the cap ... 344
Table 115 Assumptions regarding defects in the liner (MJCA, 2019a) ... 346
Table 116 Parameters to calculate the flow through the waste cells ... 347
Table 117 Proportions and properties of waste and filling materials ... 352
Table 118 Dimensions of the barrier ... 354
Table 119 Dimensions of the unsaturated zone ... 355
Table 120 Properties of unsaturated made ground ... 356
Table 121 Dimensions of the saturated zone ... 357
Table 122 Properties of saturated made ground ... 357
Table 123 Dimensions of the aquifer zone ... 364
Table 124 Dimensions of the aquifer transport zone ... 367
Table 125 Dimensions of the abstraction zone ... 367
Table 126 Habit data for the farming family irrigating soil with groundwater ... 370
Table 127 Dose coefficients used in Goldsim to match the modelling of the decay chains ... 371
Table 128 Dimensions and properties of top soil used for farming. ... 373
Table 129 Overview of parameters used for the irrigation scenario ... 374
Table 130 Sub-soil to topsoil transfer assigned to Kd bands ... 377
Table 131 Maximum annual doses from groundwater for all age groups for an abstraction point ... 379
Table 132 Maximum annual doses for all age groups from bathtubbing (adjacent resident) ... 382
Table 133 Maximum annual doses from 'what-if' scenario of fish caught in a hypothetical local pond following bathtubbing ... 385
Table 134 Peak activity released to the estuary from aquifer and breakout flow ... 390
Table 135 Habits data for a fishing family exposed to activity in the estuary from groundwater ... 392
Table 136 Doses to a fishing family from groundwater and breakout flow to estuary ... 392
Table 139 Habit data for exposure of coastal walker to eroded waste: applicable after the Period of Authorisation ... 402
Table 140 Parameters for the coastal walker exposure assessment ... 403
Table 142 Habit data for a fishing family exposed as a result of coastal erosion ... 406
Table 143 Port Clarence Local Marine Compartment Parameters following site erosion ... 406
Table 144 Doses to a fishing family after the start of tidal erosion ... 407
Table 145 Human intrusion events ... 410
Table 146 Summary of human intrusion cases and exposure pathways ... 412
Table 147 Parameters used for the borehole excavation scenario ... 418

Table 148 Dose to Borehole Drill Operative excavating at the site ... 419
Table 149 Parameters for trial pit excavation ... 421
Table 150 Dose to Trial pit excavator at the site ... 422
Table 151 Parameters for informal scavenger ... 424
Table 152 Dose to Informal scavenger at the site ... 425
Table 153 Parameters for a material recovery worker ... 429
Table 154 Dose to Material Recovery Worker ... 430
Table 155 Parameters for road excavation ... 432
Table 156 Dose to road excavator at the site ... 433
Table 157 Habit data for site resident family ... 434
Table 158 Radon parameters ... 436
Table 159 External irradiation parameters ... 438
Table 160 Radon inhalation doses for a dwelling built on a capped landfill – unit inventory ... 438
Table 161 Adult Site Resident Exposure ... 439
Table 162 Child Site Resident Exposure ... 441
Table 163 Infant Site Resident Exposure ... 443
Table 164 Parameters used in the long-term occupant scenario[1] ... 448
Table 165 Doses to site residents after 60 years ... 451
Table 167 Radon inhalation doses and radiological capacities for a dwelling built on a waste/spoil mix buried with other LLW at any depth ... 455
Table 168 Parameters for smallholding scenario ... 457
Table 169 Doses to smallholder family 60 years after closure ... 460
Table 170 Contributing foodstuff doses in the diet of an adult smallholder ... 463
Table 171 Summary of radiological assessment scenarios for different waste forms ... 465
Table 172 Parameters for site occupant ... 469
Table 173 Parameters for a site investigator (driller) ... 471
Table 174 Pathway-dependent dose to site occupant from contaminated concrete demolition slabs at 60 years after closure ... 472
Table 175 Pathway-dependent dose to site investigator from contaminated concrete demolition slabs at 60 years after closure ... 473
Table 176 Pathway-dependent dose to site occupant from activated concrete shielding blocks ... 474
Table 177 Pathway-dependent dose to site investigator from shielding blocks 60 years after site closure ... 475
Table 178 Pathway-dependent dose to site occupant from crushed concrete ... 477
Table 179 Pathway-dependent dose to site occupant from contaminated reinforced concrete ... 478
Table 180 Pathway-dependent dose to site investigator from contaminated reinforced concrete at 60 years after site closure ... 479
Table 181 Discrete Item Assessment parameters ... 486
Table 182 Scaling factors from an infinite plane source to a non-sorbing surface-contaminated spherical source of given radius at a distance of 0.3 m from the surface of the sphere. 486
Table 183 Scaling factors from a semi-infinite slab to a volume-contaminated spherical source of given radius at a distance of 0.3 m from the surface of the sphere. ... 486
Table 184 Doses at 60 years after closure from encounter with a 1 tonne sphere contaminated with 1 GBq of radionuclide at time of consignment ... 487
Table 185 Activity at time of consignment to give rise to an effective dose of 20 µSv y^{-1} based on doses calculated at 60 years after closure from a 1 hour encounter with a 1 tonne sphere. ... 490
Table 186 Radionuclide groups for Discrete Item Limits as used at LLWR ... 493
Table 187 Discrete Item Limits for LLWR ... 493
Table 188 Radionuclide groups for Discrete Item Limits at Port Clarence. ... 493
Table 189 Discrete Item Limits for Port Clarence ... 493
Table 190 Highest impact radionuclides within each Port Clarence group. ... 496
Table 191 Constants for non-linear scaling of dose per unit ingestion calculations ... 507
Table 192 Dose (mSv) from 1MBq on a particle, for two intrusion times ... 509
Table 193 Activity limit on a particle, for two intrusion times ... 510
Table 194 Risk calculations for inadvertent ingestion following site erosion ... 511
Table 195 Risk calculations for skin exposure following site erosion ... 511
Table 196 Calculated concentrations for disposal of packaged waste (Bq g^{-1}) ... 514
Table 197 Activity concentrations used to limit disposal of LLW at Port Clarence ... 517

Table 198 Radionuclide specific maximum average activity in consignment and in a package for radionuclides 518
Table 199 Activity concentrations used to limit tipping of loose LLW at Port Clarence 518
Table 200 Wildlife groups considered in the ERICA tool 520
Table 201 Radionuclide specific risk quotients for the estuarine ecosystem for the groundwater release to estuary scenario, based on a generic screening level of 10 µGy h^{-1} 523
Table 203 Radionuclide specific risk quotients for freshwater ecosystems, based on a generic screening level of 10 µGy h^{-1} and the reduction required to reduce the dose rate to 40 µGy h^{-1} 528
Table 204 Radionuclide specific risk quotients for terrestrial ecosystems (maximum of erosion and gas release scenarios), based on a generic screening level of 10 µGy h^{-1} and the reduction required to reduce the dose rate to 40 µGy h^{-1} 531
Table 205 Radionuclide specific risk quotients for terrestrial ecosystems for burrowing animals in the waste cells, based on a generic screening level of 10 µGy h^{-1} 534
Table 206 Sensitivity of dose to dilution factor: Smallholder at 60 y 537
Table 207 Sensitivity of radiological capacity to dilution factor: Smallholder at 60 y 537
Table 208 Sensitivity of scenario radiological capacity to timing of intrusion: Smallholder 537
Table 209 Impact on radiological capacity of different exposure times for the erosion - dog walker scenario 539
Table 210 Sensitivity of projected dose to exposure time: Erosion – dog walker 539
Table 211 Sensitivity of scenario radiological capacity to erosion occurrence 541
Table 213 Radiological capacity limits if leachate spillage does not occur 542
Table 214 Sensitivity of projected dose to dilution: Leachate Spillage 543
Table 215 Scenario radiological capacity if irrigation using water incorporating spilled leachate does not occur 544
Table 216 Sensitivity of scenario radiological capacity to volume of leachate: WRP processing 544
Table 217 Sensitivity of projected dose: Recreational use (0y) 545
Table 219 Radiological capacity for radionuclides if burrowing mammals are not impacted. 546
Table 221 Sensitivity to package content in 10 t consignment 547
Table 222 Radionuclide half-lives and decay constants 548
Table 223 Sorption distribution coefficients for the filling materials in the waste cells, sub-soil to top soil factor and release fraction in a fire 550
Table 224 Radionuclide dose coefficients for ingestion and inhalation for adult, child and infant 552
Table 225 Radionuclide dose coefficients for cloud immersion and external dose from a slab 555
Table 226 Radionuclide external dose coefficients and attenuation coefficients for soil 558
Table 227 External dose coefficients for different thicknesses of contamination in a semi-infinite slab 561
Table 228 Radionuclide dose coefficients from IAEA SR44 for landfill workers 561
Table 229 Uptake factors for various crops (Bq kg^{-1} fresh crop per Bq kg^{-1} soil) 563
Table 230 Transfer factors for animal produce 564
Table 231 Annual hazardous and non-hazardous waste disposal limits specified in the permits 588
Table 232 Radionuclide radiological capacity and specific activity limits 592
Table 233 Highest dose from disposal of the maximum inventory obtained in the scenarios for members of the public in the vicinity of the site during the period of authorisation 594
Table 234 Highest doses to members of the public in the vicinity of the site from disposal of the maximum inventory after the period of authorisation 595
Table 235 Notifiable countries closest to the UK 596

1 Introduction

1. This document is an Environmental Safety Case (ESC) that supports an application for an Environment Agency Permit, for the receipt and disposal of low-level radioactive waste (LLW) at the Port Clarence Landfill sites (the Port Clarence site contains two landfill sites: the centre of the hazardous waste landfill site lies approximately at OS Grid Reference NZ 51841 22242, 54.5927^{o} N 1.1992^{o} W and the centre of the non-hazardous landfill site lies at approximately at OS Grid Reference NZ 51785 22505).

2. Augean North Limited (Augean) is the operator of the Port Clarence site. The site comprises: a Waste Recovery Park (WRP) at which materials, including LLW, are recycled, recovered and hazardous properties reduced; and, two landfill sites at which a range of hazardous wastes, non-hazardous wastes and naturally occurring radioactive material (NORM) waste are disposed. The Port Clarence site covers an area of 59 hectares (ha) (MJCA, 2019a) and the landfill sites have a combined residual void space of about 4 million m^3. The current planning permission does not specify an end date for disposals. Capacity at Port Clarence will be available beyond the 2046 planned end date of the landfill at the East Northants Resource Management Facility (ENRMF), which has a permit for the disposal of LLW.

3. The Port Clarence site comprises land that was reclaimed from salt marshes and mudflats, using wastes from iron, steel and coke works and a tar distillation plant (from the 1800s to the 1960s). The location of the site is near the River Tees.

4. The guidance on requirements for authorisation of near-surface disposal facilities for solid radioactive wastes (the NS-GRA) (UK Environment Agencies, 2009) and earlier supplementary guidance (Environment Agency, 2012) have been used as the basis for this ESC. The NS-GRA contains fourteen requirements, of which Requirement 3 of the NS-GRA is for an ESC:

> "An application under RSA 93 relating to a proposed disposal of solid radioactive waste should be supported by an environmental safety case." NS–GRA (UK Environment Agencies, 2009) para 6.2.1

5. The guidance notes on how to apply for an environmental permit for the burial of radioactive waste have also been considered (Environment Agency, 2022).

Document structure

6. An ESC provides a safety assessment and related safety arguments that bear on the acceptability of proposed disposals of radioactive waste at a facility. The ESC is required to demonstrate that members of the public and the environment are adequately protected and it is required to be proportionate to the hazard presented by the waste. The section titles of this ESC indicate where each NS-GRA requirement is addressed, for example Section 4.1 has the title "Process by Agreement {R1}" indicating where Requirement 1 is addressed. The relevant sections, as numbered, are listed below:

- 4.1 Process by Agreement {R1}
- 4.2 Dialogue with Local Communities and Others {R2}
- 5.1 Environmental Safety Case {R3}
- 5.2 Environmental Safety Culture and Management System {R4}

- 6.1 Dose constraints during the period of authorisation {R5}
- 6.2 Risk guidance level after the period of authorisation {R6}
- 6.3 Human intrusion after the period of authorisation {R7}
- 6.5 Optimisation {R8}
- 6.6 Environmental radioactivity {R9}
- 7.1 Protection against non-radiological hazards {R10}
- 7.2 Site investigation {R11}
- 7.3 Use of site and facility design, construction, operation and closure {R12}
- 7.4 Waste acceptance criteria {R13}
- 7.5 Monitoring {R14}

7. Site characteristics, the local environment and its natural evolution are described in Section 2 with waste characteristics detailed in Section 3. The contents of Sections 4 to 7 cover the NS-GRA requirements as listed above and Section 8 draws together the safety assessment and related safety arguments. Supporting information is provided in appendices, and these comprise a glossary (Appendix A), a baseline radiation survey (Appendix B), Augean's governance policy statements (Appendix C), potential impacts from the disposal of illustrative waste streams (Appendix D), the radiological assessments underpinning the ESC (Appendix E), a list of major uncertainties in the ESC (Appendix G) and a transboundary assessment (Appendix H).

8. The rest of this section provides background information on LLW management within the United Kingdom (UK), provides a summary of existing site permits, describes Port Clarence development plans and the proposal for disposal of LLW and lastly highlights features of the environmental safety strategy (ESS) set out in the ESC.

1.1 Background

9. Within the UK, LLW is defined by Government policy (DESNZ and Devolved Administrations, 2024) as:

> "waste having a radioactive content not exceeding four Gigabecquerels per tonne (GBq/te) of total alpha activity or 12 GBq/te of total beta/gamma activity"

10. There is a sub-classification of LLW referred to as high volume very low-level radioactive waste (HV-VLLW) that is defined as:

> "radioactive waste with maximum concentrations of four megabecquerels per tonne (MBq/te) of total activity which can be disposed of in specified landfill sites. For waste containing tritium, the concentration limit for tritium is 40 MBq/te. Controls on disposal of this waste, after removal from the premises where the wastes arose, will be necessary."

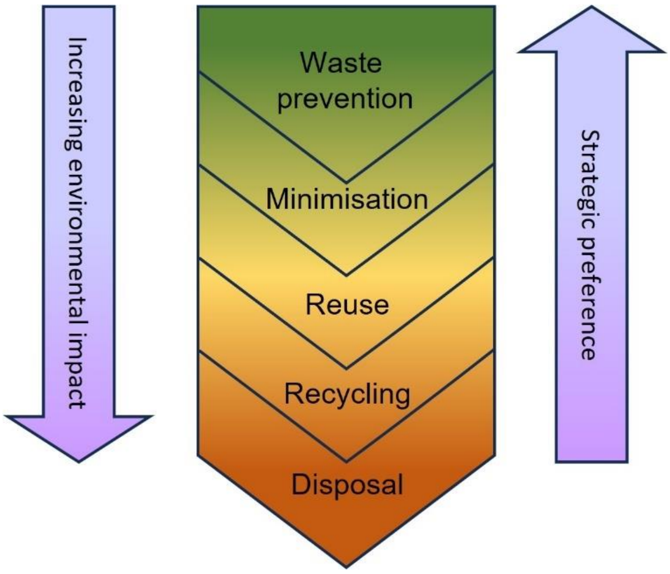
11. The amounts of 4 GBq t^{-1} and 12 GBq t^{-1} referred to above as GBq/te, are equivalent to 4,000 Bq g^{-1} and 12,000 Bq g^{-1}, respectively. Similarly, the amounts of 4 MBq t^{-1} and 40 MBq t^{-1} (above as MBq/te) are equivalent to 4 Bq g^{-1} and 40 Bq g^{-1}, respectively.

12. The UK LLW strategy for the nuclear industry was last updated in 2016 (DECC, 2016). The UK strategy for the management of solid LLW from non-nuclear sources is presented in two parts; the first considers anthropogenic radionuclides (DECC, 2012) and the second part (DECC, 2014) deals with naturally occurring radioactive materials (NORM). Disposal of LLW to landfill is authorised as a radioactive substances activity under the Environmental Permitting (England and Wales) Regulations 2016 (as amended) (UK Government SI, 2016; UK Government SI, 2018), referred to as EPR2016, using permits issued by the Environment Agency in England. An exemption from the requirement for a permit applies to disposal of NORM with activity concentrations of up to 10 Bq g^{-1}.

13. The permit application supported by this ESC will be for receipt and disposal of LLW, including HV-VLLW and reference to LLW throughout this document is assumed to include this lower activity waste classification.

14. Application of the waste hierarchy (Defra, 2011) is central to Government policy for the management of radioactive waste (see Figure 1) and there is a requirement that those responsible for creating and managing radioactive waste should use the waste hierarchy as a framework for decision making. Operators should ensure appropriate levels of waste characterisation in order to apply the waste hierarchy effectively.

Figure 1 The Waste Hierarchy



15. Where radioactive waste generation is unavoidable, the quantities generated should be minimised and created only where there are credible waste management plans and disposal routes. Operators should focus on reusing or recovering resources and recycling of waste in preference to disposal, providing that all other elements of Government policy and regulatory requirements can be satisfied (e.g. safety, security, environmental protection, public value etc.). Under these circumstances, and subject to meeting Best Available Techniques (BAT) and As Low As Reasonably Practical (ALARP) requirements, the use of landfills is an established approach to the disposal of radioactive waste with low specific activity and is supported by Government policy (DESNZ and Devolved Administrations, 2024). The NS-GRA refers to As Low As Reasonably Achievable (ALARA), the terminology used when reducing exposure to ionising radiation, which is broadly synonymous with ALARP, with both incorporating considerations on economic, environmental and societal factors (DESNZ and Devolved Administrations, 2024).

16. Nuclear Waste Services (NWS) is an operating group within the Nuclear Decommissioning Authority (NDA). NWS is responsible for the national LLW facility, the Low Level Waste Repository (LLWR), located near the village of Drigg in West Cumbria. It was recognised in the early 2000's that the LLWR did not have the capacity to meet future demand without a change to LLW management practices. NDA strategy recognises that the capacity of the LLWR is likely to need preserving in order to maximise the lifetime of the facility (NDA, 2021), which results in an on-going need for alternative disposal routes. Government policy expects NDA to ensure optimal use of the LLWR.

17. The National Waste Programme (NWP) was established to implement the UK LLW strategy (NDA, 2010), this strategy was subsequently revised in 2016 (DECC, 2016) and has three guiding themes:

- application of the waste hierarchy;
- best use of existing LLW management assets; and,
- the need for fit for purpose waste management routes.

18. The disposal of LLW at the lower end of the range of specific activity is not a sustainable use of the LLWR, which has been designed and engineered to a standard suitable for materials with a radioactive content at the higher end of the range for LLW. Alternative disposal sites for LLW with lower specific activities are limited in the UK. The NDA recognise that in order to meet all LLW disposal requirements, use of the supply chain will be required for disposal of appropriate waste streams (NDA, 2019).

19. Since establishing the NWP, the NDA has set up the Integrated Waste Management Programme (of which the NWP is a constituent programme), to facilitate collaboration and deliver initiatives for a range of appropriate disposal capabilities to safely and cost-effectively dispose of waste types generated (NDA, 2023). The Waste Metric Dashboard summarises progress on the diversion of waste away from disposal at the LLWR and on the environmental performance of the NWP (NWS, 2022).

20. There is a large variation in the types of LLW, some of which poses little risk to health or the environment. Some VLLW is suitable for disposal in landfill sites that do not have a permit for radioactive substance activities. Other VLLW and LLW is disposed of at permitted disposal sites provided by commercial operators. The UK Government's and devolved administrations' preference is for commercial operators to continue to provide sufficient capacity for disposal of both low and high volumes of VLLW and low activity LLW that is likely to arise over coming decades.

21. Port Clarence is ideally placed to serve the producers of LLW from the nuclear and non-nuclear industries in the north east (Figure 2). Able UK's facility at Seaton Port is around 3 miles from the Port Clarence site. Able has been producing NORM as part of its operations to decommission redundant oil and gas platforms. Historically some of this waste, as it has activity greater than 10 Bq g^{-1}, has had to be transported to the ENRMF or to Lancashire for final disposal. Depending on the amount of decommissioning Able UK complete each year around 100 to 200 t of NORM is produced and requires disposal. Alongside the NORM filter cake that Venator already dispose of at the Port Clarence site NORM contaminated materials and filter cloths are periodically disposed of to the LLWR and the ENRMF. These filter cloths are produced as part of the titanium dioxide production process and have activities ranging from 100 to 1000 Bq g^{-1}.

22. Port Clarence is geographically closer to EDF Power Stations (Hartlepool and Torness) than other currently permitted landfill disposal sites. Port Clarence is also closer to Sellafield and LLWR than Augean's current permitted landfill disposal facility, the ENRMF. For many of the LLW producers who dispose of their LLW currently at the LLWR near Drigg, Port Clarence provides a convenient alternative for LLW at the lower end of the range of specific activity.

23. The LLW that will be considered for disposal at Port Clarence can be handled safely by workers in a manner similar to other low hazard wastes. Although the material is radioactive waste by legal definition, these wastes do not need special security measures.

1.2 Existing site status

Planning permission

24. The most recent planning variation (planning reference 14/3135/VARY) for the site was granted by Stockton-on-Tees Borough Council in June 2015. This was supported by an Environmental Statement (ES), published in November 2014 (Augean, 2014) that considered extending the operational life of the non-hazardous and hazardous waste landfill sites beyond 2016 with no fixed completion date. The consented design is for 18 waste disposal cells within the two landfills (Augean, 2014) as shown in Figure 3. It is assumed that for the Port Clarence landfills the future operational period would be 50 years for the purpose of the ESC, noting that waste disposal is expected to end before then.

Environmental Permits - Waste to Landfill

25. Environmental controls are regulated by the Environment Agency through Environmental Permits (UK Government SI, 2016). All operations at the landfill site are performed in accordance with the conditions of permits EPR/BV/1399IT for the disposal of hazardous waste and EPR/BV/1402IC for the disposal of non-hazardous waste. The permits include a list of waste types that can be accepted at the landfill site and details for monitoring leachate, landfill gas, particulate matter and groundwater and frequency of reporting to the Environment Agency. Separate permits considered operations at the Waste Recovery Park (WRP; YP/3234XR) and Chemical Treatment Centre (YP/3024XH) until May 2015 when a consolidated permit was issued (reference EPR/YP/3234XR/V002) for these operations.

26. Annual disposal limits are specified in the environmental permits (see Table 1).

Table 1 Annual waste disposal limits specified in the permits

Category	Non-hazardous permit (BV/1402IC) Table S1.4	Hazardous permit (BV/1399IT) Table S1.4
Hazardous waste (tpa)	-	500,000
Non-hazardous waste (tpa)	995,000	-
Inert waste (tpa)	50,000	100,000(1)
Asbestos waste(2) (tpa)	150,000	-

Note: 1) For cover. 2) Including construction material containing asbestos.

27. The non-radioactive wastes accepted at the Port Clarence landfills cover a broad spectrum of waste but exclude explosive, flammable, corrosive and infectious

materials. Those defined as hazardous under the European Waste Catalogue are subject to the hazardous waste acceptance criteria under the Landfill Directive (European Commission, 1999) as defined in Council Decision 2003/33/EC (European Communities, 2003).

Disposal of NORM waste under Environmental Permitting Regulations

28. Very low-level naturally occurring radioactive waste (NORM) has been disposed at the Port Clarence site since 2016 under an exemption from the need for a Permit for Type 2 NORM. Hence, Type 2 NORM waste with concentrations between 1 and 2 Bq g^{-1} is disposed at Port Clarence through compliance with Paragraphs 18 and 19 in Section 6 of Part 6 to Schedule 23 of the EPR2016. Type 2 exemption was required because the total annual activity for disposal exceeded the limit for Type 1 NORM exemption. Augean completed a radiological assessment of the exposure to the public and workers before disposals started and used this to calculate the tonnage that could be buried in accordance with the specified dose limit for these wastes (Jones, et al., 2014).

29. Disposals of low activity NORM waste have occurred at Port Clarence since 2016 under the Type 2 exemption. The average activity of disposals was 1.01 Bq g^{-1} Th-232 and 0.47 Bq g^{-1} U-238 with a cumulative disposal of 733,508 t to end of September 2024 in the non-hazardous waste landfill.

30. The quantity of NORM waste that could be disposed at the maximum concentration (10 Bq g^{-1}) without exceeding Environment Agency guidance was derived. The calculated total capacity for the non-hazardous and hazardous landfill sites was 2.8 10^5 t and 1.5 10^6 t of NORM waste, respectively, based on allocated void space and a disposal activity concentration of 10 Bq g^{-1}. We propose using a lower dose criterion of 300 µSv y^{-1} for the period after authorisation (Jones et al. used 1 mSv) and the observed activity (1.48 Bq g^{-1}) of the disposed NORM to calculate a tonnage capacity for the site. On this basis, the adjusted site capacity is 4.9 10^6 t of NORM waste split between the two landfills on a pro-rata tonnage basis.

Figure 2 Approximate locations of the facilities at which the majority of LLW is produced

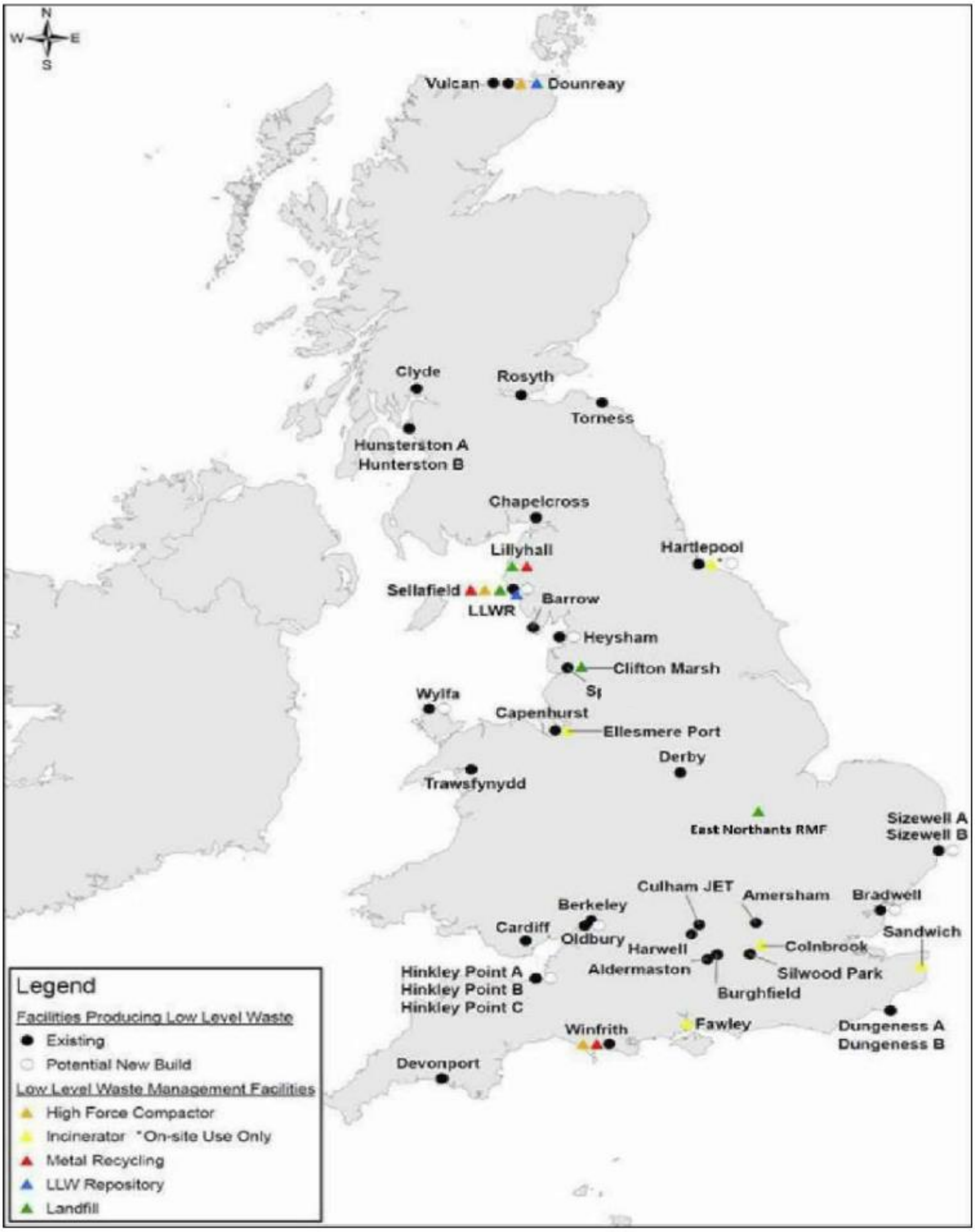
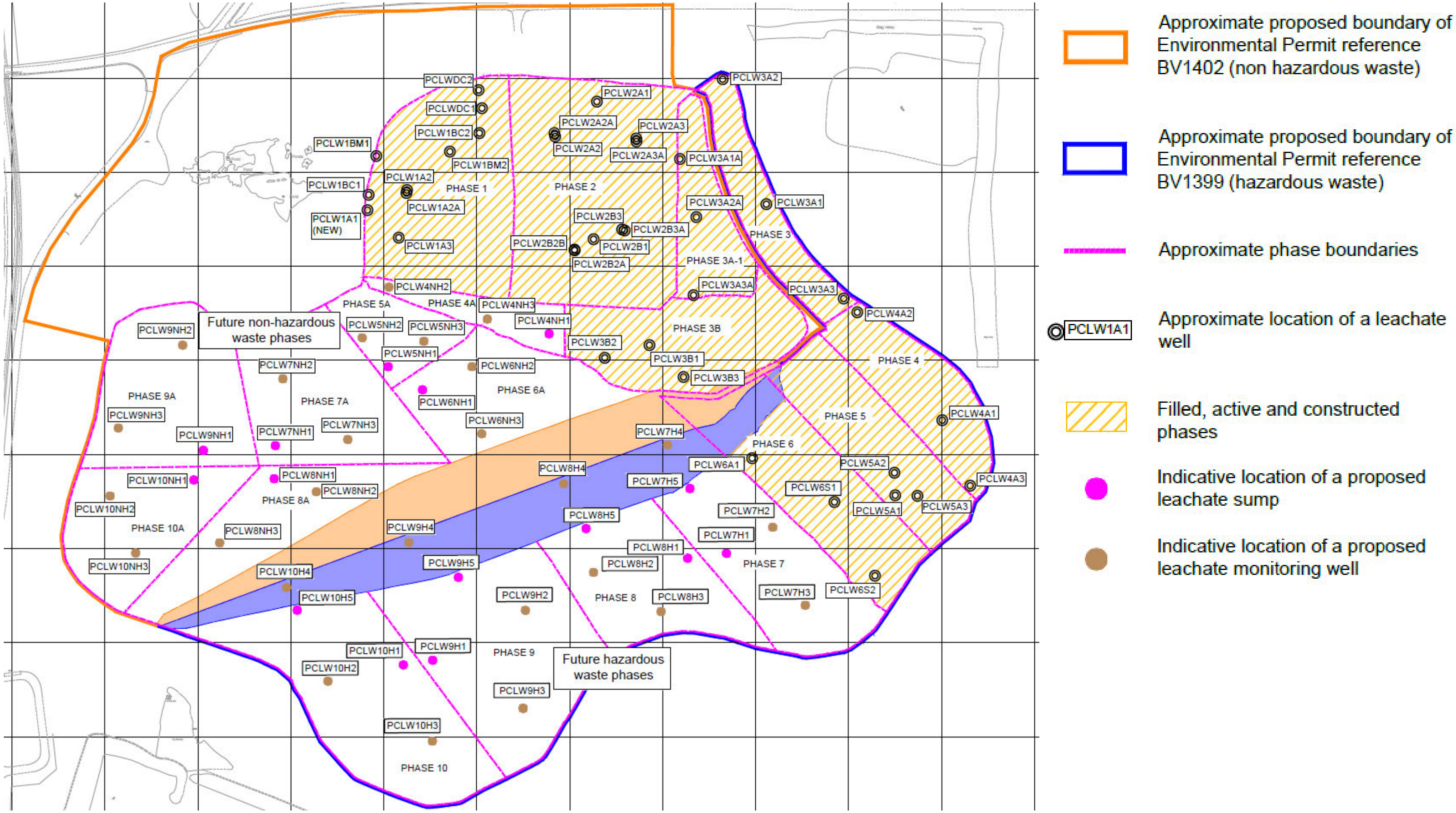


Figure 3 Consented site layout



Environmental Permitting – Hazardous Waste Treatment

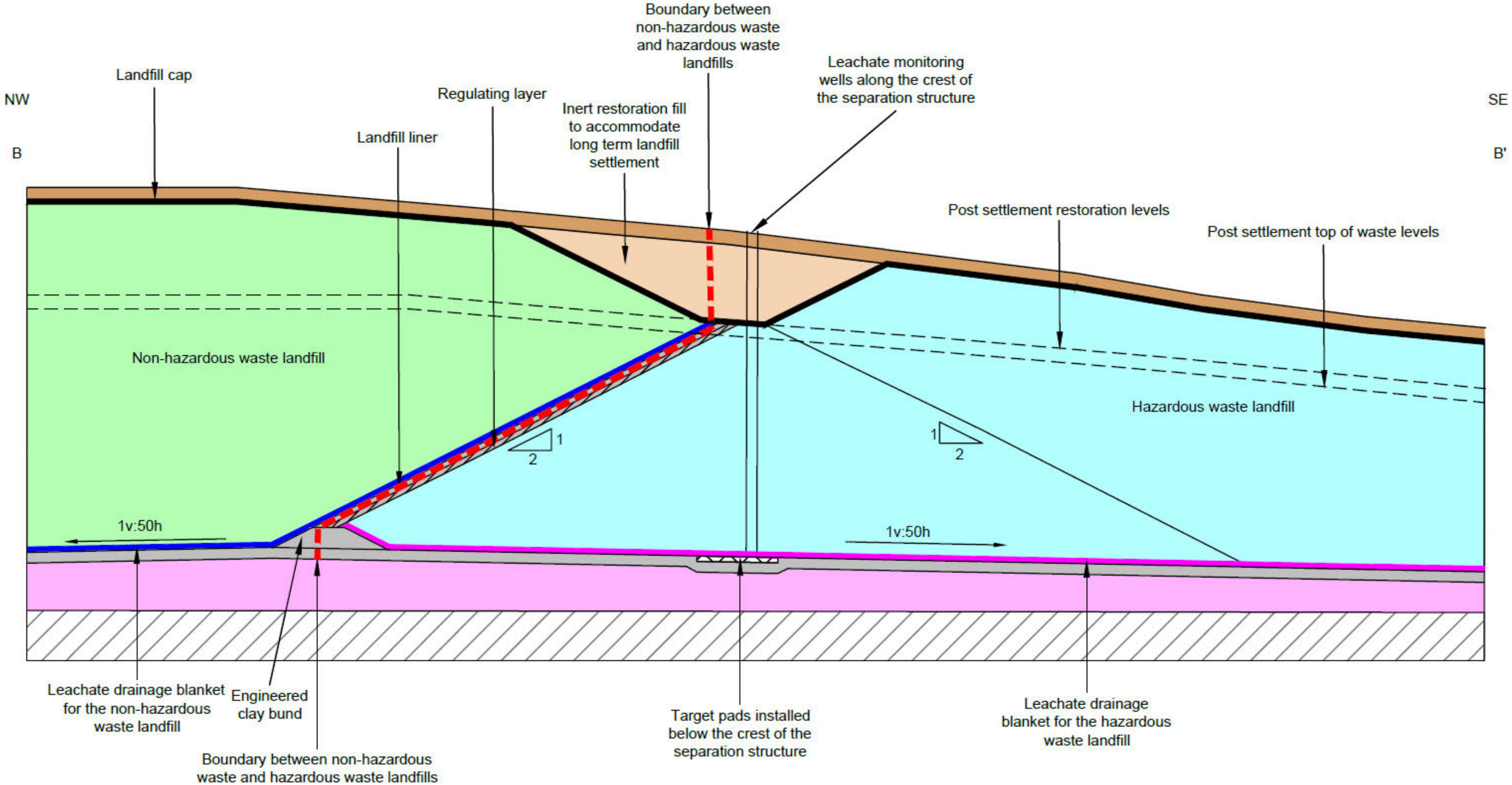
31. The WRP is located next to the hazardous waste landfill immediately to the south. The consolidated permit (reference EPR/YP3234XR/V007) for the facilities operated by Augean Treatment Limited lists the permitted waste management activities (and directly associated activities) that includes:

- Waste Wood Energy Recovery;
- Plasma Treatment;
- Thermal Desorption;
- Tank Farm;
- Effluent Treatment;
- Anaerobic Digestion;
- Waste Recovery Facility;
- Waste Transfer Station;
- Soil Washing;
- Waste Stabilisation;
- Bio-remediation;
- Storage prior to treatment;
- Cement storage and blending;
- Storage of non-hazardous wood materials;
- Gas storage and gas flare (from landfill);
- Surface water management including storage;
- Storage of non-hazardous materials (for processes); and,
- Storage of waste, oil, raw materials (for processes).

Environmental Permitting – LLW Treatment

32. The WRP is also permitted to carry on radioactive substances activities (EPR/UB3694DU/V007). The facility is operated by Augean Treatment Limited and is permitted to receive, treat and subsequently transfer LLW off-site. Limits are set of the volume and activity (limits for specific radionuclides) of waste that can be accumulated on-site and the period over which those limits apply. Disposal is permitted to the LLWR site operator or to holders of a permit to receive and dispose of radioactive waste by on-site burial.

Figure 4 Design of separation bund between non-hazardous and hazardous waste landfills



1.3 Site development plans

33. The consented design of the two landfills (MJCA, 2018) allocates 44% of the void to disposal of hazardous waste, 54% to non-hazardous waste and the remainder (2%) to an engineered separation bund constructed from specified hazardous waste (see Figure 3 and Figure 4). The hazardous waste landfill area of approximately 19.5 ha and the non-hazardous waste landfill area is approximately 20.3 ha (MJCA, 2019a). The void allocation is shown in Table 2 and this split is used for the radiological assessments.

Table 2 Void space at Port Clarence, June 2024

Waste type	Phase	Void when built (m^3)
Non-hazardous	Future phases	2,065,000
Hazardous	Future phases including separation structure	1,779,810

34. The previous Hydrological Risk Assessment (Augean, 2006) was considered adequate after a review in 2010 CE, and an update was prepared in 2019 CE (MJCA, 2019b).

35. The landfill is designed and operated based on the principle of containment in accordance with modern standards and the use of Best Available Techniques (BAT) in accordance with the Landfill Directive. The base and sides of the disposal cells are lined with engineered low permeability material and a high-density polyethylene (HDPE) flexible membrane lining system. Once waste has been placed to final levels, a low permeability engineered cap is constructed on the top and restoration materials are placed over the cap. The main difference in design between the hazardous and non-hazardous cells is the thickness of the gravel leachate drainage layer and the thickness of the artificial geological barrier comprising clay with a hydraulic conductivity no greater than 1 10^{-9} m/s. The construction designs for the cells that would be used for LLW are presented in Table 3.

Table 3 Construction design of the hazardous and non-hazardous waste cells

Design feature	Non-hazardous waste cells	Hazardous waste cells
Leachate drainage system (depth of gravel) (m)	0.5	0.5
Artificial geological barrier (depth of clay)(1) (m)	1	1.5
HDPE liner and protective geotextile (mm)	2	2

Note: 1) Clay with a hydraulic conductivity no greater than 1 10^{-9} m/s.

36. Each phase of operation is restored progressively under a defined scheme of capping and restoration. In accordance with the planning permission, the landfills will be restored to areas suitable for nature conservation and amenity use.

37. Operating details for the site are not presented here and are available in the supporting documentation for the existing permitted operations. There are more than 100 separate operating procedures and risk assessments relating to waste operations. The

operating arrangements and culture at the site are consistent with the arrangements proposed for LLW disposal in the application.

1.4 The Proposal

38. In order to dispose of LLW at the Port Clarence landfill sites an Environment Agency permit for the disposal of LLW and a variation to the existing planning permission for the site are required. The boundary for disposal of LLW matches that for the hazardous and non-hazardous waste disposal permits shown in Figure 3.

39. The permit application is for the receipt, temporary storage (a maximum of 24 hours unless quarantined pending return to origin) and disposal of radioactive waste to the hazardous and non-hazardous landfills. Augean procedures will ensure prompt burial of radioactive waste, either on the day of receipt or the next working day, if waste has been delivered to the site too late to allow burial on that day. Disposed wastes will otherwise be compliant with Augean's Conditions for Acceptance (CfA), specified in site procedures for handling LLW, relating to the properties of the waste:

- disposal of radioactive wastes to the hazardous waste landfill that would be classified as inert, non-hazardous or hazardous in terms of their content of non-radioactive materials; and,
- disposal of radioactive wastes to the non-hazardous waste landfill that would be classified as inert or non-hazardous in terms of their content of non-radioactive materials.

40. The radioactive waste disposals will not be segregated from other, non-radioactive wastes disposed in the landfills. Radioactive waste containing hazardous waste will not be disposed to the non-hazardous waste landfill. The location of disposals will be recorded using GPS.

41. Augean requires full characterisation and waste acceptance assessment in accordance with the Environmental Permitting Regulations (UK Government SI, 2016) and waste classification technical guidance (Environment Agencies, 2021) for all radioactive wastes accepted for landfill.

42. The CfA that will apply at Port Clarence will specify that the consignor must discuss with Augean the requirement for leaching tests and other tests to demonstrate compliance with waste acceptance criteria, prior to preparing the consignment for shipment. The characterisation methodology of the waste and the results must be provided in a Waste Characterisation Document/Report. The leaching test must be undertaken in accordance with BS EN 12457-2. Testing for organic matter content may use either Loss on Ignition (LOI) or Total Organic Carbon (TOC). A complete set of Port Clarence LLW draft procedures has been provided to the Environment Agency along with this ESC.

43. The proposed permit would use a sum of fractions approach to regulate disposal (see Section 1.5). The permit will require the operator to calculate, for each radionuclide, the ratio of the activity of the radioactive waste disposed of at Port Clarence to the relevant values specified in the permit's disposal table. It will be a permit condition that the sum of these ratios shall be less than 1. A sum of fractions approach allows the operator greater flexibility in determining the final radioactive waste inventory without compromising environmental safety. The sum of fractions approach has been used to control the total radioactive waste disposals in other recent permits (e.g. for the ENRMF and LLWR disposal sites). The control of the radioactive waste disposals at

the site using the sum of fractions approach will be specified in the site operating procedures (PC LLW01). In addition, the ESC assumes that no more than 5% of either landfill, on a residual void basis, will be used for the disposal of LLW.

44. To ensure the greatest flexibility for future disposals, the table of disposal limits in the permit will incorporate relevant values for individual assessment scenarios as appropriate (for example groundwater, erosion and gaseous releases). NORM waste will be accounted for as a separate waste stream and compared with the NORM capacity criteria (tonnage).

45. The specific activity limit applied to a consignment is calculated from relevant radiological assessments and is, therefore, different for each radionuclide. A sum of fractions approach will also be applied to the specific activity of a consignment. The specific activity limits apply to a consignment or over every successive 10 t whichever has the lowest mass. Based on records to December 2023, the waste streams consigned for disposal at the ENRMF have an average specific activity across all LLW consignments of about 12 Bq g^{-1}. A similar average is expected for wastes accepted for disposal at Port Clarence.

46. No waste above LLW in radioactivity content will be accepted for disposal and this is part of the site procedures. The use of constrained upper limits per radionuclide introduces an arbitrary cap on disposals and the radiological impact is therefore capped at a value lower than that stated in the NS-GRA for certain fingerprints. Using typical fingerprints for decommissioning wastes as a basis to estimate consignment activity, the disposed concentrations will not exceed about 400 Bq g^{-1}.

47. In determining the specific activity limit consideration is given to compliance with the Paris Convention (NEA, 2017). This means that the disposal activity concentrations for certain radionuclides will not exceed the values shown in Table 4. In addition, an arbitrary limit of 5,000 Bq g^{-1} is applied to any radionuclide where the value calculated from the radiological assessments, or that shown in Table 4, is greater.

Table 4 Radioactivity concentration limits for the application of the Paris Convention on Third Party Liability

Radionuclide	Bq g^{-1}
H-3	10,000
C-14	10,000
Co-60	200
Sr-90	200
Tc-99	200
Cs-137	200
U-238	200
Pu-239	100
Am-241	100

48. Methodologies have been developed to evaluate disposal of consignments containing particles and for loose tipping of a specific waste stream. It is proposed that disposal of particles is permitted to defined particle activities and loose tipping is permitted to defined specific activities in a consignment, above which Environment Agency permission will be sought. Relevant values are presented in the ESC.

49. The minimum depth of non-radioactive waste or material covering LLW and the constraining time periods for cover to be in place following disposal are 0.4 metre (m) and 8 hours (h), respectively. Operating procedures will include specifications on the

depth of non-radioactive waste that will be placed at the base (2 m), sides (2 m) and top (1 m) of a landfill waste cell. Waste will be buried within 24 h of arriving on-site. Radioactive waste will not be deposited in the engineered separation bund.

50. An additional limitation is proposed for wastes containing a significant quantity of Ra-226 (Radium contaminated wastes) with a requirement to bury these wastes at least 5 m below the restored surface of the site. The proposed criterion for wastes containing a significant activity concentration of Ra-226 is waste containing >5 Bq g^{-1} Ra-226. This limitation will be applied to disposals of NORM and LLW.

51. Port Clarence accepts Type 2 NORM waste under the conditions of the exemption from the need for a Permit under EPR2016 for Type 2 NORM. The interaction between these NORM wastes and the radiological capacity for radioactive wastes is considered in the ESC and the preferred approach is to apply a waste tonnage capacity for the Type 2 NORM and a radiological capacity for artificial radionuclides independently and to keep a record of the dose from disposal LLW and the dose from disposed NORM so that the dose from the combined disposals can be compared with relevant dose criteria. This would allow the inputs of NORM to be monitored based on tonnage delivered to the site and compared with the site capacity expressed in tonnes to ensure that the disposal capacity was not exceeded. The input of artificial radionuclides would be monitored using a sum of fractions approach, comparing the total activity of each artificial radionuclide with their radiological capacity. The LLW permit would specify the radiological capacities of the artificial radionuclides and the use of the sum of fractions approach. The LLW permit would specify the activity concentrations of the artificial radionuclides and apply the sum of fractions approach to limiting total activity concentration. It would also specify that the Type 2 NORM disposal capacity is considered separately of this radiological capacity, and that the doses from the NORM disposals remain below a dose constraint of 300 µSv y^{-1}.

52. Specific limitations on disposals of radioactive waste in the non-hazardous landfill are proposed based on the results of the ESC due to the potential for a greater organic matter content.

53. Each phase of operation is progressively restored under a defined scheme of capping and restoration. The minimum depth of restoration material above the engineered cap will be 1 m or greater, and the depth of the engineered cap will be 0.3 m. In accordance with the planning permission, the landfill site will be restored to areas of grassland, scrub and woodland and surrounding areas will be restored to areas of shallow open water, aquatic marginal vegetation, scrub, wet meadow and ruderal grassland with small hollows, banks and ridges suitable for nature conservation use.

1.5 The Sum of Fractions Approach

54. Radioactive waste that would be disposed at Port Clarence must be consistent with limits specified in the permit, and in the last few years, new permits for LLW disposal at other sites have included activity concentrations, tonnage limits and a radiological capacity.

55. For most scenarios, it is reasonable to take the view that for each radionuclide the total radiation dose is proportional to the total inventory disposed. When contaminants are transported in groundwater or leachate is discharged to a sewer, for example, it is likely that substantial mixing will occur so members of an exposed group are exposed to activity concentrations in environmental media that are a function of an average of those in the landfills. However, for certain cases, it is more reasonable to consider the

radiation dose to be proportional to the average activity concentration over some smaller volume of a landfill. This will be true, for example, as a result of growing vegetables on a small plot of contaminated soil where the contamination may derive from only a portion of the disposed waste. This is reasonable because these scenarios involve disruption of the cap and underlying waste; the exposure mechanism is also likely to result in some further mixing of the waste.

56. To account for the possibility that there could be dose contributions from more than one radionuclide at once, a limit is applied that constrains the contribution from each individual radionuclide. This is the radiological capacity. This radiological capacity ensures that the dose and risk criteria are met. The 'sum of fractions' approach is then used to limit the inventory of each radionuclide in the site to ensure that the dose criteria are met and the capacity is managed.

57. The radiological capacity for each radionuclide is calculated by considering each scenario in turn and deriving the scenario radiological capacity. At Port Clarence, there are two landfills, the landfill for non-hazardous waste and the landfill for hazardous waste. We have assumed that the receptor for the hazardous landfill scenario is the same as the receptor for the non-hazardous landfill, for all similar scenarios. Hence the scenario radiological capacity for these scenarios, and hence the sum of fractions approach, will refer to the combined inventory disposed in the separate landfills. The radiological capacity of the non-hazardous landfill also takes account of two additional scenarios: a landfill fire and collection of landfill gas for energy production (see Section 7.4) which are not relevant for the hazardous landfill.

Methodology

58. A limit, L_{Rn} is defined for each radionuclide corresponding to the total activity within either the hazardous or non-hazardous landfills separately at which the radiation dose from that radionuclide would be equal to the regulatory criterion. The adopted limit is the lowest value calculated from the specified assessment scenarios and is called the radiological capacity.

59. The sum of fractions approach restricts the disposed activity of waste containing radionuclides *Rn* such that:

$$\sum_{Rn} \frac{I_{Rn}}{L_{Rn}} \leq 1$$

with:

- I_{Rn} is the inventory of radionuclide *Rn* (TBq); and,
- L_{Rn} is the limiting radiological capacity for radionuclide *Rn* (TBq).

60. The radionuclide inventory for each landfill is assessed using this sum of fractions, and no further radioactive waste will be accepted once the sum equals 1 when values are summed for a given scenario. The sum of fractions is a standard approach, as described in an IAEA technical document (IAEA, 2003) and used in other permits (e.g. CD7914 for the Lillyhall landfill site and FB3598 for the ENRMF).

Scenario radiological capacities

61. The dose and risk criteria used to determine the radiological capacity of the Port Clarence landfills depends on the scenario being considered. In principle, these can be identified as:

- for site workers, the dose criteria are the site criterion of 1 milli Sievert per year (mSv y^{-1}; see Section 6.1);
- for the public a dose constraint of 300 micro Sievert per year (µSv y^{-1}) during the period of authorisation (the constraint applies to the entire Port Clarence site, i.e. the non-hazardous and hazardous landfill sites are considered as a single source) for all exposure pathways, other than contamination of groundwater for which 20 µSv y^{-1} is used based on leachate entering groundwater (see Section 6.1);
- in the post-authorisation period a risk criterion of 10^{-6} y^{-1} for the public is indicated in the NS-GRA and this can be considered equivalent to a dose rate of around 20 µSv y^{-1} (see Section 6.2.2); and,
- for human intrusion in the post-authorisation period a dose guidance level of 3 mSv y^{-1} is used for prolonged exposure (see Section 6.3).

62. The radiological capacity is the total activity (e.g. MBq) that can be disposed without exceeding the dose criteria specified above.

63. All assessments are based on a disposal of 1 MBq and the results presented as dose per megabecquerel (mSv MBq^{-1} y^{-1} or µSv MBq^{-1} y^{-1}) calculated for each radionuclide considered under each scenario. The appropriate dose criterion divided by the dose per megabecquerel provides the radiological capacity ($L_{Rn,\ Scenario}$) for a given scenario as:

$$L_{Rn,Scenario} = \frac{Dose_{crit}}{Dose_{Rn,Scenario}}$$

with:

- $L_{Rn,\ Scenario}$ is the scenario capacity for radionuclide *Rn* (e.g. MBq), also referred to as the scenario radiological capacity;
- $Dose_{crit}$ is the scenario dose criterion (µSv y^{-1} or mSv y^{-1}); and,
- $Dose_{Rn,\ Scenario}$ is the calculated scenario dose for radionuclide *Rn* (µSv MBq^{-1} y^{-1} or mSv MBq^{-1} y^{-1}).

64. The limiting (minimum) scenario capacity for each radionuclide is the radiological capacity, the value L_{Rn} in paragraph 63 that is used in the sum of fractions.

65. A scenario radiological capacity applies to the whole site and the disposed inventory is controlled by adding separate fractions calculated for the hazardous landfill and non-hazardous landfill. The radiological capacity for each radionuclide is presented in the tables for each scenario and in Table 41 and Table 42

66. The calculations for a future resident living on a waste/spoil mix implies a limit on the specific activity of Ra-226 bearing wastes that are disposed of within 5 m of the restored surface of the site. This has been incorporated as a waste emplacement strategy for wastes containing >5 Bq g^{-1} of Ra-226.

1.6 Environmental Safety Strategy

67. The objective is to dispose of LLW to the Port Clarence landfills in such a way as to ensure that impacts to people and to the environment are protected to a high level, both in the short and long-term, based on current limits, targets and guidance, without any reliance on waste retrieval or other intervention measures.

> "The Fundamental Protection Objective is to ensure that all disposals of solid radioactive waste to facilities on land are made in a way that protects the health and interests of people and the integrity of the environment, at the time of disposal and in the future, inspires public confidence and takes account of costs." (UK Environment Agencies, 2009) para 4.2.1

68. This will be achieved through the use of both engineered and natural barriers to contain the disposed radionuclides for as long as reasonably practicable and thereafter limit the rate at which any radionuclides are released to the accessible environment. Modern landfills are engineered facilities that are designed, built, managed and monitored in order to protect the environment from risks associated with the disposed wastes. Environment Agency design requirements consider: the stability of the lining and capping system, wastes and underlying geological strata; the leachate collection system; operational and management control of the leachate and groundwater systems; collection of landfill gas and preventing migration of gas; and, environmental monitoring.

69. The NS-GRA requires an environmental safety strategy that is supported by an ESC. Such a strategy should:

> "… present a top-level description of the fundamental approach taken to demonstrate the environmental safety of the disposal system. It should include a clear outline of the key environmental safety arguments and say how the major lines of reasoning and underpinning evidence support these arguments." (UK Environment Agencies, 2009) para 7.2.2

70. As discussed further in Section 2.10 the Port Clarence site is not at risk of erosion from the relatively slow moving River Tees but could be impacted by sea level rise due to climate warming. Consideration is also given to the long-term evolution of the site and the likelihood and potential impact of tidal erosion.

71. The strategy to achieve the objective of low impacts at all times following waste disposal consists of disposing of wastes that represent a low inherent risk (by limiting specific activity) and a restriction on the total quantity that can be disposed at Port Clarence. Our approach is the same as that used at the ENRMF and as such wastes will be disposed of at a facility that:

- has an established track record - Port Clarence has been in operation since 2000 CE with a hazardous waste landfill site and a non-hazardous waste landfill site, and has experience handling LLW at the WRP (since 2016 CE);
- is based on well tried and tested technologies that are BAT;
- is robust and incorporates multiple engineered barriers and safety functions;
- is regularly reviewed for compliance with current standards as subsequent phases for developing disposal cells are planned;
- is subject to active management control; and,
- maximises use of passive safety features.

72. The overall safety strategy for the disposal of LLW at Port Clarence involves both active (operational) management and the construction of passive barriers, ensuring that wastes disposed of will give rise to low impacts, within the dose and risk guidance levels laid down in the NS-GRA. The following approach will be taken (*italics indicate changes of approach since the ENRMF ESCs* (Eden NE, 2015a; Eden NE, 2015b; Eden NE, 2023)):

- landfill concept:
  - the landfill design with fit-for-purpose disposal cells with basal and side-wall liners, as well as a low permeability capping layer, provides an engineered barrier, reducing leachate generation and migration over periods of many decades or centuries (see Section 2.4.2);
  - cell caps will be constructed once disposal cells are full, reducing water ingress, and hence reducing potential leachate generation;
  - active collection of leachate during and following the operational period and use on-site at the treatment facilities or transported for discharge via a <u>*reed bed or*</u> aqueous waste treatment plant reduce the risk of contamination of groundwater in the vicinity of the disposal site, *disposal requirement of leachate off-site will prioritise cells that have not received LLW* (see Section 2.4.3);
- site procedures:
  - work management culture and safety procedures ensure that wastes are transported and handled safely reducing the potential for dose impact to the workforce and the risk of accidents leading to unplanned impacts on the environment (see Section 5.2.5);
  - environmental monitoring during the period of authorisation will check the integrity of barriers and safety plans (see Section 7.5);
  - waste will be placed in the landfill as soon as practicable after inspection <u>on arrival at the landfill and within a maximum of 24 hours following acceptance for disposal at the landfill site</u>, any waste not accepted for disposal will be placed in quarantine and returned to the consignor as soon as practicable (see Section 7.3.1);
- inventory controls:
  - limits will be set on the specific activity in each consignment *(Bq g^{-1}- the activity concentration)* and the total activity (MBq) that can be disposed (the total volume of waste that can be accepted is already limited by the planning consent), see Section 7.4.3;
  - Waste Acceptance Criteria (WAC) will be specified, covering radiological and non-radiological properties of the wastes, and a written specification of acceptable waste types will be provided to any person seeking to dispose of waste at Port Clarence (the CfA), (see Section 7.4.2.1);
  - waste containers must comply with transport regulations, provide good containment (ISO containers, drums or double skinned bags except in special circumstances where BAT dictates otherwise) and reduce accidental exposures (see Section 7.3.1);
  - the underpinning justification for the waste (for example, BAT reports) against the waste hierarchy to be made available to Augean (see Section 7.4.2.2);

- a waste inventory regulated using a sum of fractions approach for LLW (see Section 7.4.1.1) and a separate tonnage capacity for NORM wastes (see Section 7.4.1.3), a record will be maintained of the dose to members of the public from relevant scenarios arising from disposals of both NORM and LLW;
- *a specific activity regulated using a sum of fractions approach, with individual radionuclides limited to radionuclide specific values up to 5000 Bq g^{-1} and a consignment limit for any fingerprint of 2000 Bq g^{-1}. (see Section 7.4.1.2)*;
- *LLW disposal will be limited to 5% of the available void on the date specified in the permit (recorded on a mass basis);*

- Optimisation considerations:
  - the wastes will be covered immediately to reduce the risk of dust suspension and hence the risk of impacts via the inhalation pathway during the operational period (see Section 7.3.1);
  - consideration of other design, disposal location, operations and waste form features (see Section 6.5);
  - the surface dose rate of packages (measured at 1 m) shall not exceed 10 μSv h^{-1} (see Section 7.3.1).
- Impacts (see Sections 6.1, 6.2, 6.3 and 6.4):
  - scenarios involving exposure to waste during normal operations and expected site evolution have been considered ensuring doses or risks remain below the relevant dose and risk guidance levels;
  - a full range of scenarios involving unplanned exposure to waste have been considered, in order to ensure that for all reasonably foreseeable circumstances doses or risks remain below the relevant dose and risk guidance levels;
  - all scenarios assume the earliest possible exposure of members of the public, even though in most cases potential exposure would not occur until a long time after the period of authorisation has ended, if at all; and,
  - the impact of uncertainty in estimated doses and risks (see Appendix E.8) has been considered to demonstrate that the ESC is robust in meeting all relevant dose and risk guidance levels.

73. Waste retrieval is not planned and the assessments in this ESC relate to waste disposal (see NS-GRA, para 3.6.2). Nonetheless, retrieval would be feasible both in the short and longer term if required because the location of disposals will be recorded using GPS. This provides an assurance of last resort that, should an unforeseen (and unacceptable) impact occur, intervention to reduce or eliminate the impact could be undertaken. It is emphasised, however, that it is considered that under all foreseeable circumstances, it will not be necessary nor should it form any part of contingency planning.

2 Site Characteristics

2.1 Introduction

74. The NS-GRA (UK Environment Agencies, 2009) requires that the site characteristics, including the geological environment and the biosphere are characterised, understood and capable of analysis to the extent necessary to support the ESC. Such characterisation has been undertaken (Augean, 2014; MJCA, 2019a) and provides the basis for the description set out in this section.

75. This section presents a summary of the current understanding of the characteristics of the site, including information on the physical setting, land use and hydrology, and of the regional and local geosphere including lithology, stratigraphy, resource potential, hydrogeology and geochemistry relevant to the assessment of the proposed disposal facility. Consideration of the natural evolution of the site that may cause disruption of the landfills under reasonably foreseeable future conditions is also presented.

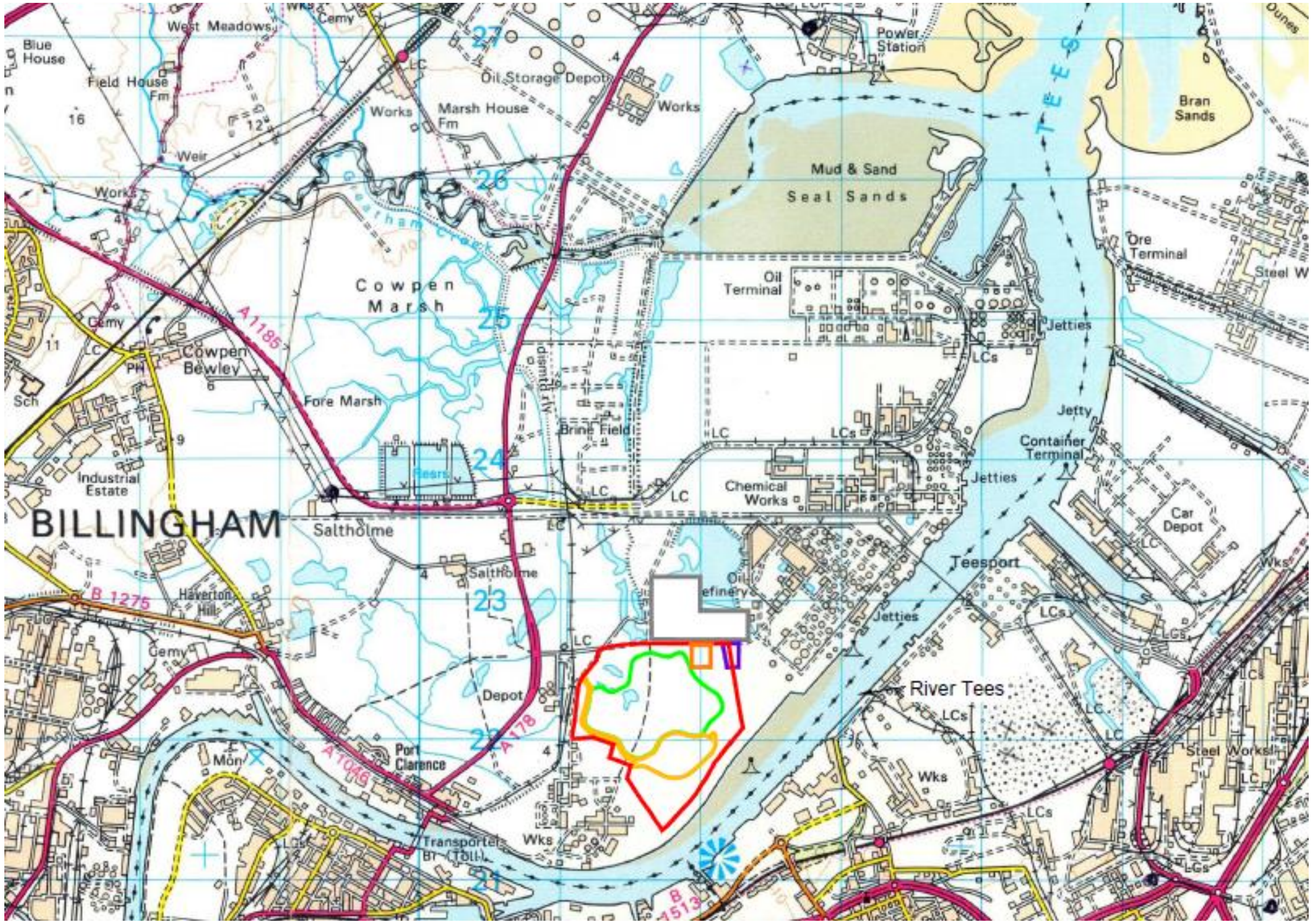
2.2 Location

76. The Port Clarence landfills are located about 7 kilometres (km) from the open sea and about 3 km from the tidal flats at Seal Sands (Figure 5). The site covers 107 ha within which the landfills occupy approximately 46 ha to the north and the WRP occupies approximately 13 ha immediately adjacent and to the south of the landfill sites. The remaining land in the area subject to the planning consent is occupied by partially re-vegetated land reclamation materials (such as industrial slag) and pools of standing water some of which have developed an ecological interest and are preserved for that purpose. An aerial photograph of the site is presented as Figure 6.

77. The operational landfill area is situated about 280 m from the northern bank of the River Tees and approximately 2.6 km north-east of Middlesbrough Station. Between the WRP and the river bank there is an embankment (about 14 to 15 m AOD [above ordnance datum] along its length).

78. The boundary of the Tees and Hartlepool Foreshore and Wetlands Site of Special Scientific Interest (SSSI) surrounds the site and is found at varying distances from the landfills depending on direction of travel. The SSSI comprises 7 units (areas) and includes Dormans Pool about 230 m north of the landfill at its closest point. The SSSI also includes the River Tees, approximately 280 m from the south east boundary of the landfill. Overlapping designations include Saltholme Nature Reserve (RSPB), the Teesmouth and Cleveland Coast Ramsar (covering the north bank of the River Tees and parts of the nature reserve, including Dormans Pool) and the Teesmouth and Cleveland Coast Special Protection Area. The nature reserve is located approximately 20 m to the north of the site at its closest point (Dormans Pool area), separated from the site by Huntsman Drive. The nature reserve also encompasses land to the west of the landfill and is designated for supporting an internationally important population of wildfowl and waders.

Figure 5 The site location



Key / Notes

- Red: Boundary of the area the subject of planning consent TDC/94/065 and the area under the control of the applicant
- Green: Boundary of the operational landfill
- Yellow: Boundary of the waste recovery park the subject of planning consent 07/2984/EIS
- Grey: Approximate extent of reclaimed land developed for waste and renewable energy facilities
- Purple: Approximate extent of a gas production facility
- Orange: Approximate extent of the vitrified aggregate storage area

Figure 6 Aerial view of the site showing approximate location of planning consent boundary

2.3 Development of the Tees Estuary

79. In the 18th century the estuary was wide and bell-shaped. The tidal limit on the River Tees was 49 km from the mouth of the estuary at Low Moor (NZ 36508 10520) with saline intrusion to 33 km (Environment Agency, 1999). The Tees Estuary developed under the influence of fluvial sediments deposited by the slow-moving river combined with coarser sediments of marine origin deposited by tidal action to form a broad expanse of tidal mudflats and salt marshes with shallow shifting channels towards the sea. Of the original 2,470 ha of inter-tidal mudflats and sandbanks present in 1850 CE, only 200 ha now remain (Environment Agency, 1999).

80. The Tees Estuary has been modified by extensive engineering works over the last 200 years. The first embankments were constructed in 1723 CE to reduce tidal flooding of Coatham Marsh, an attempt to improve grazing (Fouracre, 2005). In 1810 CE, the Mandale Cut removed a 5 km loop of the estuary to improve access to Stockton-on-Tees for shipping, in 1831 CE the Portrack Cut removed a shorter more hazardous bend and in 1855 CE the current channel from Middlesbrough Dock to the sea was formed (Fouracre, 2005) by first shutting off the northern and middle channels, constructing retaining walls and dredging to deepen the channel (Baker, et al., 2007). Routine dredging of the River Tees began in 1853 CE (Le Guillou, 1978).

81. The first edition of Ordnance Survey (OS) maps (dated 1853 CE) shows the southern limit of the high water mark (of an ordinary spring tide) as close to the route of the Middlesbrough to Redcar railway line (MJCA, 2007). Land above the Port Clarence settlement to the north is shown as liable to flooding and records indicate reclamation work started in 1853 CE (Le Guillou, 1978). Extensive embankments were in place by 1856 CE, protecting Saltholme and Port Clarence Iron Works from tidal flooding. Towards the end of the 19th century iron works are shown at many other sites on the south bank and slag waste from this industry was used in river training structures to define the navigation channel and reclaim the foreshore (Fouracre, 2005). The South Gare Breakwater at the mouth of the estuary was completed in 1888 CE (Baker, et al., 2007) and construction of the North Gare Breakwater was stopped in 1891 CE.

82. Successive maps covering the 20th century show embankments and land reclamation extending seaward. The land to the south of the Port Clarence landfills was reclaimed by 1913 CE but most of the site remained below the high water mark (of ordinary tides). By 1948 CE, embankments protect the area where the landfills are located, and at that time the area is shown as marshland surrounding a large bunded lagoon. Maps from 1955 CE onwards show further reclamation; by 1961 CE the lagoon is smaller, and by 1994 CE the lagoon no longer exists. The last major reclamation work on Seal Sands was completed in 1974 CE (Environment Agency, 1999) and reclaimed land is now dominated by large industrial complexes (Baker, et al., 2007). Waterbodies have also formed in depressions caused by brine extraction (from sub-strata) centered around Saltholme (Natural England, 2014).

83. The Tees Barrage was completed in 1995 CE (at OS grid reference NZ 46254 19036) and is now the upper limit of saline intrusion and tidal influence. The barrage has affected fluvial deposits in the lower estuary and they are now held at the barrage (Nelson, 2003). This has led to a change in the deposition of highly organic fine sediments in the upper and middle estuary with coarser, marine-derived sediments dominating at Teesmouth (Environment Agency, 1999). Accumulating sediments of marine origin are dredged periodically to provide shipping access to Teesport (Villars & Delvigne, 2001). Teesport is the fifth largest port in the UK and is a major deep sea maritime complex, contributing over £1.4 billion to the UK economy each year. The

stated ambition is that in 2050 the River Tees will be the UK's most successful port region, defined by high-value trade, sustainability and thriving communities.

2.4 Landfill History, Design and Use

2.4.1 Landfill History

84. A brief history of the industrial use of the site is provided below (MJCA, 2019a):

- 1855 CE: Port Clarence ironworks with waste blast furnace slag progressively tipped northwards across the site to reclaim the marshlands;
- early 1900s CE: industry at the site included gas works, lime works, chlorine works, soda works, blast furnaces and salt evaporating pans;
- by 1930 CE an iron and steel works had operated and been demolished at the site;
- the western part of the wider site was quarried for slag deposits up until 1976;
- the quarries were licenced to BSC Chemicals by Cleveland County Council for the tipping of potentially combustible industrial waste materials such as tar, bitumen and pitch until 1985 CE (see areas labelled CLE 45 and CLE 46 in planning application 94/1049/P); and,
- an additional licence was granted for the disposal of pulverised fuel ash, slag, ash, coke, breeze and acid tars with steel slag - material was placed in a depression running north to south to the south of the current landfill area.

85. The Port Clarence landfill sites were granted planning permission in September 1996 (planning application reference TDC/94/065) for use as a waste disposal site (see planning reference 94/1049) for a period of 16 years after waste was first disposed on-site. Landfilling commenced at the site in October 2000 and the operation of the two separate landfill sites has been carried out by Augean North Limited since February 2004. A planning variation was agreed in April 2003, increasing the limit on imported materials deposited at the landfill site to 8.5 million cubic metres (Mm^3; see planning reference 02/1987/P) in order to achieve the restoration landform previously agreed. The most recent planning variation (planning reference 14/3135/VARY) for the site was granted by Stockton-on-Tees Borough Council in June 2015.

86. At the end of June 2024:

- two areas of the hazardous waste landfill have been capped and await restoration (Phases 3 and 4), and three areas of the non-hazardous landfill have also been partially capped (Phases 1, 2 and 3A-1);
- small prepared void spaces remain in both the hazardous (Phases labelled 5, 6 North, 6 South and 7 South) and the non-hazardous landfills (Phases labelled 3B and 4 A); and,
- larger prepared voids remain in Phases 6A (non-hazardous) and Phases 8 and 9 (see Table 5), further waste cells are under preparation.

Table 5 Allocation of void space at Port Clarence landfill sites

Waste type	Phase	Area label	Void when built (m^3)	Void remaining on 20/06/24 (m^3)	Capping
Non-hazardous	Constructed	1 & 2	830,000	74,530	Partially capped area = 45,390m^2
		3A-1	230,000	10,580	Partially capped area = 4,730 m^2
		3B	444,850	22,280	Not capped
		4A	191,960	6,740	Not capped
		6A	311,620	25,370	Not capped
Hazardous	Constructed	3	60,720	11470	Capped
		4	126,500	15560	Capped
		5	221,500	18760	Not capped
		6 North	111,630	6,970	Not capped
		6 South	166,930	9,770	Not capped
		7 South	206,550	16,860	Not capped
		8(1)	569,460	28,680	Not capped
		8(2)	29,550	11,180	Not capped
		9	192,760	20,180	Not capped

Notes:
1) Including separation barrier Phase 1.
2) Separation barrier Phase 2 – first lift only.

2.4.2 Design and Construction

87. Port Clarence landfills have been operational for twenty four years. The landfill sites are designed and operated based on the principle of engineered containment with low permeability basal, perimeter and capping seals constructed to an engineering specification which is the subject of approval by the Environment Agency under the Environmental Permit for hazardous waste disposal and non-hazardous waste disposal and the Landfill Directive (European Commission, 1999).

88. The current design allocates 45% of the void to disposal of hazardous waste, 53% to non-hazardous waste and the remainder (2%) to an engineered separation bund (see Figure 3 and Figure 4). The separation bund accounts for 8% of the void and is located within the hazardous waste landfill permit boundary. A series of cells will be filled, capped and restored progressively. The site is operated in a cellular manner to minimise leachate generation. To separate the wastes from the surface environment and to minimise the infiltration of rainfall the landfill will be capped with low permeability layers overlain with restoration materials.

89. The waste cells are formed of a low permeability lining system constructed along the base and sidewalls to an engineering specification which is agreed with the Environment Agency as part of the site Environmental Permit (Augean, 2014). The low permeability liner is constructed using a low permeability mineral liner such as clay and an artificial liner such as a geomembrane. Mineral liners are formed by placing and compacting material in a series of layers until a liner of a specified thickness and low permeability has been formed. The base of each cell is constructed with a suitable gradient to drain rainfall and leachate collecting in the cell to a collection point. Each landfill cell is constructed with a drainage layer comprising free draining material along with pipework connected to a leachate collection sump used to manage leachate levels within the cell. The lining system is constructed by a specialist contractor overseen by

a construction quality assurance engineer. The lining system is subject to testing during construction and approval by the Environment Agency.

90. The separation support structure within the hazardous waste landfill permit boundary will be constructed from selected treated hazardous waste producing an engineered compacted volume inside the engineered containment.

91. Selected treated hazardous waste soils are being placed above the basal containment lining system in layers and compacted to form a separation support structure along the boundary between the two landfill sites. A side slope landfill liner for the non-hazardous waste landfill site will be constructed over the northern face of the waste separation support structure. The internal cap to the hazardous waste landfill site, which directly overlies the separation support structure, will be formed of a 0.3 m regulation layer with compacted low permeability clay above. The compacted low permeability clay will be overlain by the geomembrane which forms part of the side slope liner system for the non-hazardous waste landfill site. A cross section through the proposed separation support structure is shown in Figure 4.

92. The waste used for the separation structure will be contaminated soils treated with air pollution control residue (APCR soils). Field compaction trials and laboratory testing have been undertaken on this material and the results demonstrate that the APCR soils can be compacted to achieve high strengths and friction angles and therefore will have the geotechnical properties needed to form the separation structure (MJCA, 2019a). Alternative suitable hazardous waste materials may be proposed for use. The wastes used to form the separation structure will be placed and compacted in accordance with an agreed methodology and/or specification. In order to achieve effective cohesion, the material is placed as a wet plastic material, which has a low potential to generate dust. Radioactive waste will not be used in the separation bund as this is part of the engineering structure. In accordance with the placement specification, radioactive waste will not be placed within 2 m of the engineered separation bund.

93. The detailed design of the low permeability capping layer at the site will be agreed with the Environment Agency (see Figure 10) and will comprise, a 0.3 m regulating layer, a protection geotextile, a low permeability geosynthetic clay liner and 1 m of restoration soils (MJCA, 2019a). The ESC takes a cautious approach to the degradation of the capping layer and assumes it will deteriorate in a similar fashion to polyethylene capping material. The placement of a cap and restorations soils will significantly reduce the amount of rainfall infiltrating the site, and the generation of leachate will become minimal. A temporary cap is placed over filled cells prior to final capping if waste deposit in an area ceases temporarily or, in some circumstances, pending placement of the final cap. The ESC cautiously assumes that the permanent capping layer will slowly degrade over time.

2.4.3 Leachate Management

94. Leachate is formed as a result of the release of liquids entrained in deposited wastes and following the infiltration of rainfall through the waste. The engineered landfill containment system includes a leachate management system for the collection and extraction of leachate. A leachate drainage blanket and collection sumps are constructed at the base of the site immediately above the low permeability basal liner. The leachate levels are controlled by pumping leachate from the leachate collection

sumps or other extraction wells drilled as necessary. The level at which the leachate is maintained will be specified in the Environmental Permit.

95. The leachate generated at the site will not be used for dust suppression. The excess leachate will be pumped into a leachate storage tank and used in the on-site WRP in place of clean water. If the leachate cannot be processed in the on-site waste treatment facility it will be removed from site by tanker for treatment at a suitably authorised waste water treatment plant. Leachate is monitored for chemical characteristics to confirm that the contaminants remain below the levels specified in the hydrogeological risk assessment. This monitoring will be extended to include radiological characteristics.

96. Off-site leachate treatment facilities are the reed bed treatment facility at Norton Bottoms (Scot Bros.) and the industrial effluent treatment works at Bran Sands (Northumbrian Water Limited). Experience at the ENRMF shows that bulked leachate continues to fall outside the scope of radioactive substances regulation. We confirm that disposal of leachate that contains activity concentrations that fall under radioactive substances regulation would not be sent for disposal off-site (e.g. at the Reed Beds). The Reed beds facility would only be used if the leachate quality was suitable for treatment and subject to appropriate permitting.

97. The primary limitation on processing capacity at the WRP will be availability of APCR which is used as a reagent (a substitute for cement) in the stabilisation process. In the unlikely event that excess leachate is generated and is not suitable for disposal at the Reed Beds or Bran Sands, Augean has the option to use cement, lime or other stabilising medium and if necessary Augean can also increase operating hours taking advantage of the 24 h operating consent under planning. As cement and lime are readily available to purchase this removes any constraint on the ability to treat the leachate.

2.4.4 Landfill Gas Management

98. The management of landfill gas at the hazardous and non-hazardous landfill sites is the subject of conditions of the Environmental Permits. Landfill Gas Management Plans are in place and implemented through the Augean management systems. Landfill gas is extracted and pumped to the WRP where it is used to generate electricity for either site use or distribution into the grid, any excess gas is burned in a flare stack.

99. As the amount of landfill gas that is generated in the hazardous waste landfill site is low, a less extensive gas management system is needed compared with that needed for the non-hazardous waste landfill site (MJCA, 2019a).

100. The majority of the landfill gas generated at the site is from the non-hazardous waste landfill site. Information in respect of landfill gas generation was included in the landfill gas risk assessment (LFGRA) prepared as part of the permit application entitled ‘Landfill gas generation and risk assessment Port Clarence Landfill Site’ reference 03523434.500 and dated June 2003. The LFGRA predicted a landfill gas generation rate at the 95^{th} percentile of 2,730 $m^3\ h^{-1}$ for the year 2018 CE. Based on information provided by Augean and Renewable Power Systems (RPS) the measured average flow rate of gas extracted from the non-hazardous waste landfill site in 2018 CE was in the range 177 Normal $m^3\ h^{-1}$ ($Nm^3\ h^{-1}$) to 230 $Nm^3\ h^{-1}$ (MJCA, 2019a).

101. The hazardous wastes that are currently and will continue to be deposited at the site have an organic carbon content limited to less than 6%. Putrescible materials are not

accepted in the hazardous landfill. The LLW wastes that will be disposed of at the site will have a generally low level of organic matter and are only slowly degradable, if at all. Putrescible materials are not accepted. The levels of radioactivity in LLW are too low to give rise to risk from radiolytic hydrogen gas evolution. The site operates a gas management system that is able to manage any gas generated from the waste. It is unlikely that significant quantities of landfill gas will be generated from LLW that will be deposited at the site. If gas is generated by the non-hazardous or hazardous waste and/or LLW, the gas will be collected in the gas management system and be combusted.

102. A dual system of migration control will continue to be operated at the site. The engineered low permeability basal and sidewall liners impede lateral gas and vapour migration and the low permeability cap reduces the emissions to the atmosphere. A pumped landfill gas extraction system will continue to be operated as necessary, which prevents the accumulation of gas under elevated pressures in the landfill, minimising further the risk of the migration of gas and the emissions of gas to the atmosphere. The collected gas will continue to be directed to the power generation unit to the south east of the landfill and burnt. Combustion of the gas destroys potentially harmful and odorous components in the gas and minimises the release of methane.

103. The landfill gas pumping system and electricity generation unit are surrounded by 1.8 m high fencing. The height of the stack is 8 m. The gas management system and generation plant will remain at the site beyond the completion of landfilling.

2.4.5 Surface Water Management

104. There is no artificial surface water management system at the site as surface water all drains away naturally.

2.5 Restoration and After-use

105. The restoration of the landfill site will be undertaken in a progressive manner following the phased waste disposal operations. The approved restoration scheme is shown on Figure 7.

106. The objectives of the restoration scheme are to:

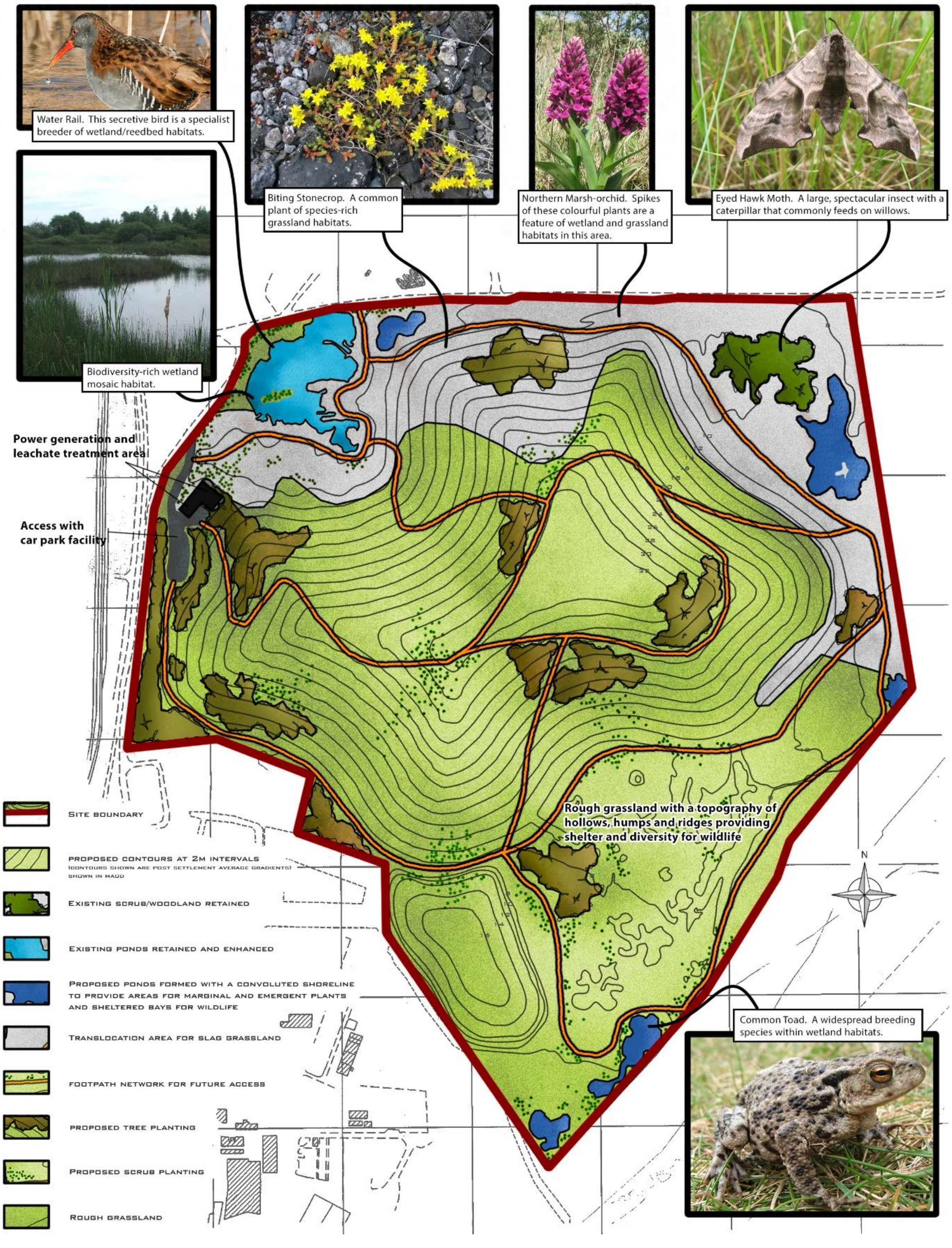
- reclaim 107 hectares of derelict industrial wasteland;
- to provide a range of ecological habitats consistent with the immediate surrounding area;
- to develop the site in such a way that many of the benefits of the restoration strategy are accomplished as early as possible based on the rate of landfilling at the site;
- to provide public access to the area such that it complements the establishment of the nearby Nature Reserve; and,
- to provide lasting and beneficial after use to the local environment and community.

107. Protection of the existing open water body and marginal vegetation in the north west of the site (which is subject to seasonal variations) or the provision of alternative water bodies is established in a Section 106 Agreement associated with the original planning

permission reference TDC/94/065. In addition, the Section 106 Agreement provides a commitment to an aftercare fund with oversight of the restoration from the Restoration Consultative Group and the establishment of public access to the restored site.

108. In accordance with the planning permission, the landfill site will be restored to rough grassland, scrub and woodland, and the surrounding areas will be restored to areas of open water, aquatic marginal vegetation, scrub, wet meadow and ruderal grassland with small hollows, banks and ridges suitable for nature conservation use.

Figure 7 Landform and landscaping of the restored site



2.6 Local Environment

2.6.1 Site Access

110. The current highway access to the Port Clarence site will continue to be used. The access to the landfill sites and WRP is from the north west via a private access road to Huntsman Drive which joins the A178 approximately 0.35 km to the north west of the site access. There are no public rights of way, bridleways or footpaths that cross the site or on immediately adjacent land.

2.6.2 Settlements and Activities

111. The site is remote from residential properties. The nearest residential properties are on Port Clarence Road about 1,140 m to the south-west of the site. The properties are separated from the landfill operations by a large area of open ground, the Clarence distribution works and the A178. Land use in the area surrounding the site comprises industrial facilities, areas of protected habitats and wildlife areas (Augean, 2014). The nearest industrial properties are about 130 m immediately to the north of the capped Phase 3 cell and uncapped Phase 1 and 2 cells.

112. Constraints that impact the site and immediate area are shown in Figure 8. The diagram shows that most of the site lies in Flood Zone 1 where flooding is very unlikely to occur. Partial flooding is most likely to occur from the north and west of the site as a result of tidal flooding in the Tees Estuary. Properties at risk of flooding are located at Port Clarence and the heavily industrialised areas around Tees Mouth. Measures have been taken to improve flood defences (Environment Agency, 2016). Flooding is exacerbated when there are concurrent high fluvial flows, off-shore winds and tidal surge due to low pressure over the North Sea. The wider area context is presented in Figure 9 which also shows the location of flood defences to the north of the site and the area that these benefit (Environment Agency, 2018). The annual probability of inundation of Flood Zone 2 is given as between 1 in 100 (1 in 200 for tidal flooding) and 1 in 1000 for river flooding. No part of the landfill area is in Flood Zone 3.

113. Two fracking licences have been granted in the immediate vicinity of Port Clarence. These are administered by Egdon Resources U.K. Limited and Third Energy UK Gas Limited (Licence references PEDL68 and PEDL259, respectively). We are not aware of any test drilling or site developments being carried out or planned under these licences.

114. The most recent topographical survey shows the ground level at the Port Clarence site is at a height of between 2.4 m to 16.5 m AOD, being lowest in the north west area and with most of the site above 5 m AOD (MJCA, 2024). Analysis of planned cell construction profiles indicates that the base of the engineered liner varies from 5.4 to 8.5 m AOD as shown in an illustrative cross section of a waste cell (Figure 10).

115. Tidal levels recorded at Tees Dock, located approximately 2.5 km north east of the site, is on average 0.37 m and varies between -1.30 to 1.89 m AOD (Good Stuff Ltd, 2024). The tidal range can be larger under extreme events and records since February 2015 indicate a range from -2.29 to 2.90 m AOD (95^{th} percentiles). The lowest and highest recorded values are -3.63 m AOD on the 20/11/2015 and 3.42 m on 10/2/2020. The base of the engineered liner is about 2 m or more above the highest recorded tides.

2.6.3 Flora and Fauna

116. The site lies close to Saltholme Pool and Dorman's Pool and to North Tees mudflat, all constituent parts of the Tees and Hartlepool Foreshore and Wetlands SSSI which itself forms part of the Teesmouth and Cleveland Coast SPA and Ramsar site (ESL, 2014a). The SSSI interests include a range of wintering and passage waterfowl. At Saltholme Pool and Dorman's Pool, breeding waterfowl include shoveler *Anas clypeata*, pochard, little grebe, great crested grebe *Podiceps cristatus* and little ringed plover *Charadrius dubius*. Feeding and roosting birds here include shoveler, teal *Anas crecca*, wigeon *Anas penelope*, gadwall, lapwing and golden plover *Pluvialis apricaria*. Birds feeding and roosting in significant numbers on the North Tees mudflats are shelduck and redshank *Tringa totanus*.

117. The SPA was designated under Article 4.1 of the Birds Directive (79/402/EEC) by supporting populations of European importance of little tern *Sternula albifrons* during the breeding season, and of Sandwich tern *Sterna sandvicensis* on passage. It also qualifies under Article 4.2 of the Directive by supporting populations of European importance of ringed plover on passage and of knot and redshank over the winter. The site further qualifies under Article 4.2 by regularly supporting at least 20,000 waterfowl over winter, including cormorant, shelduck, lapwing, knot Calidris canutus, sanderling Calidris alba and redshank.

118. The SPA also qualifies for listing as a Wetland of International Importance, especially as Waterfowl Habitat, under Criteria 5 and 6 of the Ramsar Convention. It regularly holds a total of more than 20,000 waterfowl over the winter period, and it regularly holds numbers above the qualifying level of redshank on passage, and of knot in winter. No National Nature Reserves, Local Nature Reserves or Local Wildlife Sites are present within 2km of the site (ESL, 2014a).

Figure 8 Site constraints

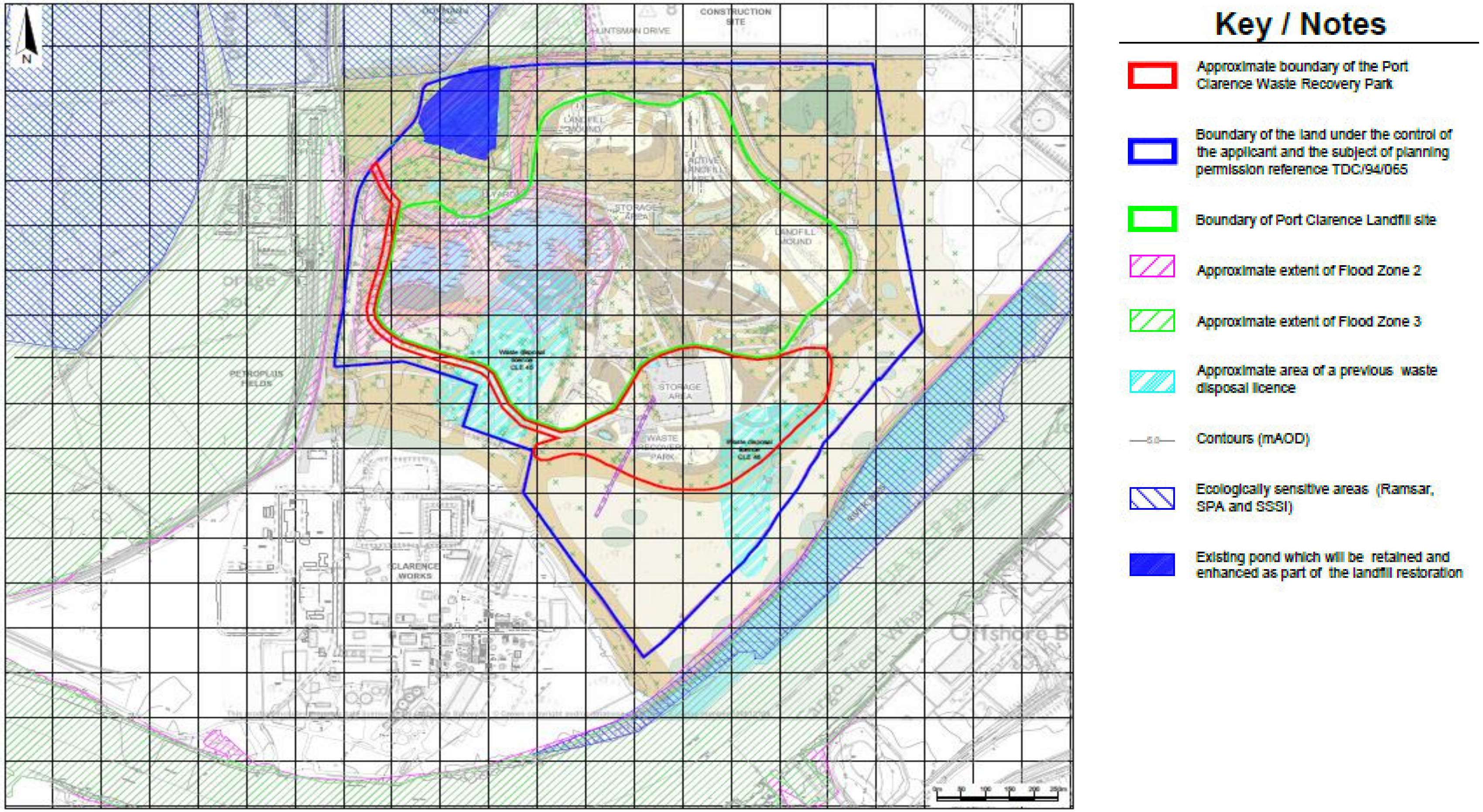


Figure 9 Flood zones

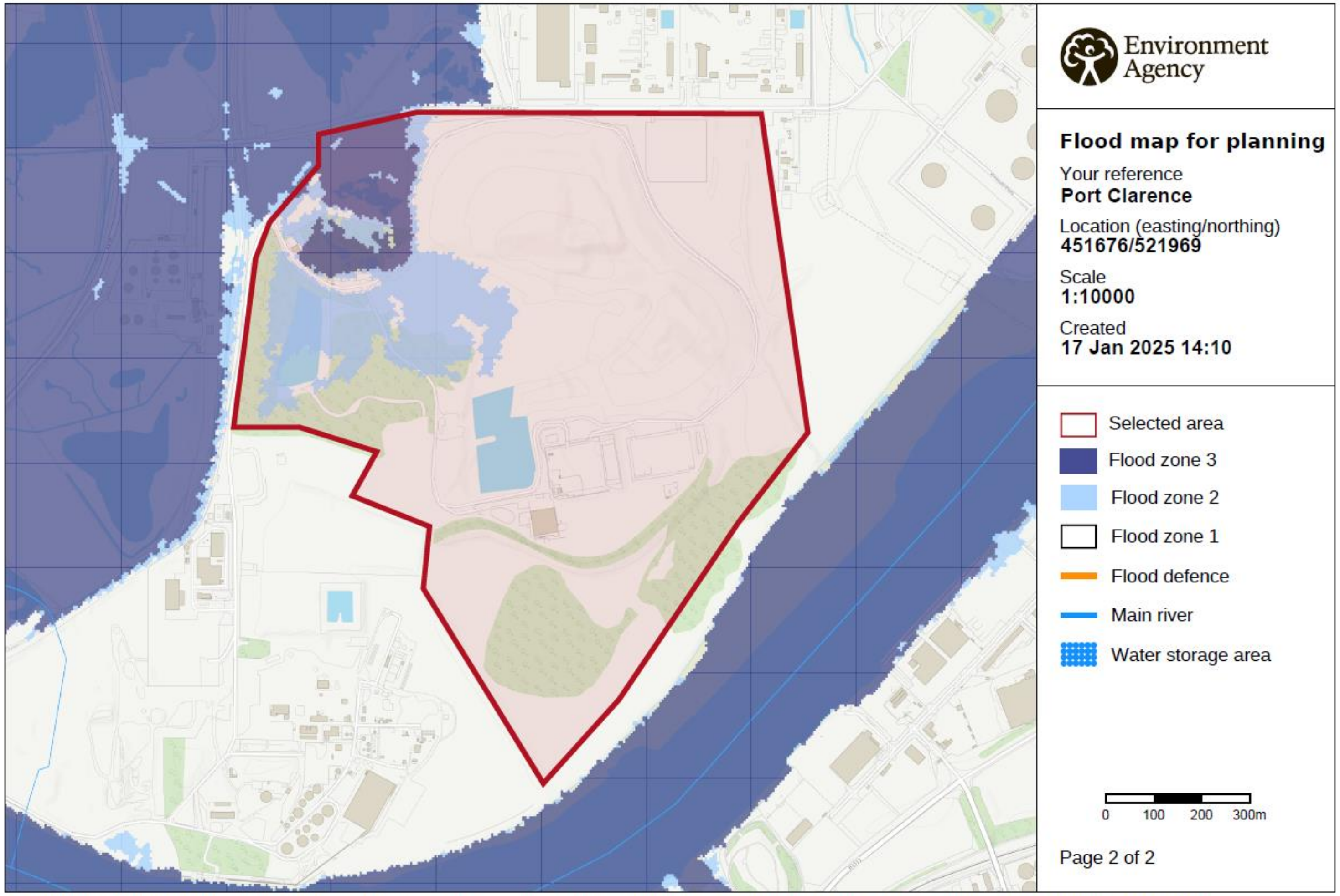


Figure 10 Illustrative cross section of the Port Clarence Landfill Site profile

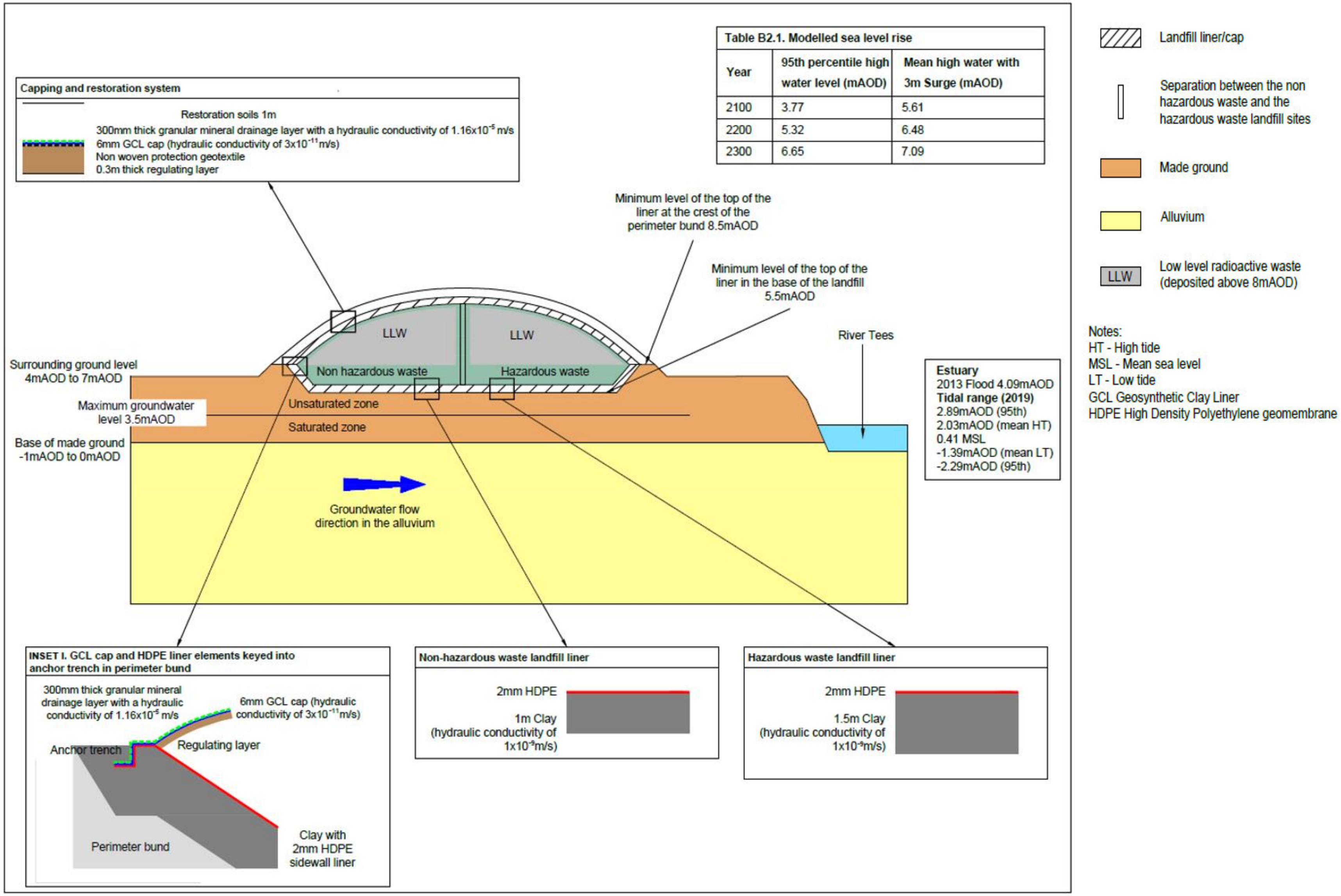


Table B2.1. Modelled sea level rise

Year	95th percentile high water level (mAOD)	Mean high water with 3m Surge (mAOD)
2100	3.77	5.61
2200	5.32	6.48
2300	6.65	7.09

119. An updated baseline ecological survey was reported in 2014 CE, this followed previous surveys in 2006/07 CE and 2010 CE (ESL, 2014a). The study considered the potential effects of the landfill on the habitats and species of international importance and the consultation process concluded:

- there would be no increased disturbance to SPA/Ramsar site birds feeding or roosting on habitats important to them as a result of increased human use of land within the site boundary;
- there would be no loss of land used by SPA/Ramsar site birds for feeding or roosting to the proposed development;
- there would be no indirect loss of land used by SPA/Ramsar site birds due to disturbance from noise, light or movement connected with or resulting from the proposed development; and,
- there would be no reduction in estuarine water quality due to discharges from the site, resulting in a reduced abundance of intertidal invertebrates forming prey species for the SPA/Ramsar site birds.

120. Natural England agreed that there will be no adverse effect on the integrity of the site from any of these causes.

121. The most recent survey found no reptiles, bats, badgers, water voles or otters (ESL, 2014a). Species recorded on the site include:

- mammals noted using the site comprised common shrew, rabbit, brown hare, field vole, wood mouse, fox and roe deer;
- common frogs;
- sixteen butterfly species were observed most common and widespread, four of importance were dingy skipper, wall, grayling and small heath.
- principal nesting bird species were lapwing, curlew, herring gull, skylark, yellow wagtail, dunnock, song thrush, starling, linnet, bullfinch and reed bunting;
- other species that are probable/possible nesters were gadwall, pochard, water rail, oystercatcher, ringed plover, snipe, meadow pipit, wheatear, lesser whitethroat, carrion crow and magpie; and,
- a further seven species were noted using the site or immediately adjacent land during other site visits, including marsh harrier (a Schedule 1 species), shelduck, lesser black-backed gull and cuckoo.

122. A further study considered ornithological impacts in greater detail (ESL, 2014b). There was a particular focus on the potential for increased disturbance to SPA/Ramsar site birds breeding, feeding or roosting on habitats important to them by increased gull populations attracted to the area as a result of the continuing use of the landfill. An earlier study (reported as Percival (2004)) indicated no adverse effect at that time, but since then conservation management has increased in the surrounding area and other landfill sites are now operating in the area. The report concluded that the gull populations would have no significant adverse effect on the integrity of the European site, alone or in combination with other developments in the area.

123. The study also concluded that the number of wetlands birds now using the study area was impressive (breeding, wintering and on passage) and had increased with the

creation and conservation management of wetlands in the area. The proposed habitat restoration scheme for the site including further wetland areas was considered beneficial in maintaining and perhaps increasing the attractiveness of the area to wetland birds.

2.7 Geology and Hydrogeology

124. The Tees Estuary surface geology of Quaternary alluvium and glacial till (formerly known as boulder clay) are underlain in turn by Triassic Mercia Mudstone Group and then Sherwood Sandstone Group. The inclined geology results in Sherwood Sandstone Group surfacing towards the north and the Jurassic Lias Group bedrocks surfacing towards the south (Inst. of Geological Sciences, 1981). The Triassic Mercia Mudstone and Permo-Triassic Sherwood Sandstone underlie the Quaternary deposits at a depth ranging from approximately 10 m to approximately 27.5 m across the site (Augean, 2014).

125. The Tidal Flat Deposits (alluvium) is designated by the Environment Agency as a secondary (undifferentiated) aquifer and the Till (boulder clay) is designated as unproductive strata. The Mercia Mudstone and Sherwood Sandstone are designated by the Environment Agency as a Secondary B Aquifer and a Principal Aquifer respectively. Both the made ground and the Tidal Flat Deposits (alluvium) are water bearing and in hydraulic continuity with each other. Groundwater in both strata flow generally to the south east towards the River Tees.

126. The River Tees is tidal where it passes the site. Although the undeveloped areas of the site are relatively flat, with no known drainage features, there are a number of surface water ponds located in the north west of the site. The water quality in the groundwater in the made ground and the Tidal Flat Deposits (alluvium) is influenced by the water quality in the Tees Estuary.

127. The pathway for the migration of leachate from the site will be through the basal liner of the landfill and vertically through the unsaturated zone of the underlying made ground. For the purpose of the assessment it is assumed that groundwater flow in the saturated zone of the made ground is predominantly vertical and flows to the alluvium. Lateral flow will occur in the alluvium towards the River Tees. It is likely that groundwater flow in the alluvium is affected by tidal influences of the River Tees (Augean, 2006).

2.8 Geomorphology and Coastal and Estuarine processes

128. The Port Clarence site is located on the inner northern bank of the Tees estuary, which drains into the North Sea along the northeast coast of England. The Tees is a shallow, funnel-shaped coastal plain estuary that has been substantially altered in terms of its estuary shape and morphology since the industrial revolution. Information regarding the local hydrodynamic conditions, stratigraphy and topography combined with wider contextual information such as estuary morphological evolution, river characteristics and anthropogenic influences are reported in an assessment of the site by the Prifysgol Bangor (Bangor University, 2023). The report examines the potential erosion rate at the site and makes the following observations:

- In terms of morphology, the Tees is a funnel-shaped coastal plain estuary with a mean depth of 8 m. Estuary sediments consist of glacially reworked quaternary deposits atop Triassic mudstones and Sandstones.

- A flood-dominant macro-tidal regime is observed, the tidal range varies from 4.6 m, 3.4 m and 2.3 m for mean spring, mean and mean neap, respectively. Mean high water spring (MHWS) tide reaches 2.65 m (Ordnance Datum, OD) and the highest astronomical tide recorded is 3.25 m (OD). The mean intertidal volume of the estuary is 0.31 km^3.
- The tidal regime is considered flood dominant causing an ebb/flood imbalance, which results in a net landward transfer of sediment, infilling the estuary with an estimated 700,000 t of marine sediment annually.
- A total area of 1,930 km^2 is defined as the Tees catchment. As a river system, the Tees is still undergoing adjustment following the last glaciation. The Tees is considered a flashy river (water transmission times to the coast generally last less than 24 hours), which can experience rapid variations in discharge. At Low Moor gauging station (the tidal reach prior to the completion of Tees barrage in 1995 CE), discharge exceeds 2 $m^3 s^{-1}$ (dry weather), 20 $m^3 s^{-1}$ (average) and 70 $m^3 s^{-1}$ (heavy rainfall) for 95 %, 50 % and 5 % of the monitoring period respectively. Mean river discharge, therefore represents less than 3 % of the estuary tidal prism. The annual fluvial sediment input into the estuary is estimated at 40,000 t.
- Local erosion at the bank next to the site is driven by wave (orbital velocities), tidal (oscillatory velocities) and river (mainly uni-directional velocities) forces. Sea level is modulated by the astronomical semi-diurnal tide, atmospheric pressure (storm surges), waves and the rate of sea level rise. The instantaneous sea level determines the location and length of time that a given section of bank is exposed to erosional drivers.
- A review of the available published and grey literature suggests, firstly, that the site bank is considered sheltered from significant wave exposure; swell waves do not propagate as far up the estuary as Teesport Container Terminal (which is opposite the site). The wave climate is, therefore, primarily driven by locally generated wind waves with limited fetch. A worst-case estimation of the maximum significant wave height is 0.3 m.
- Flow velocity measurements in the channel at two locations close to the site; on the flood tide, velocity profiles were similar at both locations, a mean velocity of 0.5 $m s^{-1}$ was measured at the left bank. Conversely, on the ebb phase, the velocity was negligible at the left bank, thought to be due to shearing effects from the training wall (compared with high right bank velocities 0.6 $m s^{-1}$). An estimate of maximum freshwater (riverine) flow velocity of 0.06 $m s^{-1}$ is presented. The maximum river flow velocity is an order of magnitude lower than the maximum flow velocity on the flood tide, suggesting that the site is dominated by the oscillatory tidal flows.
- There is an inter-tidal mudflat on the bank, previously connected to expansive Seal Sands, which is constrained by training materials at the edge of the River Tees channel and the elevated area of made ground. The inter-tidal width of the mudflat width ranges from 90 m to 130 m and there is an arc in the low water mark opposite the dry docks to accommodate ship turning, a feature that was present in maps from 1913 CE. Current aerial photographs show damage to the arc of training materials; this appears to be an area where the mudflat drains.
- Mudflats play a key role in wave energy dissipation; wave energy is a primary driver of bank erosion. Mudflat level changes in two distinct modes: periodic over various cyclic scales (e.g., tidal, seasonal, interannual and climatic fluctuations) and episodic (e.g., storm events). Cyclic fluctuations in mudflat bed levels are

common and often range between 5 mm (summer) and -35 mm (winter). Seasonal variability in wave activity, tidal cycle and river discharge cause a response in mudflat level.

2.9 Site Security

129. Site security is subject to control through the extant permits and ensures public safety, preventing interference with site operations and avoiding potential exposure to hazardous materials (for example asbestos). The landfill operations at Port Clarence are screened from the surrounding area by a perimeter bund.

130. Access to the site is restricted to authorised personnel. Lockable gates are provided at the site entrance and at the access to Phases 1 and 2. Additional lockable gates are located approximately mid-way along the northern boundary. Fencing is installed along Huntsman Drive and from Huntsman Drive to the estuary to discourage public access. In addition the estuary itself and northern pond areas that render public access difficult.

131. Specific areas of the site with security fencing are the site offices, weighbridge, machinery park area and the Waste Recovery Park. The fencing is 1.8 m high and consists of wooden posts and mesh with barbed wire in place on top of the mesh.

132. The main entrance gates can be secured and these are locked between 6:30 pm and 5:00 am. On a weekend the gates are locked once the site is closed around 2 pm. On-site security personnel are present from 5:00 pm until 7:00 am (14 hours) Monday to Friday and 24 hrs/day on a weekend. Security personnel regularly travel over the site and are equipped with short wave radios.

133. Security cameras and motion detectors are placed strategically around the site to detect any trespasser activity, these are monitored both by on-site staff and remotely by a specialist alarm receiving centre who inform site staff of any activity.

134. Additional security measures for LLW will include:

- receipt of LLW will be within a secure area before it is taken to the disposal point;
- any quarantine of LLW would take place within the secure area;
- the LLW is accompanied by driver or site personnel from access to the site to covering;
- the LLW is placed and covered immediately;
- after the LLW has been deposited and covered (0.4 m cover), gamma radiation will be measured at the landfill surface to confirm that it is less than 2 µSv h^{-1}, and if not, further cover will be applied until the radiation levels are acceptable; and,
- mobile CCTV cameras and motion detectors will be stationed at the active disposal cells and any movement during in those areas will be investigated by security personnel.

2.10 Factors influencing the natural evolution of the site

135. A fundamental component of an ESC is to demonstrate an understanding of the future evolution of the site, its environmental setting, and related uncertainties. This section considers the processes that are important to the evolution of the Port Clarence site.

Two pieces of work have been commissioned recently with staff at Bangor University to review and advise on the approach taken in the ESC (Bangor University, 2023; Robins & Lewis, 2020). These reports provide an insight into the factors that have impacted the site in the past and provide the basis for the erosion rate of landfill material assumed in the radiological assessments.

136. The NS-GRA (UK Environment Agencies, 2009) requires that disposals should occur in such a way that unreasonable reliance on human action to protect the public and the environment against radiological and any non-radiological hazards is avoided both at the time of disposal and in the future. At this site, human actions have affected site development for the last 200 years and are very likely to continue to do so into the future.

137. In the recent past, the area has been subject to land reclamation and impacted by large industrial developments. These changes have been rapid relative to radiological assessment timescales used in the ESC. In the medium term, although commercial land requirements and use of the estuary by shipping are likely to be balanced against the maintenance of local wildlife habitats, there is no guarantee this will continue indefinitely.

138. The key interacting factors that will impact evolution of the site include:

- maintaining the Tees Barrage after the planned 100 year design life;
- halting or changing dredging activities in the Tees Estuary;
- maintenance, managed realignment, enhancement or abandoning coastal and flood defence schemes;
- the rate and magnitude of sea-level rise resulting from climate change; and,
- the local shoreline sediment balance - impact of off-shore sandbanks, the potential for locations along the coast to supply sediment to the estuary and deposition of fluvial sediments.

139. The position of the site means that it is unlikely to be affected by erosion from the slow moving River Tees, which even when in spate would tend to impact the southern bank away from the landfills. Dredging activities are also highly unlikely to stop given the industrial activities of the area and the importance of the port.

140. In a reclaimed environment such as the Tees Estuary there will be a succession of management plans for the shoreline and the emphasis in these plans may change over time.

141. The current shoreline management plan for area MA13 (Guthrie & Lane, 2007) is to hold the line at North Gare and South Gare, and at Seaton Carew but consider planned realignment. The plans allow natural development of the North Gare Sands, Bran Sands and sands to the north (Seaton) and the south (Coatham) of the breakwaters. The policies remain the same for each unit until 2105 except for North Gare Sands where retreat or realignment is planned from 2055.

142. A flood prevention scheme has recently been completed in the estuary with additional defenses for Port Clarence (completed in 2015 CE) and a managed realignment of embankments at Greatham Creek (completed 2018 CE) to create new habitats (Environment Agency, 2011).

143. A supporting assessment of estuarine erosion rates for the Tees Estuary was commissioned by Augean (Bangor University, 2023). The report by The University of Bangor used four methods to estimate potential future erosion rates:

- consideration of a literature review of measured lateral and vertical erosion rates for coastal/estuarine systems was reviewed to assign the best-fitting case to the site;
- a qualitative risk index was used to estimate the potential for the release of landfill waste in comparison with other UK landfill sites;
- the site was considered as a riverbank, where a linear regression model was used to estimate the erosion rate based on driver metrics; and,
- a global database of measured riverbank erosion rates was used to assign the best-fitting case to the site.

144. The results of this study are used for the radiological assessment of coastal erosion summarised in Section 6.2 and presented in greater detail in Appendix E.4.7 and E.4.8.

2.10.1 Sea level rise

145. Coastal mudflats and saltmarshes are sedimentary intertidal habitats created by deposition in low energy coastal environments (particularly estuaries) and the natural features of an estuary are expected to move inland with sea level rise (Tees Valley Climate Change Resilience Group, 2012). This realignment of the estuary could lead to reversion of reclaimed land to mud flats and saltmarsh in the long term. The tendency of the area to accumulate sediments suggests that erosion of the site under normal conditions is not credible. In these circumstances the landfills would become surrounded by deposited sands and muds and over time become subject to tidal inundation.

146. The present-day global sea level was reached about 6,000 years ago and until about 150 years ago had varied only by about 15-20 cm (Lambeck, et al., 2014). Climate change model projections show that sea level will rise due to the increase in global air temperature, causing thermal expansion of the oceans and melting of glaciers and ice sheets (Stocker, et al., 2013). The glacial isostatic adjustment at Port Clarence (Lowe & et al., 2009) is slightly negative (-0.05 mm y^{-1}).

147. The Modaria II programme (Lindborg, 2018) has considered the long-term impact of climate change on sea-level rise and has summarised the studies available from the 2013 report of the Intergovernmental Panel on Climate Change [IPCC, (Stocker, et al., 2013)]. An IPCC synthesis report produced in 2023 completed the most recent Sixth Assessment Report. This report indicated that relative to 1995–2014, the likely global mean sea level rise under a low emissions scenario (SSP1-1.9 GHG; warming limited to 1.5°C) is 0.15–0.23 m by 2050 and 0.28–0.55 m by 2100 (medium confidence). With a high emissions scenario (SSP5-8.5 GHG; ; warming greater than 4°C) the rise is 0.20–0.29 m by 2050 and 0.63–1.01 m by 2100 (medium confidence). Over the next 2000 years, global mean sea level will rise by about 2–3 m if warming is limited to 1.5°C, 2–6 m if limited to 2°C and in excess of 15m at temperatures above 4°C (low confidence).

148. Revised climate change marine projections were published for the UK in November 2018 (UKCP18) based on the Fifth IPCC Assessment Report and indicate a sea level rise in 2100 CE of between 0.3 and 0.94 for the Edinburgh area under the cautious

RCP8.5 (equivalent to SSP5-8.5 GHG) climate change scenario (Palmer, et al., 2018). An illustrative range of 0.7 to 3.6 m was given for the year 2300 CE to be used to assess vulnerabilities. These ranges encompass the 5th to 95th percentile projections. Planning also requires consideration of the H++ sea level rise allowance for the sea level rise prior to 2100 CE for flood risk assessments (an additional 1.9 m).

149. It is unclear based on the confidence of these projections when mean sea level will rise to a level that will impact the base of waste cells (see Figure 10) located at 5.4 m AOD and above, or overtop the bund (at 7.4 m AOD and above).

2.10.2 Tidal flooding

150. The area of the site that is below the potential 2100 CE sea level (0.2 to 1.01 m AOD) is in the north western corner in the vicinity of the site offices and weighbridge. The areas of land that are below the potential 2100 CE sea level roughly correspond with Flood Zone 2 indicated in Figure 8. The diagram shows that inundation is most likely to occur from the north of the site. If the main channel to the south is not dredged, then a shallower channel may increase the likelihood of flooding but erosion of the site by the River Tees is not expected to occur (Bangor University, 2023).

151. Guidance on flood risk assessments and climate change allowances is published by the Environment Agency and an online mapping tool showing Flood Zones is available (Environment Agency, 2024). Flooding from the direction of Greatham Creek to the north and Flood Zone 2 includes land to the north and west of the site (Figure 10). A flooding event will be of relatively short duration and is unlikely to overtop a waste cell liner located at 7.4 to 10.5 m AOD in that area. LLW emplacement occurs at least 2 m above the base of each waste cell.

152. Projections of future sea level change suggest that extreme surge levels exhibit greater potential to encroach landward towards the landfill via overtopping than lateral bank retreat in the next 110 years at the site (Bangor University, 2023). Despite this, both coastal/estuarine inundation and bank erosion pose an insignificant risk to the landfill – due to (*i*) the width of the mudflat and embankment being relatively large, and (*ii*) the sediment composition (volume and bulk density) of the embankment being relatively resilient to erosion. It is therefore considered very unlikely that flood water will enter uncapped waste cells during the operational period of the site (Bangor University, 2023).

153. The highest recorded flood level in recent years was in 2013 CE affecting Port Clarence properties when low pressure and strong off-shore winds produced a storm surge with a tidal height of 4.09 m causing a breach of tidal flood defences (Stockton on Tees Borough Council, 2013). Flood defences have since been improved in two phases and were completed in 2018 CE providing protection to 4.4 m AOD.

154. We note that when flooding of waste cells first becomes possible, it will be an unlikely event (reliant on an extreme tide coinciding with a storm surge) and will therefore occur at very low frequency (60 years and previously 30 years between the most recent comparable events), however as sea level rises after this date the storm surge height required to overtop the bund will reduce until a smaller surge above a less extreme high tide will rise above the top of the bund more frequently.

155. In order for a significant volume of flood water to then enter the landfill, the cap or the seal between cap and basal liner will also need to have degraded. We conclude that

by the time there is the potential for flood water to enter the landfill, there will also be regular tidal inundation of the surrounding land that lies at 2 to 3 m AOD. Such land will be unsuitable for agricultural use or regular access for recreational purposes and the main pathway to receptors is considered to occur through the transfer of draining leachate to the marine environment. The scenario that considers erosion of waste and leachate to the estuary (at 60 years) will have a greater impact than transfer through flood water to the estuary in the event of regular flooding.

156. Local flooding or sea level rise may see saturation of soil/made ground rise to a level that is above the base of the landfill at some locations at some future time. However, there is an engineered clay barrier beneath each cell and a liner that will minimise water entering waste cells. There are also coarse materials on the base of the liner to assist with leachate collection, above which is a further 2 m of waste from which LLW will be excluded. When the HDPE liner degrades (and although still protected by the clay layer) there is the potential for saturation of the base of the landfill from floodwater for short periods and subsequent drainage to surrounding land.

157. A further component to consider is the impact of climate change on storm surge. However, at the present time, there is low confidence and no consensus on the future storm surge and wave climate, stemming from diverse projections of future storm track behaviour (ONR, 2018) and this is reinforced in UKCP18 which presents a range from a best estimate of zero additional contribution with both positive and negative impacts on sea level rise (Palmer, et al., 2018).

158. Government advice (UK Goverment, 2016) for flood planning purposes is to consider changes to relative mean sea level using the H++ scenario of 1.9 m for the total sea level rise to 2100 CE with an additional 2 mm for each year on top of sea level rise allowances from 2017 CE for storm surge.

159. A flood scenario is included in the post-closure assessments and it is assumed to occur at the end of the period of authorisation.

2.10.3 Tidal erosion

160. The Tees is a coastal plain type estuary that is shallow and tidal current dominated. Therefore, the accretion, erosion and distribution of sediment within the estuary is largely determined by tidal currents. Tidal asymmetry is generated within the estuary by the modification of the tidal currents through friction that changes with a deepening of sea levels – potentially changing the system from historically being a net importer to a net exporter of sediment. Using a modelling approach, (Robins & Davies, 2010) demonstrated for idealised estuaries of a similar type and scale to the Tees, that channel deepening through sea level rise will generally reduce velocities and sediment transport, and promote ebb-dominant tidal asymmetry (i.e. net sediment export). Hence, to address this problem appropriately requires the use of a validated depth-averaged hydrodynamic model that can simulate the tidal dynamics within the Tees Estuary, with sea level rise included, to simulate the tidal asymmetry [e.g. (Palmer, et al., 2019); (Devlin, et al., 2017)].

161. A key factor affecting coastal erosion is the strength of the waves breaking along the coastline. A wave's strength is controlled by its fetch and wind speed with longer fetches and stronger winds producing more powerful waves with greater erosive power. As waves travel into an estuary, they lose energy due to friction with the seabed, and estuaries are generally considered to be low energy environments. The

rate of coastal erosion varies with location and is affected by many factors (BGS, 2012) including topography, local currents and tidal range, wave climate and sediment supply.

162. Sediment core descriptions were considered in the erosion rate review (Bangor University, 2023) Strata descriptions of sediment type were used to provide a better understanding the evolution of erosion rate over time. The top stratum, described as fill, coarsens and increases in grain size moving from the estuary bank towards the landfill before becoming finer close to the landfill. The erosion rate would be expected to decrease towards the site, with the slowest rates where cobble size sediment occur (i.e., 64-256 mm, assumed to be reclamation material). Hydrodynamic conditions at the site suggest that the critical flow velocity would be of insufficient magnitude to erode and transport the larger sediments described within the upper stratum. Boreholes also show a natural estuarine deposit, developed in an inter-tidal or sub-tidal sandflat environment. The Bangor report suggests that, from the four boreholes examined, that under-cutting, destabilisation and then bank collapse is presently the most likely mechanism for erosion of made ground between the estuary and the landfill. The report also comments on the erosion of the landfill construction materials and wastes, concluding that current day hydrodynamic conditions are unlikely to erode or undermine cell structure.

163. In the future, sea-level rise could expose the north eastern side of the landfills to direct tidal action and the other sides to waters within a modified estuary. There is also likely to be a delay before exposure of the proposed LLW disposals due to existing completed cells (minimum of 200 m width) on the seaward side that do not contain LLW.

164. The onset of tidal erosion and the impact of sea level rise on the restored landfill is uncertain. The start of erosion depends on cell location, the increase in global temperature, the rate of sea level rise and the future management of the estuary, barrage and coastal defences. A review by Bangor University (Robins & Lewis, 2020) suggested two modeling approaches that could be used to investigate the potential future sediment behaviour as a result of sea level rise: these were the depth averaged hydrodynamic model and a validated sediment transport model using estuary characteristics and future projections of sea level rise. The models could provide improved understanding for the period until 2100 CE taking account of factors other than sea level rise. However, the period of authorisation is likely to end after 2100 CE when these models become less reliant.

165. On the basis that the timing of erosion is very uncertain and an assessment of different scenarios for estuary evolution would provide a range of dates when sea-level rise might result in erosion exposing LLW at the site (but would not provide a definitive and defensible single answer), the approach adopted here is to use a very cautious earliest time at which erosion could occur. For this reason a radiological assessment is undertaken at the end of the period of authorisation, 60 years after site closure.

166. The rate at which erosion could potentially occur has been reviewed by Bangor University using a number of approaches (Bangor University, 2023). The result of this review can be summarised as follows:

- vertical erosion of Port Clarence mudflat at 5.7 mm y^{-1} based on LIDAR observations, noting that areas that would not be expected to show changing elevation have greater variance over the same period (e.g. increased elevation of the training walls along the estuary over the same timescale giving reduced confidence that erosion is significant);

- vertical erosion rate of 0.01 m y^{-1} from a literature review of similar coastal/estuarine sites (95th percentile of 0.02 m y^{-1});
- a regression model for the River Tees estimates a lateral erosion rate of 0.21 m y^{-1} – adopted as the default erosion rate in the ESC;
- a global river bank database provides a mean lateral erosion rate of 0.51 m y^{-1} for similar sites and a maximum lateral erosion rate of 0.8 m y^{-1} for similar sites – adopted for a what-if scenario.

3 Waste Characteristics

3.1 Introduction

167. Hazardous waste and non-hazardous waste that will be disposed at the site will be consistent with the Environmental Permits for the site. The hazardous waste types principally comprise treatment residues, contaminated materials including soils, and materials containing asbestos. Wastes that cannot be accepted for disposal include liquid wastes, corrosive wastes, flammable wastes and wastes that are classified as oxidising. The non-radioactive hazardous wastes that are permitted for disposal are subject to a limit on their total organic carbon content and on the solubility of specified contaminants (subject to leaching tests). A list of non-hazardous waste permitted for disposal in the non-hazardous landfill is provided in Schedule 2 of the site permit. Analysis of the waste codes from waste received indicates a broad range of non-hazardous waste.

168. Low level radioactive waste (LLW) is a category of waste that contains small amounts of radioactivity (up to 4000 Bq g^{-1} alpha activity and 12,000 Bq g^{-1} beta/gamma activity). LLW typically comprises construction and demolition waste such as rubble, soils, crushed concrete, bricks and metals from the decommissioning of nuclear power plant buildings and infrastructure, lightly contaminated miscellaneous wastes from maintenance and monitoring at these facilities such as plastic, paper and metal, residues from plant at which LLW is incinerated and wastes from manufacturing activities, science and research facilities and hospitals where radioactive materials are used.

169. Naturally occurring radioactive material (NORM) waste is also disposed of at the site under an EPR exemption allowing disposal of waste containing less than 10 Bq g^{-1}. NORM waste contains radioactive substances that arise naturally in the environment and includes radionuclides of natural terrestrial and cosmic origin. NORM wastes generally fall into the LLW or very low level radioactive waste (VLLW) categories and are most commonly generated through processes that concentrate solid, liquid and gaseous NORM as a by-product (e.g. activities such as mining, the processing of minerals and earth materials, oil and gas operations, etc.). The physical, chemical and radiological characteristics of NORM wastes can vary markedly depending on the industrial process.

170. Activity concentration limits for LLW disposal at Port Clarence have been calculated for each radionuclide listed in the permit application.

3.2 Radioactive Waste Inventory

171. The LLW that is expected to be available for disposal may arise from:

- **Non-nuclear industry sources** for example, waste derived from hospitals, universities, the oil industry or other non-nuclear users of radioactive materials.

- **Nuclear industry sources** for example, wastes derived from decommissioning of nuclear power stations and research centers.

172. The LLW that is expected to be disposed under the Port Clarence Permit will arise from within the UK with waste arising largely from the decommissioning and clean-up

of nuclear industry sites, from production of titanium dioxide and from the oil and gas industry.

173. The waste will conform to the CfA which will include waste acceptance criteria (WAC) established by any new permit and, where required, the consigning organisation will have an appropriate transfer permit. The radionuclides included in the radiological assessments are listed in Table 6, along with their half-lives and daughters assumed to be in secular equilibrium. The permit will include an "Any other radionuclide" group to allow some flexibility for disposal of radionuclides that have not been listed explicitly.

174. When radionuclides decay they produce a daughter product that may be a stable atom, for example Po-210 has a half-life of 138 days and produces a stable daughter, Pb-206. In some cases the daughter product may also be radioactive and this can result in a sequence of radioactive daughters that is known as a decay chain. The uranium (U-238) and thorium (Th-232) series are the two most important decay chains. The longer lived radionuclides of these series are identified in Table 6. The short-lived daughters are not treated explicitly in calculations of radiological impact although their hazard is assessed by including their doses in the calculation of doses from a longer lived parent. The decay chains of interest are represented in Figures 11 to 14 below.

175. In Table 6 and taking U-238 as an example, three daughters are listed (Th-234, Pa-234m, Pa-234) that do not appear in column 1 and any dose conversion factors used for U-238 are the sum of values for each of these radionuclides. The longest half-life of these three daughters is 24.1 days (Th-234). The last column indicates that there is a further daughter U-234, it has a long half-life of 245,500 years, but this is included in column 1 and will have its own dose conversion factors. The daughter of U-234 is Th-230 and because this also has a long half-life (75,380 years) it is considered explicitly in column 1. Dose conversion factors are taken from (ICRP, 1996), (European Commission, 1995), (European Commission, 1993) and (US EPA, 2018). Half-lives are taken from the LLWR radiological handbook (LLWR Ltd, 2011b) or from the IAEA reference database where radionuclides are not included in the LLWR assessment.

Table 6 Radionuclides included in the radiological assessments

Radionuclide	Half-life (y)	Daughters assumed to be in secular equilibrium	Radioactive daughters considered explicitly
H-3	12.32		
C-14	5.70 10^3		
Cl-36	3.01 10^5		
Ca-41	1.02 10^5		
Mn-54	0.855		
Fe-55	2.74		
Co-60	5.27		
Ni-59	1.01 10^5		
Ni-63	100.1		
Zn-65	0.668		
Se-79	2.95 10^5		
Sr-90	28.79	Y-90	
Mo-93	4.0 10^3		
Zr-93	1.53 10^6		
Nb-93m	16.13		
Nb-94	2.03 10^4		
Tc-99	2.11 10^5		
Ru-106	1.02	Rh-106	

Radionuclide	Half-life (y)	Daughters assumed to be in secular equilibrium	Radioactive daughters considered explicitly
Ag-108m	418		
Ag-110m	0.684		
Cd-109	1.26		
Sb-125	2.76	Te-125m	
Sn-119m	0.802		
Sn-123	0.354		
Sn-126	$2.30\ 10^{5}$	Sb-126m, Sb-126	
Te-127m	0.290		
I-129	$1.57\ 10^{7}$		
Ba-133	10.52		
Cs-134	2.065		
Cs-135	$2.30\ 10^{6}$		
Cs-137	30.17	Ba-137m	
Ce-144	0.780		
Pm-147	2.62		
Sm-147	$1.06\ 10^{11}$		
Sm-151	90.0		
Eu-152	13.54		
Eu-154	8.59		
Eu-155	4.76		
Gd-153	0.658		
Pb-210*	22.2	Bi-210, Po-210	
Po-210*	0.379		
Ra-226*	$1.60\ 10^{3}$	Rn-222, Po-218, At-218, Pb-214, Bi-214, Po-214, Tl-210, Pb-210, Bi-210, Po-210	
Ra-228*	5.75	Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Po-212, Tl-208	
Ac-227	21.77	Th-227, Fr-223, Ra-223, Rn-219, Po-215, Pb-211, Bi-211, Tl-207	
Th-228	1.91	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Po-212, Tl-208	
Th-229	$7.34\ 10^{3}$	Ra-225, Ac-225, Fr-221, Ra-221, Rn-217, At-217, Bi-213, Po-213, Tl-209, Pb-209	
Th-230	$7.54\ 10^{4}$		Ra-226
Th-232*	$1.41\ 10^{10}$	Ra-228, Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Po-212, Tl-208	
Pa-231	$3.28\ 10^{4}$		Ac-227
U-232	68.9	Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Po-212, Tl-208	
U-233	$1.59\ 10^{5}$		Th-229
U-234	$2.46\ 10^{5}$		Th-230
U-235	$7.04\ 10^{8}$	Th-231	Pa-231
U-236	$2.34\ 10^{7}$		Th-232
U-238	$4.47\ 10^{9}$	Th-234, Pa-234m, Pa-234	U-234
Np-237	$2.14\ 10^{6}$	Pa-233	U-233
Pu-238	87.7		U-234
Pu-239	$2.41\ 10^{4}$	U-235m	U-235
Pu-240	$6.56\ 10^{3}$		U-236
Pu-241	14.35		Am-241
Pu-242	$3.75\ 10^{5}$		U-238

Radionuclide	Half-life (y)	Daughters assumed to be in secular equilibrium	Radioactive daughters considered explicitly
Pu-244	8.0 10^7	U-240, Np-240m	Pu-240
Am-241	432.2		Np-237
Am-242m*	141	Am-242, Np-238, Cm-242, Pu-242	Pu-238
Am-243	7.37 10^3	Np-239	Pu-239
Cm-242	0.446		Pu-238
Cm-243*	29.1	Am-243	Pu-239
Cm-244	18.1		Pu-240
Cm-245	8.50 10^3		Pu-241
Cm-246	4.76 10^3		Pu-242
Cm-248	3.48 10^5		Pu-244
* See paragraph 177			

176. Radionuclides with half-lives of less than three months or with half-lives significantly less than the parent radionuclide have not been explicitly assessed. Where such radionuclides arise from ingrowth, they are included through the assumption that they will be in secular equilibrium with the parent radionuclide, and the dose coefficients used are adjusted accordingly. The decay chains of coupled radionuclides are illustrated in Figure 11 through to Figure 14.

177. Short-lived daughters that are assumed to be in secular equilibrium with a longer-lived parent radionuclide have been omitted from the figures. Note that Figure 11 lists Ra-228 and Th-228 as being considered explicitly, this applies only to the Goldsim groundwater migration and radiological assessment models. In all other models Ra-228 and Th-228 are considered in secular equilibrium with the longer-lived parents. Also note that Figure 12 lists Pb-210 and Po-210 as being considered explicitly, this applies only to the Goldsim groundwater migration and radiological assessment models. In all other models Pb-210 and Po-210 are considered in secular equilibrium with the long-lived parent (Ra-226). Figure 12 also lists Cm-242 and Pu-242 as being considered explicitly, this applies only to the Goldsim groundwater migration and radiological assessment models. In all other models Cm-242 and Pu-242 are considered in secular equilibrium with the long-lived parent (Am-242m). Figure 14 lists Am-243 as being considered explicitly, this applies only to the Goldsim groundwater migration and radiological assessment models. In all other models Am-243 is considered in secular equilibrium with the long-lived parent (Cm-243).

178. Secular equilibrium describes the state that is achieved when each radionuclide in a chain decays at the same rate that it is produced. For example, as pure U-238 begins to decay to Th-234, the amount of thorium and its activity increase. Eventually the rate of thorium decay equals its production and its concentration then remains constant. As Th-234 decays to Pa-234m, the concentration of Pa-234m and its activity rise until its production and decay rates are equal. When the production and decay rates of each radionuclide in the decay chain are equal, the chain has reached secular equilibrium. Secular equilibrium between a long-lived parent and a shorter-lived daughter radionuclide is achieved after approximately five half-lives of the daughter radionuclide. Hence Ra-226 and Pb-210 would approach secular equilibrium after approximately 60 years.

Figure 11 Decay system for Cm-248 and Cm-244

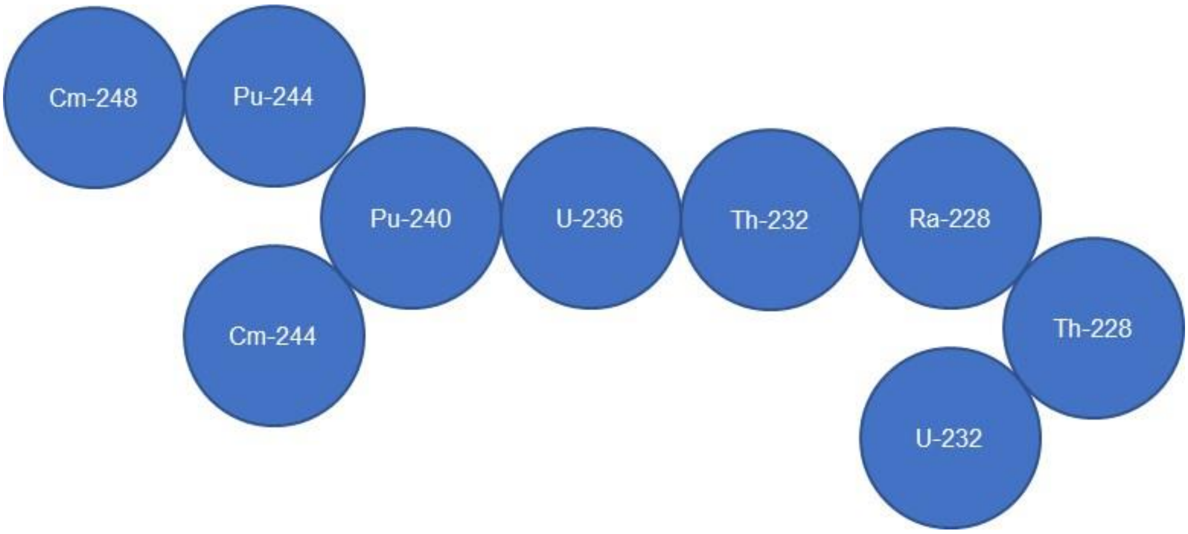


Figure 12 Decay system for Cm-246 and Am-242m

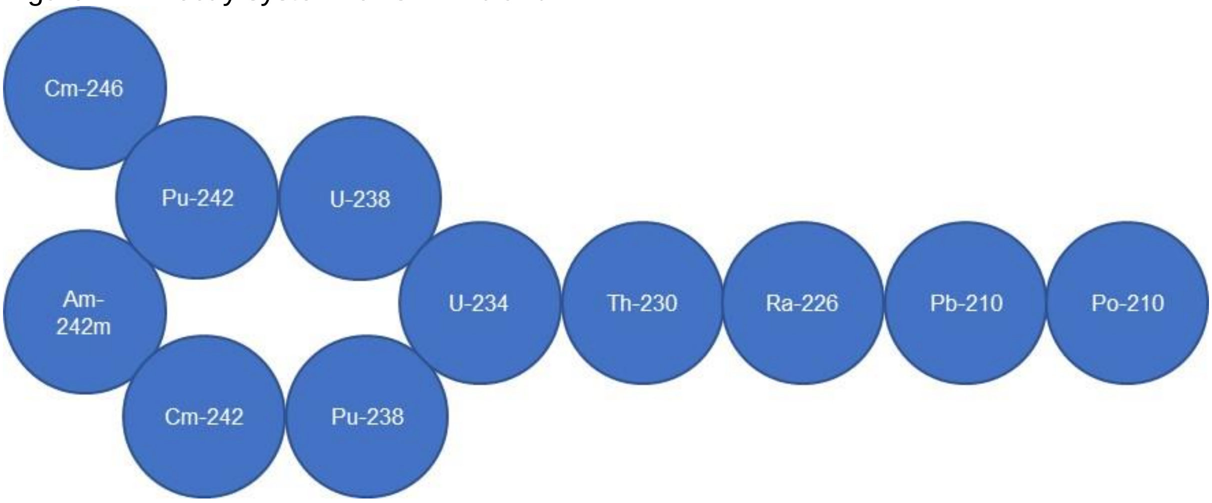


Figure 13 Decay system for Cm-245

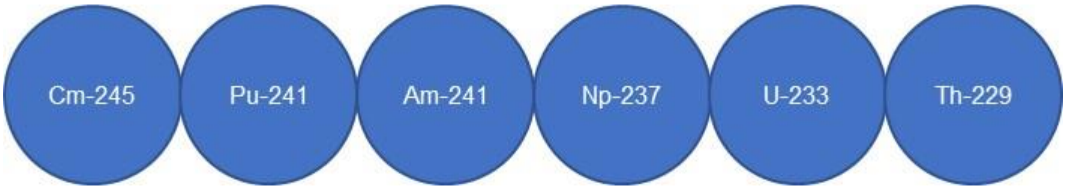
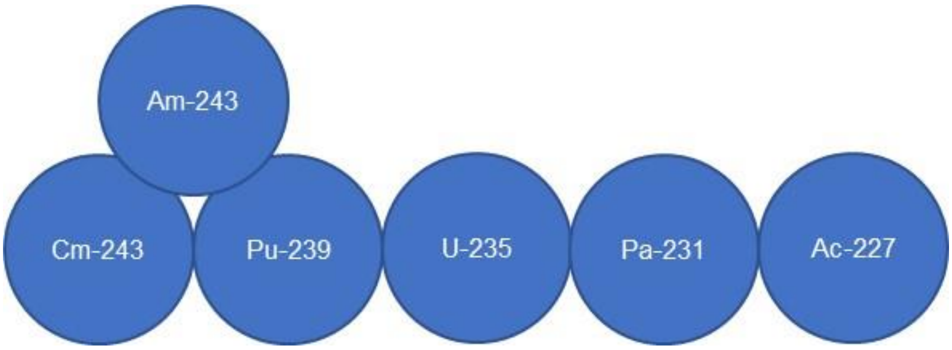


Figure 14 Decay system for Cm-243



179. In all of the assessment calculations, the quantities of long-lived daughters that have ingrown from specific parents or were directly disposed are distinguished. For example, the groundwater models consider seven categories of U-234, all with identical decay and sorption properties:

- U-234 directly disposed;
- U-234 ingrown from Pu-238;
- U-234 ingrown from U-238;
- U-234 ingrown from Pu-242.
- U-234 ingrown from Pu-242;
- U-234 ingrown from Cm-242;
- U-234 ingrown from Am-242m; and,
- U-234 ingrown from Cm-246.

180. The future disposal inventory is not known in detail because waste streams for disposal will only be identified as a result of commercial agreements subsequent to receipt of the revised permit. In view of this uncertainty estimates of radiological impact are given based on 'illustrative inventories' for waste streams that might be typical of those contributing to the total impact from disposals at the facility. These estimates are presented in Appendix D. In developing the safety case two illustrative inventories have been used, these are for wastes disposed to the ENRMF and an illustrative NORM inventory based on the composition of a local industrial waste stream that has already been disposed at the Port Clarence site.

181. These calculations do not show the total impact of the whole facility, this will be dependent on the waste that is accepted for disposal. However, the calculations illustrate the dose that would arise from waste streams typical of those that might be disposed to the Port Clarence site.

182. As stated above it is not possible, until prior to near the time of receipt of the wastes, to describe the specific form, amounts or types of wastes.

183. Radioactive waste is produced from operational and decommissioning and clean-up activities in the nuclear and non-nuclear sectors. Much of this waste is generated by the nuclear sites which are the responsibility of the NDA and EDF Energy. It includes

materials such as paper; plastics; scrap metal; reactor components; contaminated metals; organic materials; concrete; graphite and waste containing naturally occurring radioactive material (NORM). The most common wastes from the nuclear industry are rubble, soils, crushed concrete, bricks and metals that arise from demolition of buildings that were previously used for nuclear research or power generation. A large programme of work to decommission the nuclear legacy sites created since the 1940s is currently underway in the UK that will generate significant volumes of LLW. The UK Nuclear Industry LLW strategy (NDA, 2021) and supporting inventories (NDA, 2023) provide detailed information on the potential types and nature of the wastes. During decommissioning, the hazards with the highest radioactivity are removed prior to demolition of structures. What remains after decommissioning is a mixture of construction materials/soils that can either be proven clean or which sometimes contain trace levels of radioactivity. Efforts are made to separate out radioactivity, to sort wastes, to recycle materials and to reuse materials. The wastes that remain with trace levels of radioactivity after these processes, and where it is BAT to dispose of to landfill, are typical of the wastes accepted at the ENRMF. It is expected that similar wastes would be sent to Port Clarence.

184. NORM waste contains radioactive substances that arise naturally in the environment and contain radionuclides of natural terrestrial and cosmic origin. NORM wastes are most commonly generated through processes that concentrate solid, liquid and gaseous NORM as a by-product (e.g. activities such as mining, the processing of minerals and earth materials, oil and gas operations, etc. see Table 7). The physical, chemical and radiological characteristics of NORM wastes can vary markedly depending on the industrial process. NORM wastes generally fall into the LLW or very low level radioactive waste (VLLW) categories. The UK strategy for the management of NORM (DECC, 2014) included data on the types of waste, tonnage and activity concentrations produced. Those requiring specialist disposal are listed in Table 7.

Table 7 Types of solid NORM waste produced in the UK requiring specialist disposal

Industry	Waste type	Approximate quantity in tonnes per year	Approximate total activity per year
Oil and gas – offshore	Scales and sludge. May be hazardous waste due to heavy metal and hydrocarbon content	~ 160	~ 4 GBq Ra-226, ~ 2 GBq Ra-228, ~ 0.3 GBq Pb-210
Oil and gas – onshore	Scales and sludge, May be hazardous waste due to heavy metal and hydrocarbon content	< 20	< 0.05 GBq Ra-226, < 1 GBq Pb-210+
Titanium dioxide	Filter cloths	~ 10	~ 1 GBq Ra-226
China clay	Scale		
Zirconia industry	magnesium dross	~ 0.04	~232 MBq Th-232
Thorium coated lens manufacturer	Mixed solids	~ 1	~ 0.05 GBq Th-232
Contaminated land	Soil, building rubble, discrete items	Very variable	Very variable but anticipated to be less than 1 GBq Ra-226
Total		< 300	< 6 GBq Ra-226, ~ 2 GBq Ra-228, ~ 1 GBq Pb-210, ~ 232 MBq Th-232

From (DECC, 2014)

185. Under the EPR (UK Government SI, 2016) a consignor can dispose of 5 10^{10} Bq y^{-1} of NORM waste containing up to 5 Bq g^{-1} to landfill under an exemption i.e. without requiring a Permit (i.e.10,000 t y^{-1} of NORM at 5 Bq g^{-1}). There are also provisions for disposal of NORM waste containing up to 10 Bq g^{-1} at a landfill site without the need for a Permit, subject to the prior submission of a safety case to the Environment Agency and the receipt of no objections from them.

186. The general nature of the waste inventory is described in the national inventories for radioactive waste (NDA, 2023). If the consigning site has established that disposal to landfill is BAT, then subject to ensuring that the high levels of environmental protection afforded by the site are not compromised, radioactive wastes with elevated levels of total organic carbon content and the specified soluble contaminants will be accepted at the site for disposal.

187. It is recognised that many disposed wastes are heterogeneous in terms of the distribution of activity within packaged material. For waste that remains in a waste cell the safety case can be based on the assumption that the wastes are broadly homogeneous. Where intrusion occurs the safety case needs to consider radionuclides that may be distributed heterogeneously in some waste materials. Consideration has therefore been given in the ESC to the potential impact of variable activity distribution within a waste package.

4 Authorisation of Disposal

4.1 Process by Agreement {R1}

188. The NS-GRA suggests that a developer is expected to enter into a voluntary agreement with the environment agencies to discuss a proposed facility and subsequent development (Requirement 1):

> "The developer should follow a process by agreement for developing a disposal facility for solid radioactive waste." (NS–GRA (UK Environment Agencies, 2009) para 5.2.3)

189. Early dialogue with the Environment Agency has been conducted. Discussions with the Environment Agency regarding the acceptance of LLW at the site date back to February 2018 and subsequent meetings (via Microsoft Teams or in person) have occurred on the 20th December 2018, 16th May 2019, 19th September 2019, 26th February 2020, 31st March 2020, 9th June 2020, 14th November 2020, 10th January 2021, 6th August 2021, 21st January 2023, 24th October 2023 and 1st February 2024 at which dialogue has continued.

4.2 Dialogue with Local Communities and Others {R2}

190. The NS-GRA expects the developer to engage widely in discussion of the developing ESC (Requirement 2):

> "The developer should engage in dialogue with the planning authority, local community, other interested parties and the general public on its developing environmental safety case." (NS–GRA (UK Environment Agencies, 2009) para 5.7.1)

191. A communications strategy was produced that included a programme of dialogue with stakeholders including the planning authority and the local community. This was developed based on the following principles:

- to comply with Local Authority and Combined Authority Statements of Community Involvement as well as guidance from Central Government and the relevant Ministries, the nuclear industry and its representative bodies and Regulators;
- to promote the fullest understanding and facts about the proposals and any potential impacts they may have to dispel any misunderstandings and misapprehensions at an early stage;
- to communicate in a timely and responsive manner with all stakeholder groups in order to reassure, educate and inform them about the proposals directly so that they feel confident about the safety of the proposals;
- to encourage dialogue and discussion about the proposals and allow the community to feedback their ideas, obtain clarifications where necessary and influence in a constructive manner;
- to be clear to all stakeholders how they can become involved in the process; and,
- to comply with the statutory obligations and procedures as imposed by the planning and permitting process.

192. In line with Augean's policy to proactively communicate about any intended planning applications, engagement with Stockton on Tees Borough Council was initiated far in advance of the commencement of the project to apply for an Environmental Permit and planning permissions for the treatment and disposal of low level radioactive waste at Port Clarence Landfill and Waste Recovery Park. The first meeting to discuss the project in broad terms was held in March 2018, at the feasibility study stage. This was intended to give advance notice in acknowledgement that it may be controversial so that council officers would have time to discuss the implications of such planning applications internally and with the council's cabinet members.

193. Once the ESC (Eden NE, 2019) was in the latter stages of preparation, Augean discussed the proposal to dispose of LLW at Port Clarence with Stockton on Tees Borough Council planning officers and environmental health officers (3rd April 2019). The meeting included a discussion regarding public consultation on the planning applications.

194. Council officers from Stockton Council asked that a summary of the proposed development should be prepared, which would be used as a first step towards inviting Councillors and council officers to attend a briefing opportunity in advance of the scheme being made public through the wide circulation of invitations to the local community to attend pre-application consultation events.

195. It was agreed with the Environment Agency (EA) that this briefing note and any subsequent meetings with the Councillors should be timed for shortly after the submission of the ESC in case any of the Councillors chose to put details of the proposed development into the public domain before the EA was prepared to deal with any enquiries that would arise from that situation. Accordingly, the summary with an invitation to further brief the Councillors was sent out once the ESC had been duly made in August 2019.

196. The meeting to brief the Councillors on the proposals and discuss with them the most meaningful and effective ways of consulting with the local community was held at the end of September 2019. The EA's consultation on the ESC was not circulated to Councillors until the meeting had been held, although it had already gone live on Citizen Space.

197. Following advice from Councillors to allow members of the public to engage in the public consultation regarding the proposals, 18,000 public information leaflets were distributed to homes and businesses in Port Clarence, Cowpen Bewdley and Billingham as well as special interest groups. As a result of the substantially increased interest in the proposals Augean decided to extend the consultation area to include all the Town and Parish councils within the Stockton on Tees Borough Council area as well as sending information to key stakeholders within Middlesbrough Council, Redcar and Cleveland Borough Council and Hartlepool Borough Council and the Teesside Combined Authority.

198. The public consultation events were promoted further by posters displayed in the area, advertisements, engagement with the news media and through social media.

199. A preview event was held for near business neighbours and elected representatives at the Clarences Community Centre on 13 November 2019.

200. Public exhibitions for the local community to attend and discuss the proposals with Augean and their professional team were held in the Clarences Community Centre on

13 November 2019 and at Low Grange Community Centre, Billingham on 14 November 2019. The Environment Agency were available to answer questions as part of their separate consultation on the Environmental Permit application for the landfill sites. The exhibitions were well attended.

201. The site visits as part of the consultation events were well received by all who took the opportunity to go on the tour.

202. Augean recognises the importance of promoting transparency and understanding about the site, the site operations and the company itself. An Open Day was arranged for 21 March 2020, but unfortunately, had to be postponed due to Covid-19 restrictions. Augean has held Open Days on 1 September 2023 and 12 October 2024. Transport from Port Clarence village was made available. Despite wide promotion in the locality, the Open Days were not well attended, although appreciated by those who did.

203. Since 2020 a site-specific edition of Augean's biannual Community Newsletter has been distributed to all homes and businesses in Port Clarence village. For the most recent edition, the distribution has been extended to Cowpen Bewley and the Low Grange area of Billingham to the North of the site following advice from the local MP. The newsletter is distributed to elected representatives at all levels within the Stockton on Tees Borough Council area as well as to selected representatives in the wider Teesside area. It is sent to neighbouring businesses, special interest groups and other stakeholders who have expressed an interest in the site.

204. Augean's approach is based on experience at the ENRMF, tailored to the needs of the local communities near Port Clarence based on advice from local elected representatives.

205. Augean will report back to the local community via the register of stakeholders about the planning application and the environmental permit. Augean uses the register of stakeholders to contact those interested in the proposals via an electronic newsletter. This provides a good and responsive medium for offering further opportunities to visit the site, and explaining in a detailed way aspects of the scheme by giving further information about specific topics that may be of particular interest or concern raised during the consultation process.

206. On submission of the updated ESC Augean will inform the local community of the submission. The non-technical summary of the ESC will be prepared for circulation in the community. Community consultation events and opportunities to visit the site will be organised during 2025 at which the community can discuss the application with Augean and the company's expert advisors. The Environment Agency will be invited to take part in this event.

207. Other initiatives have been identified to help to reassure the local community in the long term which include:

- Liaison Group - The creation of a Liaison Group would provide a forum where any concerns can be discussed on a regular basis. Augean would welcome attendance by the Environment Agency should it wish to participate.
- Electronic newsletters - An electronic newsletter is already a well-established method of communication at other Augean sites. It enables efficient feedback on issues raised and, enables circulation of information regarding events and opportunities at the site.

- Website and email - The company website www.augean.co.uk not only gives company wide information about all operational sites and services but also has become an important hub to enable the public to access documentation relating to planning applications. There is a dedicated consultation email consultation@augean.co.uk which allows visitors to the website to submit questions, raise concerns or sign up to the Register of Stakeholders.
- Telephone helpline - A dedicated helpline number exists to allow members of the public to request further information on the proposals or to raise concerns verbally.
- Open Door Policy - The company has an Open Door policy and is pleased to welcome visitors at all its sites by appointment.
- Publication of site monitoring data - In response to requests at the exhibition, Augean has undertaken to publicly share a summary of the key monitoring results from the site to provide reassurance that human health and the environment are not being harmed by the presence of LLW and other wastes at the site. This will be updated on a regular basis.

5 Management Requirements

208. Eden NE produced this ESC and has procedures in place for the production, checking and review of technical reports that are part of our ISO 9001(2015) accredited quality management system. A thorough quality assurance check is undertaken on all spreadsheets, GoldSim, PC Cream and Erica calculations, and transcription checks are undertaken to verify that relevant data are transferred to the report correctly.

5.1 Environmental Safety Case {R3}

209. This document has been designed to fulfil the requirement for an environmental safety case that is proportionate to the level of risk represented by the proposed waste disposal at Port Clarence. The supporting technical basis for the radiological assessments used to support the ESC is presented in Appendix E. The safety assessments and related safety arguments presented throughout the document are drawn together in the summary (see Section 8).

210. Augean's approach to the handling and disposal of LLW builds on the experience gained performing this work at the ENRMF site since December 2012. The processes for acceptance, checking and disposal of the waste have been optimised by taking the learning from ENRMF and applying this to the Port Clarence site. These processes are captured in Management Procedures.

211. Augean works with clients to ensure that waste forms and packaging can be handled safely during disposal operations, and the waste producers have a requirement to show that BAT has been used in the generation and packaging of the waste. Augean requests copies of BAT assessments for all wastes.

212. Disposal is not generally considered BAT if a suitable reuse, recycling or treatment option is available. For example, BAT for surface contaminated metallic waste is currently to remove the contaminated surface layer (a process undertaken at the WRP), with the bulk of the metal being recycled and only the surface coatings and radioactive contamination being disposed at Augean sites.

213. The packages used for LLW will typically have to meet the requirements of Class 7 Transport under ADR Regulations. Note that some lower activity waste may be Exempt from Class 7 due to the low activity. Waste packages that are suitable for road transport as Class 7 are robust and will have been loaded onto the vehicle using some form of fork-lift vehicle. Augean would replicate this process in reverse when offloading the waste for disposal. Waste packages that are suitable for transport on public roads are suitable for transport short distances on Augean landfill sites. Augean would review all proposed packages in the form of a Package Handling Assessment to ensure that they can be handled safely on our sites.

5.2 Environmental Safety Culture and Management System {R4}

214. The NS-GRA outlines a requirement for a positive environmental safety culture supported by an appropriate organisational structure and management systems (Requirement 4):

> "The developer/operator of a disposal facility for solid radioactive waste should foster and nurture a positive environmental safety culture at all times and should have a management system, organisational structure and resources sufficient to

> provide the following functions: (a) planning and control of work; (b) the application of sound science and good engineering practice; (c) provision of information; (d) documentation and record-keeping; (e) quality management.” NS–GRA (UK Environment Agencies, 2009) para 6.2.5

215. Augean has an established effective integrated management system and safety culture. The system ensures:

- Effective planning and control of work;
- Application of sound science and engineering practice;
- Safe acceptance and handling of waste;
- Maintenance and availability of comprehensive records and information; and,
- Quality management.

216. This system is subject to regular audit and inspection by internal independent compliance teams and external auditors including UK Health Security Agency (UKHSA) formerly Public Health England (PHE), the British Standards Institute and customers, together with the Environment Agency. Augean has demonstrated that it is fully capable of assuring environmental safety through its organisational structure, strong leadership and appropriate resourcing, competencies and culture. The proposal for Port Clarence is a continuation of existing practice and does not require change to the integrated management system and safety culture. A summary of the business structure and management systems is provided below. The structure of the Management Board and areas of responsibility is shown in Figure 15.

217. Any operational procedure changes and all monitoring reports require sign off by the Director of Corporate Stewardship, this ensures that any changes in procedure, new information and monitoring results that may affect the ESC are reviewed. Some of the key aspects that may trigger an update of the Port Clarence ESC are:

- new climate change predictions;
- a change in commercial waste availability;
- a change (novel) waste characteristics not bounded by the ESC;
- a change to landfill design during construction and operation of the facility; or
- changes to parameter value recommendations.

218. A summary of the Augean business structure and management systems is provided below.

5.2.1 The Augean Business and Culture

219. Augean was formed in 2004 CE, and is a UK-based specialist waste and resource management group (https://www.augean.co.uk/). The group provides a wide range of services for difficult, hazardous and radioactive wastes through its treatment, transfer, landfill disposal and recycling operations. Since 2004, the business has developed through a series of stages of acquisition, planning and development to establish a waste business operating to modern standards and responding to regulatory change.

220. Augean is committed to Corporate Social Responsibility (CSR) as demonstrated through the annual publication of a CSR Report since 2005 which measures their performance in respect of business, health and safety, their employees, their neighbours and the environment. The CSR Report is published on the Company Website.

221. The Augean CSR Report is a record of company performance and how they are working together to improve that performance in respect of business values, health and safety, the environment and within our local communities. This annual exercise is a valuable discipline to help them demonstrate their commitment to responsible care, evaluate their performance against stated objectives and provide focus on their aspirations for the year ahead.

222. An essential element of their approach to business is their core business values supported by business principles.

"Augean's core business values are:

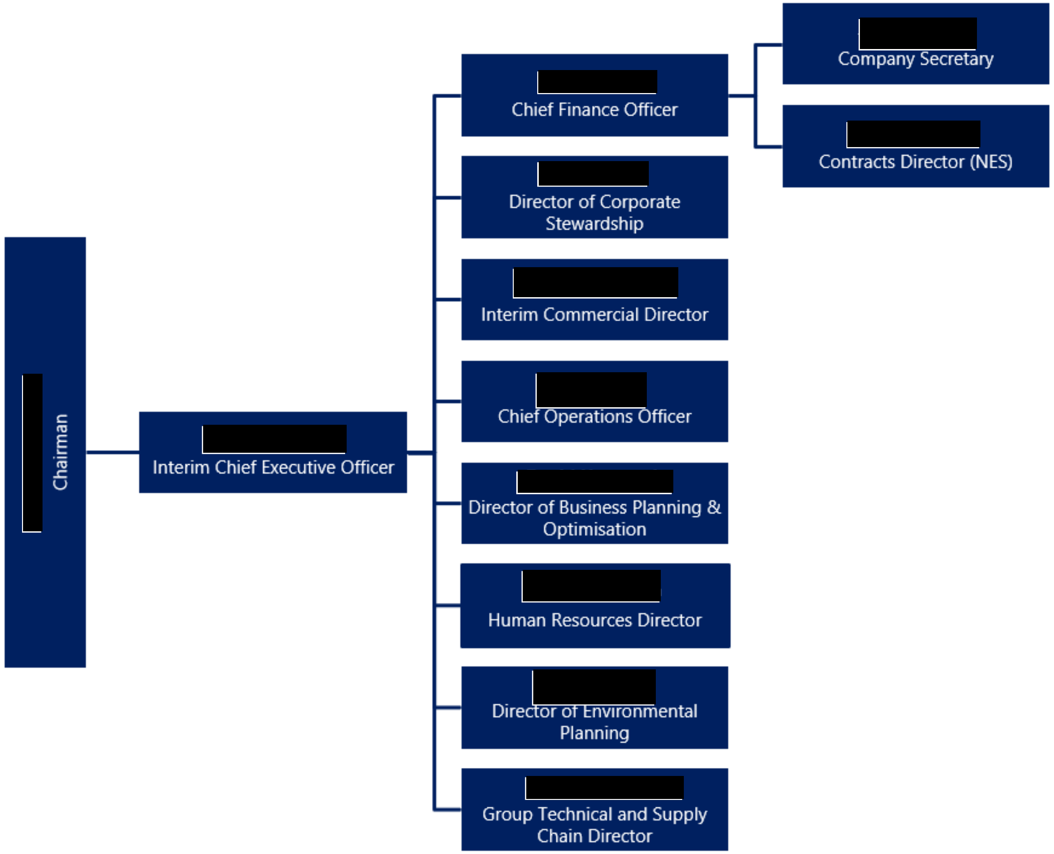
- *Teamwork - We work better together.*
- *Integrity - We demonstrate that we can be trusted.*
- *Growth - Our business will grow in a sustainable manner.*
- *Excellence - We strive to achieve our ambition.*
- *Respect - We show we value our people and others we work with.*
- *Solutions - We find the best solutions for our customers..*

Based on these values Augean operate on the following business principles:

- *Priorities – we take action according to the priority: Safety, Compliance, Profit;*
- *Safety – we stop the job if we are not sure it is safe;*
- *Environmental responsibility – we respect the environment and take a planned approach to protecting it;*
- *Social and community responsibility – we invest time to build constructive relations with the communities in which we operate;*
- *Technical excellence – we value the expertise of our staff and use up-to-date techniques and equipment; and,*
- *Transparency – we are open and transparent in all that we do."*

223. Augean is committed to the principle of equal opportunity in employment and to creating a harmonious working environment which is free from harassment and bullying and in which every employee is treated with respect and dignity. Accordingly, well established policies are in place to ensure that recruitment, selection, training, development and promotion procedures result in no job applicant or employee receiving less favourable treatment on the grounds of race, colour, nationality, ethnic or national origin, religion or belief, disability, trade union membership or non-membership, sex, sexual orientation, gender, marital status, age or status as a part-time or fixed-term employee. Equal opportunity policies are set out in their Employee Handbook.

Figure 15 Augean Management Board



5.2.2 Management systems

224. Operational performance is maintained through a certified Integrated Management System (IMS) delivering protection of health and safety, both internally and externally, and the management, protection and improvement of the environment for nature and our local communities. The IMS is certified by the British Standards Institute to the following standards:

- ISO 9001:2015 Quality management system;
- ISO 14001:2015 Environmental management system;
- ISO 45001:2018 Occupational health and safety management system; and,
- PAS99:2012 Integrated management system.

225. Central to the IMS is the Health, Safety, Quality and Environment Policy statement which is presented at Appendix C.

226. Delivery of the policy objectives is set out in the Augean Business Manual which:

- Defines roles of key positions in the organisation and provision of appropriate resources. This is further supported by specific job descriptions.
- Identifies the importance of training and competence which is supported by Corporate training requirements procedure.
- Identifies the provision of operational procedures.
- Describes the approach to the management of health and safety and environmental events by the provision of site-specific emergency plans and an event management system.
- Sets out the need for document control including record keeping.
- Describes auditing of compliance with the IMS which is supplemented by monthly compliance inspection at all sites.
- Includes systems for corrective and preventative action in the case of non-conformance.

227. The IMS provides a framework that considers the different aspects of the business and determines the impact of business activities on the workforce and the environment. Risk assessments have been conducted for all operational activities and where necessary to ensure adequate operational control procedures have been developed and implemented. Appendix C shows an overview of the IMS and lists the main corporate procedures within the system.

5.2.3 Corporate Reporting and Communication

228. The business has a range of mechanisms for developing policy, decision making and communication. Policy is usually determined at Management Board level. Policy decisions are communicated directly through the corporate structure and through a wide range of other mechanisms including Director Engagement Visits and

presentations, training, safety campaigns and the monthly publication of Augean's monthly newsletter "Fresh off the Filter Press".

229. The outcome of auditing and inspection, near miss and safe act reporting, incident investigation and training are all reported to the Management Board on a monthly basis in a Compliance Report. The Compliance Report is reviewed each month at the Management Board meeting. More strategic and policy matters together with high potential near miss and incidents are reviewed at the monthly Compliance Review meeting attended by the Management Board and Head of HSEQ together with invited site managers.

5.2.4 Site organisation

230. The Port Clarence Site Manager is responsible for the quality, health and safety and environmental performance of the landfill sites. The Site Manager reports directly to the Management Board which is ultimately responsible for the quality, health and safety and environmental performance of the Augean Group. The Site Manager at Port Clarence is a holder of a Certificate of Technical Competence for the management of hazardous and non-hazardous landfills. The Site employs trained Radiation Protection Supervisors (RPSs). The entire operating team receives specific training in the operating procedures relevant to their function.

231. Operational meetings are held weekly. Health and safety meetings are held quarterly. There are Health and Safety Representatives in the landfill, treatment and administrative areas of the site.

232. Augean employs a range of highly qualified professionals with expertise in environmental and health and safety legislation, environmental management, chemistry, ecology, planning, engineering and waste management. As necessary, expertise is outsourced from external consultants. The Company maintains a list of approved consultants who are selected on the basis of qualification and experience and whose place on the list is dependent on good service.

233. The "Intelligent Customer" role is maintained through a team with defined roles and responsibilities, and each role has a nominated deputy. Technical support and expertise is provided by the Corporate Stewardship team, including the Health Safety Environment and Quality Managers (HSEQ Managers) who monitor legislative compliance and the Monitoring team that monitors the environmental impact of the site in all media. The site chemists provide laboratory facilities and determine the suitability of waste for acceptance at the site. The HSEQ Managers undertake regular inspections of the site including compliance with Environmental and Radiological Permits. Periodic audits of procedures are undertaken in accordance with the IMS the frequency of which is determined on a risk basis. The HSEQ Managers report all inspections onto the company's event management system (called EcoOnline, at the time of this report). The Director of Corporate Stewardship is a member of the Management Board and advises the Board on health and safety and environment issues. HSEQ Managers have received radiological training relevant to the operation of the Augean sites and include qualified RPSs. The ENRMF Site employs four RPS on-site who ensure that all operations are in line with the Local Rules as written by our Radiation Protection Advisor.

234. Augean employs a dedicated Technical Assessment (TA) Team providing a centralised service to the business. The LLW TA team comprises three to four

experienced professionals educated to HNC or BSc level, or higher, in chemistry or a related scientific subject. The purpose of this team is to assess waste streams, determine how the waste can be managed in accordance with the waste hierarchy and the suitability of the waste for acceptance at a specified site. The team tracks and monitors waste inputs, including radiological capacity (see Monitoring Tool example provided), to site through computer software. Specifically, in respect of radioactive waste the TA team are further supported on a consultancy basis by UKHSA and Eden NE where required. The TA team is independent of the operational team and based at the Company Headquarters at Wetherby. The Technical Assessor collates waste characterisation information and undertakes the initial chemical and radiological evaluation of the suitability of waste for disposal at the site. The final approval for booking of the waste to the site is given by the Site Manager. The process for acceptance of waste is set out in the pre-acceptance and acceptance procedures.

235. To support the site and in accordance with the Ionising Radiation Regulations and to provide staff training as necessary Augean will retain the services of UKHSA or other suitably qualified organisations as Radioactive Waste Advisor and Radiation Protection Advisor. The main scope of the support provided by the UKHSA is:

- Support during Permit transfer and variation;
- Preparing a comprehensive Radiation Risk Assessment of the impact on employees at the site;
- Local rules and procedures;
- Training site staff; and,
- Multiple site visits per annum to audit the waste handling operation, records and undertake additional monitoring.

5.2.5 Arrangements Specific to LLW Disposal Operations

236. The following arrangements are incorporated into the management system specific to LLW disposal operations:

- A radiation protection plan and risk assessment as required by the Ionising Radiations Regulations, prepared by the site Radiological Protection Advisor (currently UKHSA). Local rules in accordance with the Ionising Radiations Regulations and the conditions of the Environmental Permit. Defined roles and responsibilities include the following:
    - Radiation Protection Advisor (UKHSA),
    - Radioactive Waste Advisor (UKHSA),
    - Radiation Protection Supervisor(s), and,
    - Dangerous Goods Safety Advisor (Class 7).
- A procedure for the pre-acceptance of waste including the conditions for acceptance for LLW for use in contractual arrangements with consignors (PC LLW01, the CfA).
- A procedure for the pre-acceptance of waste by the central technical team (PC LLW02).

- A procedure for acceptance and the receipt of waste, assay, waste emplacement (including loose tipping), coverage, record keeping and general LLW disposal operations (PC LLW03).
- A procedure for the quarantine of non-compliant waste packages received at Port Clarence (PC LLW04).
- A procedure for monitoring employee doses and instructions for measuring X-Ray and Gamma Radiation dose rates during acceptance of LLW waste at Port Clarence (PC LLW05).
- A procedure outlining actions to be taken if consignments are unable to reach the site entrance in order to minimise risks to staff, the site and wider community (PC LLW06)
- Local rules written in accordance with Regulation 17 of the Ionising Radiations Regulations 2017 listing designated areas, authorised persons, safe working procedures, personal monitoring and contingency plans for spillage (PC LLW07).
- A procedure for the compliant return of containers to the consignor's site once all radioactive waste has been removed (PC LLW08).
- An emergency plan including response arrangements to identified fault scenarios including (PC 01):
    - Dropped load or spillage;
    - Fire;
    - Loss or theft of LLW;
    - Contamination discovery;
    - Non-compliant or un-fit load;
    - Dose above threshold discovery; and,
    - Potentially contaminated person or wound.
- Procedures for environmental monitoring incorporated into the Monitoring and Action Plans (MAPs).
- A procedure for handling asbestos bearing packages of LLW.

5.2.6 Principles that would be applied to waste retrieval

237. Waste retrieval is not planned following emplacement and is not expected under all foreseeable circumstances. The Environment Agency has previously requested consideration of the principles that would be applied should a package of unsuitable waste be inadvertently deposited at the site.

238. For waste arriving in packages, given the robustness of the packaging and the method of placement it is considered that the containers will remain intact in the landfill for an extended period. The placement of the waste in robust containers in accurately recorded locations will facilitate recovery of waste if it is considered necessary. Detailed risk assessments would be undertaken and methods would be developed and agreed with the Environment Agency and the Radiation Protection Supervisor (in consultation with the Radiation Protection Adviser) in advance of the exercise taking

into account the specific circumstances of the removal but in principle the following approach would be taken:

- identification of the location of the waste from the GPS records - this information also includes details of the types of hazardous waste deposited in the locality;
- determination from GPS records the quantity and characteristics of waste that would need to be excavated to access the specific waste that must be removed;
- identification of stockpiling areas for excavated material and standards for stocking;
- consider the need for undertaking the operation under cover;
- removal of the majority of soil and/or waste covering by machine and by hand where necessary;
- monitor the emissions from the packaged waste to confirm that they remain less than 10 μSv h^{-1} at a distance of 1 m from the package (i.e. measure to confirm before it is moved);
- in respect of bags locating of the carrying straps and then lifting out of the waste bag using the forks of a forklift truck;
- in respect of drums use of drum handler attachments on a forklift truck to remove the waste drum;
- in respect of ISO containers use of a crane;
- if necessary the containers would be brushed down to remove extraneous adhered material;
- in the unlikely event that any of the containers are compromised they would be repacked or over packed at the excavation area;
- the containers would be loaded onto a lorry in the working area;
- suitable personal protective equipment would be specified based on risk assessment and potential exposure would be monitored;
- removal of the material from the site in accordance with the relevant Transportation Regulations; and,
- replacement of wastes into the excavation using suitable cover material to infill interstices.

239. It is not envisaged that loose tipped waste will be retrieved. The activity concentration limit of loose tipped waste is specified and is significantly lower than that proposed for packaged waste consignments.

6 Radiological Requirements

240. The NS-GRA specifies dose constraints to members of the public that may arise from the Port Clarence landfills during the period of authorisation, a risk guidance level after the period of authorisation and dose constraints for human intrusion. This section summarises the dose assessments that have been undertaken to support the ESC (detailed in Appendix E). The results are presented as effective doses per unit disposal (µSv y^{-1} MBq^{-1} or mSv y^{-1} MBq^{-1}) and as effective doses (µSv y^{-1} or mSv y^{-1}) from disposal of the maximum inventory (MBq) of each radionuclide.

241. The radiological capacity (also called the relevant value in this report) is the radionuclide inventory of each radionuclide that can be disposed at Port Clarence that would not result in a dose greater than the relevant dose criterion from any of the exposure scenarios. It is therefore the minimum of the values calculated for specified exposure scenarios (see Appendix E). The radiological capacity for a specified scenario is called the scenario radiological capacity. All calculations detailed in Appendix E are inherently cautious ensuring that the prospective dose is overestimated and, because the radiological capacity is inversely proportional to the dose, the radiological capacity is therefore minimised.

242. The scenario radiological capacity of the Port Clarence landfills (values for both the hazardous and non-hazardous landfills) for each radionuclide and scenario is presented in Section 7.4 and these values, together with the sum of fractions approach, are used to control disposals. Calculating the fraction of the scenario radiological capacity that has been used by each disposed radionuclide in turn and ensuring that the sum of fractions is ≤1.0 for all the specified scenarios will ensure that the dose from all disposed radionuclides does not exceed the relevant dose criterion. Hence, the sum of fractions approach ensures that the dose criteria are not exceeded if a mix of radionuclides is disposed of. The 'relevant values' presented in Table 41 and Table 42 (Schedule 3 of the proposed Permit) are these scenario radiological capacity values based on the dose criteria.

243. Note that whilst there is no site constraint on the amount of LLW tonnage that can be disposed to the site it is assumed for the purpose of the risk assessment that LLW will comprise no more than 5% of the remaining void at the Port Clarence landfills. This limit on the tonnage of LLW and radionuclide specific activity concentration limits provides a theoretical maximum inventory that could be disposed of to the site for each radionuclide. The maximum inventory is the minimum of the radiological capacity and the tonnage disposed at the activity concentration limit; the maximum inventory is therefore sometimes less than the radiological capacity. The results of the dose assessments presented here show doses due to the maximum inventory that could be disposed of each radionuclide. The maximum inventory values are not appropriate for use as 'relevant values' for the proposed Permit as they would overestimate the fraction of the available radiological capacity used for disposal.

244. The results of the dose assessments presented in Sections 6.1, 6.2 and 6.3 show the maximum inventory that could be disposed of each radionuclide, in each of the Port Clarence landfills. This is followed by discussions of waste heterogeneity (Section 6.4), optimisation considerations (Section 6.5) and other biota (Section 6.6)

245. Estimates of radiological impact based on 'illustrative inventories' for waste streams that might be typical of those contributing to the total impact from disposals at the facility have been produced. These estimates are presented in Appendix E.

6.1 Dose constraints during the period of authorisation {R5}

246. The NS-GRA specifies dose constraints for members of the public for the period of authorisation (Requirement 5):

> "During the period of authorisation of a disposal facility for solid radioactive waste, the effective dose from the facility to a representative member of the critical group should not exceed a source-related dose constraint and a site related dose constraint.
>
> The UK Government and Devolved Administrations have directed the environment agencies to have regard to the following maximum doses to individuals which may result from a defined source, for use at the planning stage in radiation protection:
>
> - 0.3 mSv/y from any source from which radioactive discharges are made; or,
> - 0.5 mSv/y from the discharges from any single site."
>
> (UK Environment Agencies, 2009), para 6.3.1 and 6.3.2

247. For the purpose of the assessments reported here the Port Clarence landfills are considered to be a source from which radioactive discharges occur (i.e. the 0.3 mSv y^{-1} dose constraint applies to the entire landfill site - the non-hazardous and hazardous landfill sites are considered as a single source). The ESC uses the term "period of authorisation" to cover the time when active management controls are maintained and the Permit remains in force. This period is assumed to last until 2135 CE in these assessments (50 years operation from the present followed by 60 years post closure). Post-closure or after the period of authorisation refers to the time when the permit has been revoked, and there is no active management or control at the site (2135 CE onwards is assumed in these assessments, although the period of authorisation may be much longer).

248. UKHSA (formerly Public Health England [PHE] and before that the Health Protection Agency [HPA]) recommends a lower annual dose constraint for members of the public of 0.15 mSv for a new facility and the GRA notes that HPA has recommended that this lower value is applied to a new disposal facility (HPA, 2009). However, the GRA does not formally adopt this recommendation, and this lower dose constraint has not been adopted in the recent update of the Environmental Permitting Regulations. Therefore, it is not considered further.

249. For workers, the legal dose limit is 20 mSv y^{-1}, and the criterion used for the safety case for Port Clarence is 1 mSv y^{-1}, which is the same as the current legal dose limit for the public. This is an operational criterion and is not used to set the radiological capacity of the landfill because the exposure arises in a manner unrelated to the total capacity of the site. This criterion does affect some of the authorisation conditions, particularly the external dose limits on packages. This criterion will be used for radiation protection purposes during operation of the facility.

250. Doses and risks need to be assessed for a range of hypothetical exposure groups in order to identify those at greatest risk at a given time. The present-day land use can be used to inform calculations of the impact during the period of authorisation. Throughout this report, the term "scenario" is used to describe a situation or class of situations leading to future exposures.

251. The radiological assessment has considered a range of potential scenarios. A review of generic guidance and existing publicly available ESCs identified a set of scenarios that are discussed in detail in Appendix E and those considered for Port Clarence for the period of authorisation are summarised in Table 8. In cases where a scenario has not been quantitatively assessed, because it will not or is very unlikely to occur at Port Clarence, the reasons for this are described. The scenarios discussed below consider both workers and members of the public (adult, child and infant) during the period of authorisation, and these are divided into two broad categories – those that are likely to occur and those that are unlikely to occur i.e. have a low likelihood of occurrence.

252. There is no abstraction of drinking water near the Port Clarence site due to saline intrusion from the estuary (Jones, et al., 2014). There are no public water supplies in the north-east from the Sherwood Sandstone Group that underlies the site (Allen, et al., 1997). It was agreed with the Environment Agency in December 2018 that the groundwater pathway would not result in exposure during the period of authorisation and is not, therefore, considered further for this period.

Table 8 Summary of radiological assessment scenarios during the period of authorisation

Scenario	Exposed group
Period of Authorisation – likely to occur	
Direct exposure	Worker
Loose tipping	Worker
	Member of public
Leachate processing off-site at treatment works	Treatment worker
	Angler
	Farming family
Leachate processing using Reed bed	Treatment worker
Leachate processing on-site	Treatment worker
Release to atmosphere	Member of public
Release to groundwater	Member of public
Cell excavation*	Worker
Period of Authorisation – unlikely to occur	
Dropped load	Worker
Wound exposure	Worker
Leachate spillage	Farming family
Landfill fire	Member of public
Barrier failure*	Member of public
Aircraft impact*	Member of public
Other unlikely events*	

* Not assessed quantitatively.

253. The list in Table 8 includes scenarios that are not quantitatively assessed and these are cell excavation, barrier failure, an aircraft impact and Other unlikely events. The reasons why these events have not been assessed in detail are given in Appendix E.3.1.

6.1.1 Dose assessments for the period of authorisation: likely to occur

6.1.1.1 Direct exposure: waste handling

254. It is not intended that waste is stored on-site prior to disposal. Wastes will be placed in a landfill cell as soon as practicable on receipt. If the conditions for the acceptance of LLW at Port Clarence are not met, waste may need to be quarantined temporarily while

deciding on a course of action. To allow some flexibility for waste delivery times and operational activities the ESC assumes a maximum of 24 h between receipt and disposal.

255. Wastes will be covered by at least 0.4 m thickness of suitable cover after each emplacement campaign or at the end of the working day such that there is no exposed face. Sufficient cover will be used to ensure the dose rate at 1 m above the waste is less than 2 µSv h^{-1}.

256. The exposed group considered for quarantine, waste handling and emplacement is landfill workers. Waste handling, emplacement and quarantine will not expose the public near to the site to radiation because there is no line of sight for direct radiation from the quarantine area or landfill void, and site access is controlled. The dose criterion used for this scenario is the site criterion of 1 mSv y^{-1} for workers.

257. Doses from direct exposure while handling waste are based on calculations that were performed for the ENRMF, and experience at the ENRMF, since these are directly relevant to handling waste at Port Clarence. Radiation risks to employees from normal operations were last reviewed by the UKHSA for the ENRMF in 2017 CE (Jakes, 2017). A conservative estimate of the dose to ENRMF workers for disposal of wastes containing up to 200 Bq g^{-1} of Co-60 as a result of three work activities suggests an annual dose of about 0.79 mSv if the same worker undertook waste receipt, monitoring, transfer and placement in the landfill and worked in the covered waste area. UKHSA considered it unlikely that the same person would be exposed during all the listed work activities. An assessment of exposure resulting from a wound (see Section 6.1.2.2) concluded that internal doses from a contaminated wound would be very unlikely to exceed 1 mSv in practice.

258. The external radiation exposure to workers from their occupancy near a waste package prior to disposal was also assessed by the UKAEA (Augean, 2009a). UKAEA considered the external radiation dose for a series of cases and package types. The hypothetical worst case was identified to be a flexible type waste container with 200 Bq g^{-1} of Co-60. This was an unlikely case and another case was also included to illustrate more typical exposures. The hypothetical worst case dose identified a dose rate of 14.5 µSv h^{-1} measured at a distance of 1 m from the package face. A dose rate of 10 µSv h^{-1} at a distance of 1 m from the package is used at the ENRMF as an acceptance criterion to limit total exposure below 1 mSv and constrains the contents of the package to comply with this limit. The same dose rate criterion will be applied at Port Clarence and included in the CfA.

259. Dose assessments for workers handling and emplacing waste carried out for this ESC use the proposed activity concentrations in disposed waste at Port Clarence (see Appendix E.3.3). The assessments show that the site constraint of 1 mSv y^{-1} could be exceeded for several radionuclides (Mn-54, Co-60, Zn-65, Ru-106, Ag-110m, Sb-125, Ba-133, Cs-134, Eu-152, Eu-154) if the package contained only these nuclides at the proposed activity concentrations. However, the dose rate limit for waste acceptance of 10 µSv h^{-1} at a distance of 1 m from the package will independently constrain the contents of these packages and ensure that the 1 mSv y^{-1} site constraint will be met.

260. The dose to a member of the public standing at a distance in direct line of sight of a waste package/shipment is also considered. The maximum dose rate at 50 m is estimated to be 4 10^{-3} µSv h^{-1} for a package that meets the 10 µSv h^{-1} at a distance of 1 m from the package criterion. If the person stands in that location for 8 hours per day and there is waste with the maximum surface dose rate in that location every day, then

the person would receive 12 µSv y^{-1}; the corresponding dose at a distance of 100 m would be 3 µSv y^{-1}. These are low doses and the calculations are very conservative. Another scenario could involve a dog walker moving along the site perimeter every day, spending 0.5 h d^{-1} about 120 m from the holding area. In the unlikely event that a consignment was present each time the walker passed by then the annual dose would be about 0.1 µSv y^{-1}.

261. The ENRMF assessments used a maximum activity concentration of 200 Bq g^{-1} for each radionuclide whereas the approach at Port Clarence is to calculate activity concentration limits for disposal of each radionuclide at the Port Clarence landfills and then apply the sum of fractions for a mix of radionuclides. In addition, the dose rate criterion of 10 µSv h^{-1} at a distance of 1 m from the package will be applied and this will constrain the activity concentration of some radionuclides to lower values (the exact value will depend on the mix of radionuclides in the package).

262. The external dose to workers during the operational phase will be managed through occupational radiation dose protection practices, hence the external dose assessment for waste handling has not been used to constrain the overall radiological capacity of the site.

6.1.1.2 Direct exposure: waste emplacement and cell excavation

263. Waste will be emplaced in the landfill and immediately covered. The advice of the radiation protection advisor at the ENRMF is that the maximum radiation dose 1 m above the covered waste should be less than 2 µSv h^{-1} in order to ensure the occupational dose is considerably less than the dose criterion of 1 mSv y^{-1}. The same dose rate criterion is adopted for Port Clarence.

264. The external radiation exposure of workers in the vicinity of the emplaced waste after it has been covered was assessed by the UKAEA (Augean, 2009a) for the ENRMF. The assessment demonstrated that for most cases, a 0.3 m thick cover layer will more than achieve the specified dose rate. For the worst case of waste containing Co-60, at 200 Bq g^{-1}, a cover layer of 0.7 m is required to reduce the dose rate.

265. At Port Clarence a more cautious minimum cover layer of 0.4 m will be adopted, and if the dose rate 1 m above the covered waste is greater than 2 µSv h^{-1} then further cover will be added in order to achieve the dose rate. The minimum cover layer of 0.4 m is adequate to ensure daily physical protection of the waste. This condition will be specified in the site operating procedures.

266. Direct exposure is also calculated at the time of site closure and reported in Section 6.2.1.1.

267. Additional “as low as reasonably achievable” (ALARA) precautions will be adopted:

- all wastes will be handled by machines;
- the only people on foot are those unstrapping loads and undertaking health physics monitoring; and,
- workplace monitoring will confirm actual doses and enable dose limitation to be managed.

268. Workplace monitoring at the ENRMF has been undertaken continuously since 2011 and to date has shown no measurable doses.

269. Cell excavations during the period of authorisation are not assessed in the ESC. Any excavations will be undertaken with full knowledge of where waste is placed within each cell and appropriate precautions will be taken. Installation of the landfill cap requires landfill workers to locate the side liner of a waste cell. Operating procedures at Port Clarence will require at least 2 m of non-radioactive waste to be placed between the side liner and LLW to make certain that workers do not come into contact with packages or loose tipped LLW when the landfill is permanently capped. No LLW will be placed within 1 m of the surface of the landfill.

270. The external dose to workers during the operational phase will be managed through occupational radiation dose protection practices, hence the external dose assessment for waste emplacement has not been used to constrain the overall radiological capacity of the site.

271. This scenario is one of the scenarios used to determine the proposed radionuclide activity concentration limits for packaged wastes (see Section 7.4.1.2 for further details) to ensure protection of the workers placing waste in the vicinity of LLW that has already been covered.

6.1.1.3 Impact due to loose tipping LLW

272. Loose tipping will occasionally be undertaken where necessary and subject to a BAT assessment. Loose tipping could have implications for on-site and off-site doses during operations i.e. during the period of authorisation. Post-closure scenarios are not affected by loose tipping because the containers are ignored in terms of the fate of disposed activity in the ESC.

273. UKHSA has provided a worker assessment for the deposition of a bulk load of waste at the ENRMF (Jakes, 2017) using cautious assumptions about dust generation and an activity concentration twice the average for the ENRMF site (20 Bq g^{-1}). This assessment indicates the dominant exposure pathway is due to dust inhalation of actinides. The highest estimated doses were for Ac-227 and Th-229. In most cases it is expected that the waste will be damp and therefore give rise to little airborne dust, or if dry and dusty, local dust suppression (water spray) will be used to minimise airborne dust. In reality therefore, internal doses are likely to be lower than those estimated. It was considered reasonable to assume that, as a worst case, annual internal doses to workers of the order of 0.2 mSv per year might be associated with loose tipping LLW operations where the average activity concentration is 20 Bq g^{-1}.

274. The ESC has considered worker and public exposure from a dust plume created when tipping loose waste (see Appendix E.3.4). The scenario considers the tipping of 15 t of a dry solid waste with the nearest member of the public 50 m away, with an exposure period lasting 30 minutes per consignment. The assessment considers there are 80 consignments of tipped waste each year and the waste is immediately covered after each tip. The dose assessment is very cautious and takes no account of operating procedures that might apply to loose tipped waste to prevent dust emission. However, it is assumed that the current practice of immediately covering radioactive waste is maintained. Optimisation considerations may for example include dust suppression requirements or tipping the LLW into a trench that has been dug in the non-radioactive waste within a cell, a practice used at Clifton Marsh (Eden, 2010) and not tipping during windy conditions. Members of the exposed group are assumed to be adult, a child or an infant and to be exposed as a result of inhalation of contaminated dust.

275. In all cases the limiting exposure is to a worker and the greatest impact is due to inhalation of actinides. The radionuclides that are most limiting are listed in Table 9 based on a cut-off at 100 Bq g^{-1}. The dose to the public when the activity concentration is limited by the worker dose (to ensure the 1 mSv y^{-1} site constraint is met) is always less than about 0.2 µSv y^{-1}.

Table 9 Limiting concentrations for loose tipping based on worker exposure

Radionuclide	Limiting specific activity (Bq g^{-1}) (worker dose of 1 mSv y^{-1})
Ac-227	1.5
Cm-248	2.3
Th-229	3.3
Th-232	5.0
Pa-231	6.0
Pu-240	7.0
Pu-239	7.0
Am-242m	7.3
Pu-244	7.7
Pu-242	7.7
Pu-238	7.7
Th-230	8.4
Cm-245	8.5
Cm-246	8.6
Am-243	8.8
Am-241	8.8
U-232	10.4
Cm-243	12.2
Ra-228	14.1
Cm-244	14.8
Np-237	16.8
Th-228	19.3
Ra-226	43.1
Pb-210	84.2
U-233	87.7
Sm-147	87.7
U-234	89.5
U-236	96.8
U-235	99.0

276. The dose to workers during the operational phase will be managed through occupational radiation dose protection practices and site monitoring, hence the dose

assessment for loose tipping waste has not been used to constrain the overall radiological capacity of the site.

277. This scenario is one of the scenarios used to determine the proposed radionuclide activity concentration limits for loose tipped wastes (see Section 7.4.1.2 for further details).

6.1.1.4 Impact due to leachate treatment

278. The permit application involves no specific liquid discharge routes. Leachate is currently used at the on-site soil treatment facility or treated off-site at a suitable treatment facility. Any discharges from Port Clarence will be subject to permitting when activity concentrations exceed the relevant exemption levels for aqueous disposals specified in legislation (UK Government SI, 2018). Radionuclide activity in leachate would, however, be monitored on a regular basis. This will ensure that the workers at the off-site treatment facility will not be exposed as a result of undeclared radioactivity in the leachate sent for treatment. Monitoring experience at the ENRMF has not detected any significant radioactivity in ENRMF leachate.

279. An assessment has been made of the radiological impact arising from the treatment of contaminated leachate. The dose criteria used in the assessment are 1 mSv y^{-1} for workers at the on-site facility and 0.3 mSv y^{-1} for doses to public and workers at the off-site facility.

280. Under normal circumstances leachate generated in the landfill is treated on-site through the waste stabilisation plant (about 20,000 m^3 y^{-1}). This process binds the leachate in the stabilisation matrix. The stabilised material is then disposed of in the landfill. Use of leachate at the on-site soil treatment facility is covered by the local assessment for the treatment facility in compliance with the Ionising Radiation Regulations (IRR). In the event that the capacity of the stabilisation plant is insufficient to accommodate the amount of leachate that must be removed from the landfill (for example during plant maintenance), the excess leachate is sent to a suitable treatment works which currently is the Billingham Reed Beds (Scott Bros. Ltd) but could also be sent to Bran Sands Industrial Effluent Treatment Works (Northumbrian Water Limited). Under normal operating circumstances it is necessary to send approximately 3,800 m^3 y^{-1} of leachate for off-site treatment. Details of the calculations for these scenarios are provided in Appendix E.3.7.

281. Output from a GoldSim groundwater model of the site provides an estimate of the maximum leachate activity concentrations during the period of authorisation and these are used to assess the potential doses arising from leachate treatment. The calculations are conservative because they do not take into account sorption within LLW materials (except for technetium) whereas, in reality, the LLW received at Port Clarence is likely to provide sorption sites within waste cells.

282. The radiological assessment is based on the Environment Agency initial radiological assessment tool [EA IRAT, (Environment Agency, 2022a; Environment Agency, 2022b)]. The EA IRAT approach for a sewage treatment works is used here as a proxy for a hazardous waste processing facility, taking into account an appropriate total input flow rate. The Reed Bed assessment considers contamination of the total area of the Reed Beds (49,000 m^2) and accumulation over 7 years which is the anticipated operating life of the beds. The treated leachate is then discharged to the estuary via Billingham Beck. A complete assessment to support an application for authorised

discharges of leachate to the reed beds would also need to consider disposal of reed bed materials.

283. The flux of radionuclides to off-site treatment (Bq y^{-1}) uses the peak leachate activity concentrations (per MBq input to the landfill) to the end of the active control period (60 years after capping) and the leachate export rate from the site (3,778 m^3 y^{-1}; the average over the last 6 years). The ingrowth of daughters is modelled using GoldSim and the activity concentrations of the daughters are propagated through the model and the dose contributions summed.

284. The radionuclides showing the greatest doses are presented in Table 10. The dose to on-site workers is used to constrain LLW disposal. Disposal of leachate exceeding the relevant exemption levels would not be disposed without a permit. Treatment of 20,000 m^3 at the WRP produces doses that limit the radiological capacity of Mn-54, Co-60, Ru-106, Ag-110m, Sb-125, Ba-133, Eu-154, Eu-155 and Gd-153.

Table 10 Dose estimated for exposure from the treatment of leachate

Radionuclide	Maximum Inventory (MBq)	WRP facility worker		Off-site treatment worker	
		Dose rate (µSv y^{-1} MBq^{-1})	Dose from disposal of maximum inventory (µSv y^{-1})	Dose rate (µSv y^{-1} MBq^{-1})	Dose from disposal of maximum inventory (µSv y^{-1})
Ba-133	$2.12\ 10^{8}$	$4.72\ 10^{-6}$	$1.00\ 10^{3}$	$1.74\ 10^{-6}$	$3.69\ 10^{2}$
Sb-125	$1.10\ 10^{9}$	$4.91\ 10^{-8}$	$5.38\ 10^{1}$	$7.19\ 10^{-9}$	$7.88\ 10^{0}$
Eu-154	$1.10\ 10^{9}$	$4.80\ 10^{-8}$	$5.26\ 10^{1}$	$1.46\ 10^{-8}$	$1.60\ 10^{1}$
Eu-152	$4.39\ 10^{8}$	$4.54\ 10^{-8}$	$1.99\ 10^{1}$	$2.09\ 10^{-8}$	$9.19\ 10^{0}$
Ag-110m	$4.39\ 10^{8}$	$2.88\ 10^{-8}$	$1.26\ 10^{1}$	$4.72\ 10^{-9}$	$2.07\ 10^{0}$
Cs-134	$1.10\ 10^{9}$	$9.06\ 10^{-9}$	$9.94\ 10^{0}$	$6.72\ 10^{-10}$	$7.38\ 10^{-1}$
Ru-106	$1.10\ 10^{9}$	$6.27\ 10^{-9}$	$6.88\ 10^{0}$	$2.32\ 10^{-10}$	$2.55\ 10^{-1}$
Mn-54	$1.10\ 10^{9}$	$3.23\ 10^{-9}$	$3.54\ 10^{0}$	$3.02\ 10^{-10}$	$3.31\ 10^{-1}$
Zn-65	$1.10\ 10^{9}$	$2.43\ 10^{-9}$	$2.67\ 10^{0}$	$2.27\ 10^{-10}$	$2.50\ 10^{-1}$
U-232	$1.10\ 10^{7}$	$2.03\ 10^{-7}$	$2.22\ 10^{0}$	$2.21\ 10^{-7}$	$2.43\ 10^{0}$
Co-60	$4.39\ 10^{7}$	$4.79\ 10^{-8}$	$2.10\ 10^{0}$	$9.03\ 10^{-9}$	$3.96\ 10^{-1}$
Eu-155	$1.10\ 10^{9}$	$1.08\ 10^{-9}$	$1.19\ 10^{0}$	$1.85\ 10^{-10}$	$2.02\ 10^{-1}$
Ag-108m	$2.19\ 10^{7}$	$3.98\ 10^{-8}$	$8.74\ 10^{-1}$	$5.63\ 10^{-8}$	$1.24\ 10^{0}$
Sr-90	$4.39\ 10^{7}$	$1.52\ 10^{-8}$	$6.67\ 10^{-1}$	$1.18\ 10^{-8}$	$5.18\ 10^{-1}$
Ra-228	$4.39\ 10^{7}$	$9.09\ 10^{-9}$	$3.99\ 10^{-1}$	$1.81\ 10^{-9}$	$7.95\ 10^{-2}$
I-129	$4.39\ 10^{7}$	$7.85\ 10^{-9}$	$3.44\ 10^{-1}$	$5.24\ 10^{-9}$	$2.30\ 10^{-1}$
Gd-153	$1.10\ 10^{9}$	$2.96\ 10^{-10}$	$3.24\ 10^{-1}$	$2.76\ 10^{-11}$	$3.03\ 10^{-2}$
Tc-99	$1.73\ 10^{7}$	$1.76\ 10^{-8}$	$3.06\ 10^{-1}$	$2.60\ 10^{-8}$	$4.50\ 10^{-1}$
Th-228	$4.39\ 10^{7}$	$6.10\ 10^{-9}$	$2.68\ 10^{-1}$	$1.05\ 10^{-9}$	$4.62\ 10^{-2}$
Nb-94	$2.19\ 10^{7}$	$1.02\ 10^{-8}$	$2.24\ 10^{-1}$	$1.52\ 10^{-8}$	$3.33\ 10^{-1}$

285. The calculations of doses from leachate treatment are very conservative and assume no retention by the LLW and an instantaneous deposit of the radiological capacity. There is no allowance for radioactive decay of short half-life radionuclides.

286. The radiological capacity of each radionuclide that could lead to leachate exceeding a radionuclide specific Exemption Level for Disposal of low concentration aqueous radioactive waste to sewer, river or sea (Bq l^{-1}; ELL) is also considered (DESNZ, 2024). There is limited information on the fraction of a landfill inventory that might appear in leachate. Monitoring of leachate since 2015 at the ENRMF does not provide empirical evidence for calculation of the fraction. The modelling work used in the ESC to estimate

the activity in leachate is very cautious and indicates that a relatively small inventory could produce radionuclide activity concentrations in leachate that exceed the ELLs.

287. The closest analogue for landfill disposal is the trench disposals at the LLWR near Drigg. A comparison of the annual discharges through the marine pipeline with estimates of the disposed inventory (Augean, 2009a) indicates that a factor of at least $1x10^{-3}$ y^{-1} should be applied to determining what fraction of the inventory might be in leachate. Initial concentrations, and concentrations of more insoluble elements, would probably be lower than this. This factor has therefore been used for all radionuclides as a conservative assumption in deriving the trigger capacities. Where a substance contains multiple radionuclides a summation rule is applied using the sum of the ratio, “activity in leachate divided by the ELL”.

288. The radiological capacities that could result in leachate concentrations exceeding the ELL (DESNZ, 2024) are listed in Table 11 for radionuclides where the trigger is less than the maximum inventory. A default ELL (0.01 Bq l^{-1}) is applied if the radionuclide is not listed in regulations. The ratio in the right hand column in Table 11 suggests that disposals of Ba-133 and Ca-41 (these are the lowest ratios) would have the greatest impact on leachate concentrations and the summation rule for ELLs.

289. This leachate treatment pathway is used to limit radiological capacity due to use of leachate at the WRP, although it is stressed that leachate disposal is controlled by Augean and that leachate is unlikely to contain activity concentrations above the ELLs. Operational experience at the ENRMF also shows that the assessment model assumptions concerning leachate concentrations are very cautious (a consistent approach is used at both sites). The leachate management plan is discussed in Section 7.3.2 and trigger levels for leachate monitoring are described in Section 7.5.4.

Table 11 Disposal estimated to exceed the ELL in leachate

Radionuclide	ELL (Bq l^{-1})	Cumulative Disposal to exceed ELL (MBq)	Maximum Inventory (MBq)	Ratio of Cumulative Disposal to Maximum Inventory
Ba-133(1)	0.01	$3.59\ 10^{4}$	$2.12\ 10^{8}$	$1.69\ 10^{-4}$
Ca-41(1)	0.01	$4.54\ 10^{5}$	$1.05\ 10^{9}$	$4.32\ 10^{-4}$
Po-210	0.001	$5.24\ 10^{6}$	$4.39\ 10^{8}$	0.012
Eu-154	0.01	$1.44\ 10^{7}$	$1.10\ 10^{9}$	0.013
Se-79(1)	0.01	$1.11\ 10^{7}$	$4.39\ 10^{8}$	0.025
Eu-152	0.01	$1.40\ 10^{7}$	$4.39\ 10^{8}$	0.032
Cs-134	0.01	$9.16\ 10^{7}$	$1.10\ 10^{9}$	0.083
I-129	0.1	$3.93\ 10^{6}$	$4.39\ 10^{7}$	0.090
Mn-54	0.01	$1.39\ 10^{8}$	$1.10\ 10^{9}$	0.126
Eu-155	0.1	$1.53\ 10^{8}$	$1.10\ 10^{9}$	0.140
Sn-119m	0.01	$1.93\ 10^{8}$	$1.10\ 10^{9}$	0.176
Ru-106	0.1	$2.79\ 10^{8}$	$1.10\ 10^{9}$	0.255
Sn-123(1)	0.01	$4.36\ 10^{8}$	$1.10\ 10^{9}$	0.397
Sb-125	1	$4.39\ 10^{8}$	$1.10\ 10^{9}$	0.400
C-14	0.1	$5.54\ 10^{7}$	$1.19\ 10^{8}$	0.467
Cs-135	0.1	$6.64\ 10^{8}$	$1.10\ 10^{9}$	0.605

Radionuclide	ELL (Bq l^{-1})	Cumulative Disposal to exceed ELL (MBq)	Maximum Inventory (MBq)	Ratio of Cumulative Disposal to Maximum Inventory
Gd-153	0.1	$6.86\ 10^{8}$	$1.10\ 10^{9}$	0.626
Sr-90	0.1	$2.96\ 10^{7}$	$4.39\ 10^{7}$	0.674
Co-60	0.01	$3.02\ 10^{7}$	$4.39\ 10^{7}$	0.689

Note: 1) The default value of 0.01 applies to any radionuclide not listed in regulations.

6.1.1.5 Impact due to atmospheric releases

290. The permit application involves no specific permitted gaseous discharge routes. However, the inadvertent release of gases during operations may expose landfill workers on the site and public exposure to gas may also occur but at some distance from the source. The gas pathway considers radioactive carbon, tritium and radon. The aim is to restrict chemical and biological processes occurring within the hazardous waste landfill once disposal has taken place and there are limits on the total organics in waste disposed in the hazardous landfill to reduce the prospect of C-14 and H-3 releases. No waste is accepted in liquid form, waste must not be corrosive, oxidising or flammable, it should not contain ion exchange resins or complexing agents and hazardous waste leaching criteria apply to the non-radioactive content of LLW where practicable. These conditions reduce the likelihood that rapid or high volume gaseous release will occur in the hazardous landfill and hence the assumptions used in the calculations are very conservative. The release of gas from the non-hazardous landfill has been considered, although disposal of organics is limited in practice because it is not BAT.

291. The ESC calculations assume that waste is covered on a daily basis to a depth of 0.4 m, and covered again within 2 months, there is no radioactive decay and members of the public are always present in the downwind direction resulting in the highest dose (Appendix E.3.5.1). Similar assumptions are used for workers but they are assumed to be at the point of discharge with dilution by the average wind speed. The carbon-based peak gas release rates were calculated based on the work for the ENRMF ESC (Eden NE, 2023) that used a model of landfill gas evolution (GasSim). Doses are based on the peak rate of gas production following disposal of the inventory. The fraction of a year a member of the public spends in the plume varies by age group, from 0.73 for an adult to 0.88 for a child. The doses in Table 12 are from disposals at the maximum inventory.

Table 12 Dose estimated for exposure from gas released during operations

Radionuclide	Maximum Inventory (MBq)	Dose* (µSv y^{-1})		
		Worker	Public	Public receptor
H-3	$1.88\ 10^{8}$	$7.37\ 10^{0}$	$1.31\ 10^{1}$	Child
C-14	$1.19\ 10^{8}$	$1.60\ 10^{2}$	$2.47\ 10^{2}$	Child
Ra-226**	$1.39\ 10^{6}$	$1.27\ 10^{1}$	$5.01\ 10^{0}$	Infant

*Based on the peak release rate following disposal of the inventory given in Column 1.
** Dose arises from radon gas.

292. Doses from exposure to gas when each radionuclide is disposed at the maximum inventory (see Table 12) are significantly below the site criterion for workers (1 mSv y^{-1}) and lower than the public dose constraint (0.3 mSv y^{-1}). The dose estimates indicate

that the highest doses are from C-14 exposure for both a worker and a member of the public. The calculated peak dose to a child member of the public using the radionuclide fingerprint currently disposed at the ENRMF is about 3 µSv y^{-1}.

293. An assessment also considered exposures that could occur from landfill gas collected after site capping that is burnt with exhaust gases released from a stack. Radon would decay during migration to the collection points. The dose from this pathway was modelled using PC Cream and site weather data, and was less than 0.01 µSv y^{-1} for H-3 and about 3 µSv y^{-1} for C-14.

6.1.1.6 Release to groundwater

294. The gradual deterioration of the HDPE liner is expected to occur and is considered in the groundwater risk assessments.

6.1.2 Dose assessments for the period of authorisation: unlikely to occur

295. A number of events that are unlikely to occur during the period of authorisation have been considered (Table 8). Assessments have been undertaken for spillage from waste containers and of leachate during transport to an off-site leachate treatment facility, and for a fire in a waste cell. These are all considered very unlikely events but have been considered. The gradual deterioration of the HDPE liner is expected to occur and is considered in the groundwater risk assessments.

296. The maximum doses arising from a dropped container and leachate spillage are given in Table 13 and Table 14, respectively. In the first case the doses depend on the specific activity of waste and for the leachate spillage the doses depend on the activity concentration in the leachate.

6.1.2.1 Potential impact from a dropped load

297. The dropped load assessment calculations assume that the bag is filled with a loose dry material that disperses readily, that the package fails and that the worker does not respond correctly. These are highly conservative assumptions. The assessment is described in detail in Appendix 0.

298. The dropped load assessment is one of the exposure scenarios used to determine the limiting activity concentrations in waste consignments. The activity concentration in the load is initially assumed to be 200 Bq g^{-1} and the load is 1 t. The activity concentration limits associated with the dropped load scenario can then be obtained from scaling the doses given in Table 13 to the relevant dose criteria. The potential impact from specific radionuclide concentrations in the waste is calculated by scaling the doses given in Table 13 by the proposed activity concentration limit (see Section 7.4.1.2).

Table 13 Doses from a dropped bag containing 200 Bq g^{-1}

Radionuclide	Dose due to dropped bag*		
	Worker (mSv)	Public (mSv)	Public receptor
Ac-227	$2.67\ 10^{0}$	$6.48\ 10^{-3}$	Adult
Cm-248	$1.69\ 10^{0}$	$4.11\ 10^{-3}$	Adult

Radionuclide	Dose due to dropped bag*		
	Worker (mSv)	Public (mSv)	Public receptor
Th-229	1.20 10^{0}	2.92 10^{-3}	Adult
Th-232	7.95 10^{-1}	1.93 10^{-3}	Adult
Pa-231	6.56 10^{-1}	1.60 10^{-3}	Adult
Pu-240	5.63 10^{-1}	1.37 10^{-3}	Adult
Pu-239	5.63 10^{-1}	1.37 10^{-3}	Adult
Am-242m	5.43 10^{-1}	1.32 10^{-3}	Adult
Pu-244	5.16 10^{-1}	1.25 10^{-3}	Adult
Pu-242	5.16 10^{-1}	1.25 10^{-3}	Adult
Pu-238	5.16 10^{-1}	1.25 10^{-3}	Adult
Th-230	4.69 10^{-1}	1.14 10^{-3}	Adult
Cm-245	4.64 10^{-1}	1.13 10^{-3}	Adult
Cm-246	4.59 10^{-1}	1.12 10^{-3}	Adult
Am-243	4.50 10^{-1}	1.09 10^{-3}	Adult
Am-241	4.50 10^{-1}	1.09 10^{-3}	Adult
U-232	3.78 10^{-1}	9.19 10^{-4}	Adult
Cm-243	3.25 10^{-1}	7.90 10^{-4}	Adult
Ra-228	2.80 10^{-1}	6.80 10^{-4}	Adult
Cm-244	2.67 10^{-1}	6.50 10^{-4}	Adult

* Based on 200 Bq g^{-1} and 200 MBq in package

299. The results of the dropped load dose assessment using 200 Bq g^{-1} meet the site criterion for workers for all radionuclides except Ac-227 (2.7 mSv), Cm-248 (1.7 mSv) and Th-229 (1.2 mSv); however, the proposed concentration limit in a consignment for Ac-227 and Cm-248 is 50 Bq g^{-1}, reducing these doses by a factor of 4, and there is a proposed 20 Bq g^{-1} concentration limit for Th-229 (thus dose is an order of magnitude lower). All doses to the public are below 10 µSv at 200 Bq g^{-1}, the highest dose is from Ac-227 (6 µSv), and at the proposed concentration limit of 50 Bq g^{-1} for Ac-227 this dose would be below 2 µSv.

300. The limiting activity concentrations proposed for the Port Clarence waste acceptance criteria based on worker exposure are all lower than those that can be calculated using this scenario based on public exposure. All doses to the public are below 10 µSv at the proposed consignment average activity concentrations. We also test that the maximum activity concentration per package that is part of a consignment (a factor of 1 to 5 above the consignment activity limit, depending on the radionuclide) remains appropriate i.e., the resulting dose does not exceed the dose constraint. For members of the public, this demonstrates that in the unlikely event of a spillage, doses at the consignment average activity concentration and the peak package activity concentration allowed in a consignment would not exceed the dose constraint.

301. A key measure to mitigate dropped load dispersion events is to use waste containers that withstand or substantially withstand accidental drops during handling. UN certified drums and flexible intermediate bulk containers (FIBCs) rated under existing

dangerous good transport regulations for transport of radioactive material have to withstand a drop test.

302. The Port Clarence emergency plans are found in the local rules for handling LLW. These rules detail the mitigation measures that would be taken, in the event that LLW is found to have escaped from a container, as follows:

- If a person is suspected of being contaminated, they should change and wash exposed skin, and then be checked with a contamination monitor to confirm that they are clean;
- Where possible, steps to avoid spreading contamination should be taken. The aim should be to:
  - avoid disturbing any loose contamination;
  - designate the immediate area as a Controlled Area;
  - plan the clean-up operation under the supervision of an RPS;
  - a Controlled Area entry/exit point should be set up, and ensure that persons and equipment leaving the area are checked for contamination;
  - as a precaution, persons involved in cleaning up spills should wear Respiratory Protective Equipment RPE with a minimum protection factor of 5;
  - steps to minimise airborne dust during the clean-up should be taken, for example damping down; and,
  - all spilled LLW should be placed into a suitable disposal container, and then disposed of in accordance with normal procedures.
- The area of the spill should be monitored after cleaning to ensure that no residual contamination exists. If the area remains contaminated, the Controlled Area should remain and the RPA should be consulted. If the area is clean, the Controlled Area should be de-designated.

303. This scenario has not been used to constrain the radiological capacity because it has a low probability of occurrence and is independent of the total tonnage and total activity received at Port Clarence.

304. This scenario is one of the scenarios used to determine the proposed radionuclide activity concentration limits for packaged wastes and for loose tipped wastes (see Section 7.4.1.2 for further details).

6.1.2.2 Worker exposure through a wound

305. Radionuclides can enter the body via wounds and absorption through intact skin. This is not a reasonably foreseeable scenario under normal circumstances. However, it is a possible accident scenario.

306. Material likely to be entering a wound would be dust or grit, which are not soluble. As such, using the NCRP ‘fragment’ category dose coefficient is the most realistic. The

highest doses result from Pu-239, Pu-240, Th-232, Pu-238 and Th-230. For all radionuclides for which data is available, doses when using the fragment coefficient are less than 1 mSv even if the activity concentration is the maximum proposed for a package within a consignment. Details of the calculations are given in Appendix E.3.9.

6.1.2.3 Potential impact from leachate spillage

307. It is expected that a spillage of landfill leachate will be subject to mitigation measures based on a detailed assessment of any ground contamination. Doses to site workers would be kept within site constraints. However, leachate that enters water resources would become diluted and effective mitigation measures would be more difficult to achieve. The assessment of leachate spillage therefore focusses on pathways related to the use of water resources (drinking, irrigation, livestock and angling).

308. For this assessment, it is assumed that a tanker load of leachate enters a small reservoir that is used for drinking water, irrigation and fishing. The leachate activity concentration used in the calculations is the maximum observed during the period of authorisation based on output from the GoldSim model. This is a very conservative set of assumptions. Details of the calculations are given in Appendix E.3.10.

Table 14 Doses from a leachate spillage

Radionuclide	Maximum Inventory	Dose due to leachate spillage arising from disposal of the maximum inventory	
		Dose to a farming family ($\mu Sv\ y^{-1}$)	Public receptor
I-129	$4.39\ 10^{7}$	$4.83\ 10^{1}$	Infant
Se-79	$4.39\ 10^{8}$	$1.62\ 10^{1}$	Infant
Po-210	$4.39\ 10^{8}$	$1.54\ 10^{1}$	Infant
Ba-133	$2.12\ 10^{8}$	$8.84\ 10^{0}$	Child
Cs-134	$1.10\ 10^{9}$	$3.89\ 10^{0}$	Infant
Ca-41	$1.05\ 10^{9}$	$3.34\ 10^{0}$	Child
Zn-65	$1.10\ 10^{9}$	$1.33\ 10^{0}$	Infant
Ra-228	$4.39\ 10^{7}$	$1.04\ 10^{0}$	Infant

309. The greatest radionuclide specific doses arising from disposing of the maximum inventory are presented in Table 14, this shows all potential doses greater than 1 μSv, with a maximum dose of 48 μSv for I-129. This scenario does constrain the radiological capacity of 11 radionuclides if mitigation measures are not taken. The event has a low probability of occurring and clean-up actions would be taken to mitigate the event and these would be based on the actual circumstances at the time of the spillage.

6.1.2.4 Landfill fire

310. This scenario is only relevant to the non-hazardous landfill. Details of the calculations are described in Section E.3.6.2 and the dose assuming two fires occur in a year are given in Table 84. Doses are calculated for members of the public, who are assumed to be working 250 m downwind of the fire. It is assumed that the fire burns for one hour at ground level and consumes 100 m^3 of the waste.

311. The dose rates to members of the public for radionuclides where this scenario limits the radiological capacity of the non-hazardous landfill are presented in Table 15. All doses are below 0.3 mSv when the maximum inventory is considered except for Pb-210.

Table 15 Doses from a fire in the non-hazardous landfill

Radionuclide	Maximum Inventory (MBq)	Public dose rate (mSv MBq^{-1})	Public receptor	Dose at maximum inventory (mSv)
Fe-55	1.10 10^{9}	2.88 10^{-14}	Child	3.16 10^{-5}
Zn-65	1.10 10^{9}	8.05 10^{-12}	Child	8.83 10^{-3}
Ru-106	1.10 10^{9}	1.88 10^{-10}	Adult	2.06 10^{-1}
Cd-109	1.10 10^{9}	2.88 10^{-13}	Child	3.16 10^{-4}
Sb-125	1.10 10^{9}	3.70 10^{-11}	Adult	4.06 10^{-2}
Sn-119m	1.10 10^{9}	6.38 10^{-14}	Child	7.00 10^{-5}
Sn-123	1.10 10^{9}	2.47 10^{-13}	Child	2.71 10^{-4}
Te-127m	1.10 10^{9}	2.88 10^{-11}	Child	3.16 10^{-2}
Cs-134	1.10 10^{9}	5.82 10^{-11}	Child	6.39 10^{-2}
Ce-144	1.10 10^{9}	1.95 10^{-12}	Infant	2.14 10^{-3}
Pm-147	1.10 10^{9}	1.44 10^{-13}	Child	1.58 10^{-4}
Pb-210	7.84 10^{6}	1.42 10^{-7}	Adult	1.11 10^{0}
Po-210	4.39 10^{8}	1.22 10^{-10}	Adult	5.37 10^{-2}
Ra-228	4.39 10^{7}	1.70 10^{-9}	Adult	7.45 10^{-2}
Ac-227	1.10 10^{7}	1.62 10^{-8}	Adult	1.78 10^{-1}
Th-228	4.39 10^{7}	1.24 10^{-9}	Adult	5.45 10^{-2}
Cm-242	4.39 10^{8}	1.69 10^{-10}	Child	7.41 10^{-2}
Cm-243	4.39 10^{7}	1.97 10^{-9}	Adult	8.65 10^{-2}
Cm-244	4.39 10^{7}	1.62 10^{-9}	Adult	7.12 10^{-2}

312. This scenario is used in the radiological capacity calculations for the non-hazardous landfill.

6.2 Risk guidance level after the period of authorisation {R6}

313. The NS-GRA provides guidance on the level of risk to be applied after the period of authorisation (Requirement 6):

> "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)." (UK Environment Agencies, 2009), para 6.3.10

314. Based on the recommended risk to dose conversion factor of 0.06 per Sv (HPA, 2009), and assuming that the event is certain to occur, the risk guidance level corresponds to a dose of approximately 20 µSv y^{-1}. For situations where the probability of receiving a dose is less than one, doses could be greater than 20 µSv y^{-1} while still maintaining consistency with the risk guidance level and, for situations where the probability is very much less than one, doses could be very much greater than 20 µSv y^{-1}. Where the probability is less than 1 justification for any adopted value is required.

315. The NS-GRA does not lay down an absolute requirement for the risk guidance level to be met. The value of 10^{-6} y^{-1} (per year) is consistent with HSE advice that this is "a very low level of risk" above which people may be prepared to tolerate risks in order to secure benefits and below which risks are broadly accepted (HSE, 2001). The "risk

guidance level" does not apply to human intrusion scenarios as these have a specific dose guidance level (see Section 6.3).

316. This ESC provides a quantitative assessment of the potential future effects of the contamination that can be compared with the risk criterion, using systematically developed and justified, site-specific mathematical models. A cautious best estimate approach is adopted when selecting parameter values and the models themselves are cautious.

317. The results of the assessments relating to longer term impacts, after the period of authorisation (post-closure), are described in Appendix E, Section E.4. The radiological assessment has considered a range of potential scenarios and these are summarised in Table 16. In cases where a scenario has not been explicitly assessed, because it will not or is very unlikely to occur at Port Clarence, the reasons for this are discussed. The scenarios discussed below are divided into two broad categories – those that are likely to occur and those that are unlikely to occur (i.e. scenarios which have a low likelihood of occurrence). The dose assessments considering exposure of members of the public, site residents and farming families after the period of authorisation all include adult, child and infant age groups.

Table 16 Summary of radiological assessment scenarios considered after the period of authorisation (excluding intrusion scenarios and non-human biota)

Scenario	Exposed group
After the Period of Authorisation – likely to occur	
Recreational user	Member of public
Groundwater release to estuary	Member of public
Site erosion	Member of public
Inundation from sea	Member of public
After the Period of Authorisation – unlikely to occur	
Groundwater abstraction	Farming family
Bathtubbing	Farming family
Gas release and external	Site resident
Site re-engineering*	Worker
Other unlikely events*	

* Not quantitatively assessed.

318. The detailed results of the assessments for the post-closure period are presented in Appendix E.4. The effects of very long-term climate change on-site erosion and inundation from the sea are considered in the natural evolution of the site (see Section 2.10). Future glaciation would have similar or lesser effects than the "residential intrusion scenario" considered in Appendix E.5.8. The list in Table 16 includes a category of "Other unlikely events" which covers seismic events, transport accidents and a criticality event. The reasons why these events and site re-engineering have not been assessed in detail are given in Appendix E.4.

6.2.1 Dose assessments after the period of authorisation – expected to occur

6.2.1.1 Impact on recreational users due to gas releases and external radiation

319. The intended end use of the site includes woodland, scrub and grassland with paths. An assessment is therefore made of the doses to a member of the public who spends time walking over the restored site for 2 h d^{-1} (hours per day) and is exposed to gases released from the waste and receives external exposure from buried waste packages.

The results are calculated at the time of closure and then 60 years later (the assumed period of authorisation in the aftercare or post-closure period). The assessment includes the effects of radioactive decay and ingrowth upon the calculated doses. Doses from radon gas are shown under Ra-226. Details of the calculations are described in Section E.4.3.

320. Table 17 presents the radionuclide specific doses arising from disposing of the maximum inventory where the calculated dose is greater than 10^{-19} µSv y^{-1}. The highest dose is from C-14 at closure and is 20 µSv y^{-1} because this scenario limits the radiological capacity of the site for C-14. This scenario also limits the radiological capacity of Zr-93, Ni-63, Nb-93m and Ni-59 but the doses shown below for these radionuclides are lower than 20 µSv y^{-1} because the maximum inventory is lower than the radiological capacity. The peak dose will always be lower than 20 µSv y^{-1} due to application of the sum of fractions approach. The assumptions concerning gas release in this period are very conservative and this results in overestimating gas doses to recreational users of the site.

Table 17 Doses to recreational users of the restored site at the time of closure and 60 years after closure

Radionuclide	Maximum Inventory (MBq)	At closure		60 years after closure	
		Dose per unit disposal (µSv y^{-1} MBq^{-1})	Dose at maximum inventory (µSv y^{-1})	Dose per unit disposal (µSv y^{-1} MBq^{-1})	Dose at maximum inventory (µSv y^{-1})
C-14	$1.19\ 10^{8}$	$1.69\ 10^{-7}$	$2.00\ 10^{1}$	$3.35\ 10^{-8}$	$3.97\ 10^{0}$
Zr-93	$1.10\ 10^{9}$	$6.13\ 10^{-9}$	$6.72\ 10^{0}$	$6.13\ 10^{-9}$	$6.72\ 10^{0}$
Mo-93	$5.95\ 10^{7}$	$5.37\ 10^{-9}$	$3.20\ 10^{-1}$	$5.32\ 10^{-9}$	$3.17\ 10^{-1}$
H-3	$1.88\ 10^{8}$	$5.23\ 10^{-9}$	$9.83\ 10^{-1}$	$7.25\ 10^{-11}$	$1.36\ 10^{-2}$
Ni-63	$1.10\ 10^{9}$	$5.18\ 10^{-9}$	$5.68\ 10^{0}$	$3.42\ 10^{-9}$	$3.75\ 10^{0}$
Nb-93m	$1.10\ 10^{9}$	$9.60\ 10^{-10}$	$1.05\ 10^{0}$	$7.29\ 10^{-11}$	$8.00\ 10^{-2}$
Ni-59	$1.10\ 10^{9}$	$5.82\ 10^{-10}$	$6.38\ 10^{-1}$	$5.81\ 10^{-10}$	$6.38\ 10^{-1}$
Ra-226*	$1.39\ 10^{6}$	$2.14\ 10^{-10}$	$2.97\ 10^{-4}$	$2.08\ 10^{-10}$	$2.89\ 10^{-4}$
U-232	$1.10\ 10^{7}$	$7.84\ 10^{-15}$	$8.60\ 10^{-8}$	$4.29\ 10^{-15}$	$4.70\ 10^{-8}$
Th-232	$2.16\ 10^{6}$	$4.91\ 10^{-15}$	$1.06\ 10^{-8}$	$4.91\ 10^{-15}$	$1.06\ 10^{-8}$
Ra-228	$4.39\ 10^{7}$	$4.91\ 10^{-15}$	$2.16\ 10^{-7}$	$3.55\ 10^{-18}$	$1.56\ 10^{-10}$
Fe-55	$1.10\ 10^{9}$	$4.46\ 10^{-15}$	$4.89\ 10^{-6}$	$1.12\ 10^{-21}$	$1.23\ 10^{-12}$
Th-228	$4.39\ 10^{7}$	$3.15\ 10^{-15}$	$1.38\ 10^{-7}$	$1.13\ 10^{-24}$	$4.95\ 10^{-17}$
Co-60	$4.39\ 10^{7}$	$1.02\ 10^{-16}$	$4.47\ 10^{-9}$	$3.81\ 10^{-20}$	$1.67\ 10^{-12}$
Th-229	$4.27\ 10^{6}$	$9.80\ 10^{-18}$	$4.18\ 10^{-11}$	$9.74\ 10^{-18}$	$4.16\ 10^{-11}$
Ag-110m	$4.39\ 10^{8}$	$6.46\ 10^{-18}$	$2.83\ 10^{-9}$	$2.53\ 10^{-44}$	$1.11\ 10^{-35}$
Zn-65	$1.10\ 10^{9}$	$6.40\ 10^{-18}$	$7.02\ 10^{-9}$	$5.77\ 10^{-45}$	$6.33\ 10^{-36}$
Eu-154	$1.10\ 10^{9}$	$5.90\ 10^{-18}$	$6.47\ 10^{-9}$	$4.66\ 10^{-20}$	$5.12\ 10^{-11}$
Eu-152	$4.39\ 10^{8}$	$4.27\ 10^{-18}$	$1.87\ 10^{-9}$	$1.98\ 10^{-19}$	$8.68\ 10^{-11}$
Nb-94	$2.19\ 10^{7}$	$9.27\ 10^{-19}$	$2.03\ 10^{-11}$	$9.25\ 10^{-19}$	$2.03\ 10^{-11}$
Mn-54	$1.10\ 10^{9}$	$8.99\ 10^{-19}$	$9.86\ 10^{-10}$	$6.65\ 10^{-40}$	$7.30\ 10^{-31}$
Cs-134	$1.10\ 10^{9}$	$3.73\ 10^{-19}$	$4.09\ 10^{-10}$	$6.68\ 10^{-28}$	$7.33\ 10^{-19}$
Sn-126	$1.10\ 10^{7}$	$2.16\ 10^{-19}$	$2.37\ 10^{-12}$	$2.16\ 10^{-19}$	$2.37\ 10^{-12}$

* The gas dose shown for Ra-226 is from the release of Rn-222. Ra-226 is disposed with other LLW.

6.2.1.2 Impact due to the erosion of landfill

321. The landfill site has been reclaimed from salt marsh and mudflats over many decades through the deposition of wastes, clinker and slag deposits from industries including

gas works, lime works, chlorine works, soda works, blast furnaces and salt evaporating pans (Augean, 2014). The landfill restoration profile rises above the floodplain.

322. It is possible that local or national policies maintaining shipping access and managing flood defences could change and impact the future evolution of the estuary. If dredging activities stopped there would be accumulation of sediments and further development of salt marshes and mudflats. The Bangor report noted that hydrodynamic conditions at the site are unlikely to exceed the force required to erode or undermine the landfill cell structure (Bangor University, 2023), the sediment deposits and sea level rise would therefore impact flooding rather than erosion at the Port Clarence site.

323. Although it is considered unlikely to occur in the near future, erosion of the landfill has been assessed using cautious assumptions. Access to the site on a regular basis may not be possible once erosion starts due to the inundation of low-lying land that surrounds the site. However, it is assumed that erosion starts 60 years after closure and scenarios consider both recreational use of the site and releases into the sea.

324. The intended end use of the site includes public access to scrub and grassland with paths. An assessment is therefore made of the doses to a member of the public who spends time walking over the restored site and it is assumed that this continues once erosion starts to impact the site (see Appendix E.4.7). We have partitioned time spent close to the eroding materials by assuming a daily walk of 1 hour, passing the exposed face once, assuming a face length of 1 km and walking at 5 km h^{-1}. The walker inadvertently ingests soil, inhales dust and receives an external exposure from exposed waste.

325. Table 18 presents the dose rate per MBq (µSv y^{-1} MBq^{-1}) calculated from the assessment at two different times of erosion (60 and 20,000 years after site closure) for 13 radionuclides. The calculation was repeated at 20,000 years to consider the potential impact of in-growth and the minimum radiological capacities of the two runs is adopted. This scenario limits disposal of these radionuclides and doses arising from disposing of the radiological capacity are, therefore, 20 µSv y^{-1}. The maximum inventory for 12 of these radionuclides are lower than the radiological capacity and hence the potential doses from the maximum disposals are all lower than 20 µSv y^{-1}, except in the case of Th-230.

Table 18 Radiological capacity limited by doses to a walker due to erosion of landfill

Radionuclide	Maximum Inventory (MBq)	Dose per unit disposal (µSv y^{-1} MBq^{-1})	Dose at maximum inventory (µSv y^{-1})
Se-79	$4.39\ 10^{8}$	$2.33\ 10^{-8}$	10.2
Sm-151	$1.10\ 10^{9}$	$3.39\ 10^{-10}$	0.4
Ra-228	$4.39\ 10^{7}$	$4.17\ 10^{-9}$	0.2
Ac-227	$1.10\ 10^{7}$	$6.53\ 10^{-7}$	7.2
Th-230	$2.03\ 10^{6}$	$9.86\ 10^{-6}$	20.0
U-232	$1.10\ 10^{7}$	$9.44\ 10^{-7}$	10.4
Pu-238	$4.39\ 10^{7}$	$2.68\ 10^{-7}$	11.7
Pu-241	$1.10\ 10^{9}$	$1.21\ 10^{-8}$	13.2
Am-241	$2.19\ 10^{7}$	$3.63\ 10^{-7}$	8.0

Radionuclide	Maximum Inventory (MBq)	Dose per unit disposal (μSv y^{-1} MBq^{-1})	Dose at maximum inventory (μSv y^{-1})
Am-242m	2.19 10^{7}	4.83 10^{-7}	10.6
Cm-242	4.39 10^{8}	1.37 10^{-9}	0.6
Cm-243	4.39 10^{7}	8.48 10^{-8}	3.7
Cm-244	4.39 10^{7}	3.20 10^{-8}	1.4

326. The assessment of impacts from erosion of the landfill to sea uses PC-CREAM 08 to derive the dose per unit activity following radionuclide release into the sea. The dose per unit release (DPUR) has been calculated using PC-CREAM 08 with the default habit data. In these scoping calculations, it is cautiously assumed that all radionuclides within the landfill mass are completely soluble. The erosion rate (0.21 m y^{-1}) used is based on the analysis undertaken by Bangor University, and it is assumed to apply to the cross section of the landfill (about 900 m) to derive an annual average loss rate for LLW to the sea.

327. It is assumed that erosion will occur from the seaward side of the landfill and that contamination will be leached from the landfill materials as they are eroded. It is also assumed that the leached contamination will predominantly enter the sea rather than a confined estuary.

328. The assessment considered a constant discharge over a period of 1, 5, 50, 500, 2000 and 4286 years. The latter is the maximum period over which the site would erode at the erosion rate adopted. The approach does not allow for radioactive decay of the source over the release period and, therefore, will result in overestimates of the DPUR for radionuclides with a shorter half-life than the release period. We have cautiously selected the highest DPUR from the six release periods for use in the assessment.

329. The assessment considers the consumption of crustaceans, fish, molluscs and seaweed, external irradiation from beaches and fishing equipment and sea spray inhalation. The results for this scenario are presented in Table 19 for the 10 radionuclides giving the highest dose rates (μSv y^{-1} MBq^{-1}). Table 19 also gives the dose based on disposing of the maximum inventory (μSv y^{-1}).

Table 19 Peak doses due to erosion of landfill to sea

Radionuclide	Maximum Inventory (MBq)	Dose per unit disposal ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose at maximum inventory ($\mu Sv\ y^{-1}$)
Ra-226	$1.39\ 10^{6}$	$1.44\ 10^{-5}$	20.0
Pb-210	$7.84\ 10^{6}$	$2.55\ 10^{-6}$	20.0
Nb-94	$2.19\ 10^{7}$	$2.55\ 10^{-7}$	5.6
Se-79	$4.39\ 10^{8}$	$9.42\ 10^{-9}$	4.1
Cm-246	$4.39\ 10^{7}$	$6.45\ 10^{-8}$	2.8
Pu-238	$4.39\ 10^{7}$	$4.71\ 10^{-8}$	2.1
Sn-126	$1.10\ 10^{7}$	$1.46\ 10^{-7}$	1.6
Th-232	$2.16\ 10^{6}$	$5.80\ 10^{-7}$	1.3
Pu-241	$1.10\ 10^{9}$	$1.38\ 10^{-9}$	1.5
Am-242m	$2.19\ 10^{7}$	$6.16\ 10^{-8}$	1.4

330. Erosion to sea would restrict the radiological disposal capacity at Port Clarence for five radionuclides (Nb-94, Sn-126, Eu-152, Pb-210 and Ra-226). The sensitivity of the radiological capacity to erosion rate is considered as a sensitivity (see Appendix E.8.1.3). Increasing the rates of erosion to the global maximum for similar sites (0.8 m y^{-1}) reduces the capacity of these five radionuclides, and this scenario becomes limiting for Se-79, Ni-59 and Eu-154.

6.2.1.3 Impact due to groundwater and leachate entering the estuary

331. The potential impact from flow of radiologically contaminated water into the Tees Estuary has been considered. Radiologically contaminated water could enter the estuary after the period of authorisation via groundwater or as overland flow (if bathtubbing occurs and more water overtops the landfill than can percolate through subsoil).

332. The assessment of impacts uses output from the GoldSim model to derive DPURs as a result of release to the estuary, as discussed in Appendix E.4.5.

333. PC-CREAM 08 was used to derive a dose from a release of 1 Bq/y into the estuary and subsequently into the sea. The doses were calculated using PC-CREAM 08 default habit data. The doses were scaled to reflect a unit release from the landfill to derive DPURs.

334. The discharge rate for each radionuclide was taken to be the combined peak release rates to estuary via groundwater and overland flow as a result of a unit disposal in the landfill. This is cautious as the peak releases via groundwater and overland do not necessarily occur at the same time.

335. The assessment considers the consumption of crustaceans, fish, molluscs and seaweed, external irradiation from beaches and fishing equipment and sea spray inhalation. The results for this scenario are presented in Table 20 for the 10 radionuclides giving the highest dose rates ($\mu Sv\ y^{-1}\ MBq^{-1}$). Table 20 also gives the dose based on disposing of the maximum inventory ($\mu Sv\ y^{-1}$).

Table 20 Peak doses due to release of contaminated water to the estuary

Radionuclide	Maximum Inventory (MBq)	Dose per unit disposal (μSv y^{-1} MBq^{-1})	Age group	Dose at maximum inventory (μSv y^{-1})
C-14	1.19 10^{8}	6.60 10^{-9}	Adult	7.83 10^{-1}
Pb-210	7.84 10^{6}	6.74 10^{-8}	Adult	5.28 10^{-1}
I-129	4.39 10^{7}	7.25 10^{-9}	Adult	3.18 10^{-1}
Ba-133	2.12 10^{8}	3.05 10^{-10}	Adult	6.47 10^{-2}
Nb-94	2.19 10^{7}	1.72 10^{-9}	Adult	3.78 10^{-2}
Mo-93	5.95 10^{7}	4.20 10^{-10}	Adult	2.50 10^{-2}
Ag-108m	2.19 10^{7}	8.15 10^{-10}	Adult	1.79 10^{-2}
Ni-59	1.10 10^{9}	1.50 10^{-11}	Adult	1.64 10^{-2}
Pu-238	4.39 10^{7}	3.07 10^{-10}	Adult	1.35 10^{-2}
Am-242m	2.19 10^{7}	3.68 10^{-10}	Adult	8.08 10^{-3}

6.2.1.4 Impact due to inundation from the sea

336. The effects of very long-term climate change are assessed due to the location of the site close to the Tees Estuary. Consideration has also been given to the timescale over which sea level rise could occur (see Section 2.10) leading to the potential flooding of the site. With sea level rise, the area surrounding the landfill is likely, in due course, to be subject to periodic flooding. At some stage, the peak flood height will begin to overlap the basal liner (the base of the engineered barrier is at 5.4 m AOD and the basin side wall rises above this). Water may enter the base of the landfill through the same channels that leachate is assumed to seep out of the landfill.

337. Flooding is included in the GoldSim model as a one-off event that does not influence the contaminant or water balance of the other pathways. Flooding is assumed to occur to a height of 1 m above the edge of the low-permeability basin (the base of the engineered liner varies from 5.4 to 8.5 m AOD (see Figure 10), requiring a minimum flood depth of about 9 m AOD). This leads to 1 m head of excess leachate that is generated in and can then seep out of the landfill. It is then absorbed by the surrounding soil, leaving behind contaminating radionuclides. The concentration of these radionuclides in the soil is then used for dose assessment calculations.

338. The activity concentration of each radionuclide is taken as its maximum activity concentration over the period being assessed. Two periods are considered: between the end of the Period of Authorisation and 100,000 years after closure of the facility; and between 140 y after the end of the Period of Authorisation (200 y after closure) and 100,000 years after closure of the facility.

339. It is unlikely that the site or its immediate surroundings will be developed for housing, especially if the area is subject to flooding. Nevertheless, a scenario is considered in which flooding is assumed to contaminate soil below the garden of a house that has been built adjacent to the landfill. Vegetables are assumed to be grown in the garden. This is the approach adopted for the ENRMF Bathtubbing scenario (Eden NE, 2023).

340. The results for both inundation timeframes are presented in Table 21 for the radionuclides that limit the radiological capacity of the site, and give the associated doses (µSv y^{-1}) based on disposing of the maximum inventory.

Table 21 Peak doses due to an inundation event after the period of authorisation.

Radionuclide	Maximum Inventory (MBq)	Resident (60+ years)	
		Dose per unit disposal (µSv y^{-1} MBq^{-1})	Dose at maximum inventory (µSv y^{-1})
H-3	$1.88\ 10^{8}$	$1.06\ 10^{-7}$	20
Cl-36	$5.08\ 10^{5}$	$3.94\ 10^{-5}$	20
Tc-99	$1.73\ 10^{7}$	$1.15\ 10^{-6}$	20
Ca-41	$1.05\ 10^{9}$	$1.25\ 10^{-9}$	$1.31\ 10^{0}$
I-129	$4.39\ 10^{7}$	$1.05\ 10^{-8}$	$4.62\ 10^{-1}$
Mo-93	$5.95\ 10^{7}$	$3.70\ 10^{-9}$	$2.20\ 10^{-1}$
U-232	$1.10\ 10^{7}$	$5.65\ 10^{-9}$	$6.20\ 10^{-2}$
Np-237	$7.47\ 10^{4}$	$4.08\ 10^{-7}$	$3.05\ 10^{-2}$
Pu-238	$4.39\ 10^{7}$	$2.44\ 10^{-10}$	$1.07\ 10^{-2}$
Am-242m	$2.19\ 10^{7}$	$2.27\ 10^{-10}$	$4.98\ 10^{-3}$
Radionuclide	Maximum Inventory (MBq)	Resident (200+ years)	
		Dose per unit disposal (µSv y^{-1} MBq^{-1})	Dose at maximum inventory (µSv y^{-1})
H-3	$1.88\ 10^{8}$	$2.28\ 10^{-12}$	$4.28\ 10^{-4}$
Cl-36	$5.08\ 10^{5}$	$1.63\ 10^{-6}$	$8.26\ 10^{-1}$
Tc-99	$1.73\ 10^{7}$	$9.32\ 10^{-7}$	$1.61\ 10^{1}$
Ca-41	$1.05\ 10^{9}$	$1.31\ 10^{-10}$	$1.38\ 10^{-1}$
Np-237	$7.47\ 10^{4}$	$4.06\ 10^{-7}$	$1.78\ 10^{1}$
U-232	$1.10\ 10^{7}$	$1.38\ 10^{-9}$	$8.22\ 10^{-2}$
U-236	$4.24\ 10^{6}$	$2.08\ 10^{-9}$	$2.28\ 10^{-2}$
U-238	$4.17\ 10^{6}$	$1.99\ 10^{-9}$	$1.49\ 10^{-4}$
Am-242m	$2.19\ 10^{7}$	$1.90\ 10^{-10}$	$8.32\ 10^{-3}$
Pu-238	$4.39\ 10^{7}$	$8.09\ 10^{-11}$	$1.78\ 10^{-3}$

341. Inundation resulting in contamination of soils cultivated by a household adjacent to the site would restrict the disposal radiological capacity of Port Clarence for three radionuclides (H-3, Cl-36, Tc-99) if the flooding event occurred immediately after the period of authorisation. At later times the scenario does not limit radiological capacity.

6.2.2 After the Period of Authorisation – unlikely to occur

342. The following scenarios (water abstraction, Bathtubbing, gas release, site engineering) are unlikely to occur. Other unlikely events are addressed in Appendix E.3.1.

6.2.2.1 Water abstraction

343. The abstraction of potable water is not known to occur from the aquifer beneath the Port Clarence site. The groundwater is not potable due to saline intrusion and would also not be suitable for irrigation or livestock. This scenario is therefore considered as a 'what if' scenario and is not used to limit the radiological capacity because the water cannot be used for irrigation or animal consumption.

344. The groundwater risk assessment takes into account gradual deterioration of the HDPE waste cell liner (see Appendix E.4.4). This assumes a doubling time every 100 years for the HDPE component of the liner defects that allow a flux of water from the waste cells to the unsaturated zone beneath the waste cells and subsequently to the groundwater.

345. Water abstraction from a well 100 m from the boundary of the site was modelled using GoldSim and annual doses were calculated from drinking contaminated water and from the use of water for irrigation of crops and livestock. The activity concentration at the well varies over time, generally rising to a peak and then subsequently reducing. The peak activity concentration was used to derive the annual dose and hence these values are peak annual doses occurring at different times post closure.

346. The results for selected radionuclides are given in Table 22. The complete set of results is presented in Appendix E, Table 132. The peak dose will always be lower than this due to application of the sum of fractions approach.

Table 22 Peak doses due to groundwater abstraction after the period of authorisation

Radionuclide	Maximum Inventory (MBq)	Drinking water pathway dose per unit disposal (µSv y^{-1} MBq^{-1})	Irrigation pathway dose per unit disposal (µSv y^{-1} MBq^{-1})	Total dose per unit disposal (µSv y^{-1} MBq^{-1})	Dose at maximum inventory (µSv y^{-1})	Age group
Cl-36	$5.08\ 10^{5}$	$4.59\ 10^{-6}$	$1.29\ 10^{-5}$	$1.75\ 10^{-5}$	$8.88\ 10^{0}$	Infant
I-129	$4.39\ 10^{7}$	$8.99\ 10^{-9}$	$2.78\ 10^{-8}$	$3.68\ 10^{-8}$	$1.62\ 10^{0}$	Child
Tc-99	$1.73\ 10^{7}$	$3.45\ 10^{-8}$	$7.38\ 10^{-8}$	$1.08\ 10^{-7}$	$1.88\ 10^{0}$	Infant
Ca-41	$1.05\ 10^{9}$	$1.40\ 10^{-11}$	$5.56\ 10^{-11}$	$6.96\ 10^{-11}$	$7.31\ 10^{-2}$	Child
Np-237	$7.47\ 10^{4}$	$2.75\ 10^{-11}$	$3.40\ 10^{-9}$	$3.42\ 10^{-9}$	$2.56\ 10^{-4}$	Adult
U-235	$2.09\ 10^{5}$	0	$9.61\ 10^{-12}$	$9.61\ 10^{-12}$	$2.01\ 10^{-6}$	Adult
U-238	$4.17\ 10^{6}$	0	$4.51\ 10^{-13}$	$4.51\ 10^{-13}$	$1.88\ 10^{-6}$	Adult
U-236	$4.24\ 10^{6}$	0	$3.32\ 10^{-13}$	$3.32\ 10^{-13}$	$1.41\ 10^{-6}$	Adult
U-233	$2.52\ 10^{5}$	0	$5.06\ 10^{-12}$	$5.06\ 10^{-12}$	$1.28\ 10^{-6}$	Adult

347. The GoldSim calculations are evaluated to 100,000 years. The variability in time to peak dose means that the sum of fractions approach will be overly cautious for this scenario.

6.2.2.2 Bathtubbing

348. Calculations to show the impact of bathtubbing have been undertaken (Appendix E, Section E.4.5). Bathtubbing involves degradation of the cap so that the infiltration of water into the landfill is greater than the percolation through the liner, leading to saturation of a waste cell and overtopping of the side liner. The design of the waste cells at Port Clarence is shown in Figure 10. However, the cap design includes a geosynthetic clay layer and restoration soil, materials that will not degrade. The restoration programme includes areas of open water adjacent to the landfill area with aquatic marginal vegetation, scrub, wet meadow and ruderal grassland with small hollows, banks and ridges suitable for nature conservation use.

349. The Goldsim model was adapted to include a pathway for the flow of water overtopping the side liner, either downwards to the aquifer or overland to the nearest surface water body. It is unlikely that the site or its immediate surroundings will be developed for

housing. Nevertheless a scenario is considered in which the overtopping is assumed to contaminate soil below the garden of a house that has been built adjacent to the landfill. Vegetables are assumed to be grown in the garden. This is the approach adopted for the ENRMF (Eden NE, 2023).

350. As leachate level monitoring will continue following the completion of filling, capping and placement of the restoration materials, leachate levels will be controlled as necessary so that compliance limits are not exceeded. The control of leachate levels at the site will continue until it is considered by the Environment Agency that the landfill is unlikely to present a significant risk to the environment if leachate management ceases. This means that bathtubbing will not occur during the period of authorisation. The Environmental Permit for landfill sites cannot be surrendered until the Environment Agency considers that the site no longer presents a potentially significant risk to the environment and human health including groundwater. On this basis, the potential for overtopping of leachate at a stage when the leachate could have an unacceptable impact on the environment is very unlikely to occur. Accordingly, the bathtubbing event is considered very unlikely to occur in practice. Nevertheless, the impact of bathtubbing is considered at a time after closure determined by GoldSim.

351. Two scenarios are considered. The first assumes that an area adjacent to the site is subject to leachate released due to bathtubbing and all activity is assumed to accumulate in the affected area (500,000 m^2, see Figure 19). Seepage will occur at the top of the side liner and this will be at least 1 m below restored ground levels. It is also assumed that a proportion of activity introduced at depth (>1 m) reaches the cultivated surface soils (Shaw, et al., 2004). The basis for this assumption and derivation of values is detailed in Appendix E.4.4.9. The remainder is assumed to drain to sub-strata based on the drainage observed in the surrounding area. No account is taken of potential dilution by rain falling in the surrounding area and draining to the same point. The doses are calculated for a household growing food on the contaminated land.

352. The results for this first bathtubbing scenario are presented in Table 23 for the radionuclides giving the highest doses (µSv y^{-1}) based on disposing of the maximum inventory.

353. The second scenario modelled transfer of overtopping leachate to the nearest surface water body on the site and considered exposure of a fisherman through fish consumption. Although this pathway was included in the model, results showed that no activity reached a nearby pond and hence there was no exposure through this pathway due to the drainage properties of the soils surrounding the landfill. Scoping calculations were therefore undertaken on a what-if basis. This used the leachate spillage assumptions and cautiously assumed that 10% of the seepage outflow entered a hypothetical water body. The doses corresponding to the radionuclides limited by bathtubbing are shown in Table 23. Whilst the doses for a 97.5th percentile fish consumer shown below are low, the peak dose was 5.7 µSv y^{-1} from Ca-41 at the maximum inventory (see Appendix E.4.4.10). However, because Goldsim modelling shows that there is unlikely to be transfer to a local waterbody (other than to the estuary), the fish consumption scenario is therefore considered as a ‘what if’ scenario and is not used to limit the radiological capacity.

Table 23 Peak doses due to bathtubbing after the period of authorisation.

Radionuclide	Maximum Inventory (MBq)	Resident			Fish consumer ‘what-if” case	
		Dose per unit disposal (µSv y^{-1} MBq^{-1})	Dose at maximum inventory (µSv y^{-1})	Age group	Dose per unit disposal (µSv y^{-1} MBq^{-1})	Dose at maximum inventory (µSv y^{-1})
Ca-41	1.05 10^{9}	1.91 10^{-8}	20.0	Infant	5.45 10^{-9}	5.72 10^{0}
Mo-93	5.95 10^{7}	3.36 10^{-7}	20.0	Infant	4.32 10^{-11}	2.57 10^{-3}
I-129	4.39 10^{7}	2.14 10^{-7}	9.4	Adult	1.09 10^{-9}	4.79 10^{-2}
Sm-147	3.83 10^{7}	5.22 10^{-7}	20.0	Adult	1.71 10^{-11}	6.57 10^{-4}
Th-229	4.27 10^{6}	4.68 10^{-6}	20.0	Adult	2.48 10^{-12}	1.06 10^{-5}
Th-232	2.16 10^{6}	9.24 10^{-6}	20.0	Adult	6.68 10^{-10}	1.45 10^{-3}
Pa-231	7.73 10^{5}	2.59 10^{-5}	20.0	Adult	2.03 10^{-10}	1.57 10^{-4}
U-233	2.52 10^{5}	7.93 10^{-5}	20.0	Adult	2.32 10^{-10}	5.84 10^{-5}
U-234	1.55 10^{6}	1.29 10^{-5}	20.0	Adult	2.77 10^{-11}	4.29 10^{-5}
U-235	2.09 10^{5}	9.58 10^{-5}	20.0	Adult	2.35 10^{-12}	4.91 10^{-7}
U-236	4.24 10^{6}	4.71 10^{-6}	20.0	Adult	6.37 10^{-12}	2.70 10^{-5}
U-238	4.17 10^{6}	4.80 10^{-6}	20.0	Adult	3.13 10^{-12}	1.31 10^{-5}
Np-237	7.47 10^{4}	2.68 10^{-4}	20.0	Adult	2.45 10^{-12}	1.83 10^{-7}
Pu-239	3.89 10^{6}	5.13 10^{-6}	20.0	Adult	1.90 10^{-14}	7.40 10^{-8}
Pu-240	5.98 10^{6}	3.34 10^{-6}	20.0	Adult	2.84 10^{-14}	1.70 10^{-7}
Pu-242	3.41 10^{6}	5.87 10^{-6}	20.0	Adult	1.27 10^{-10}	4.34 10^{-4}
Pu-244	1.80 10^{6}	1.11 10^{-5}	20.0	Adult	1.83 10^{-12}	3.29 10^{-6}
Am-243	7.73 10^{6}	2.59 10^{-6}	20.0	Adult	1.49 10^{-10}	1.15 10^{-3}
Cm-245	1.45 10^{7}	1.38 10^{-6}	20.0	Adult	8.65 10^{-10}	1.25 10^{-2}
Cm-246	4.39 10^{7}	4.19 10^{-7}	18.4	Adult	1.12 10^{-9}	4.91 10^{-2}
Cm-248	1.25 10^{6}	1.60 10^{-5}	20.0	Adult	1.34 10^{-10}	1.67 10^{-4}

354. Bathtubbing resulting in contamination of soils cultivated by a household adjacent to the site would restrict the disposal radiological capacity of Port Clarence for these 21 radionuclides.

6.2.2.3 Gas release

355. The development of the site for residential purposes is very unlikely due to the slope of the restored site, its location in an industrial area, a risk of potential flooding of the surrounding low-lying areas alongside potential changes due to sea level rise and growing nature conservation interests. Hence, dose to residential users of site from gas release is not considered further. The impact of a residential development on the site is considered in the section on human intrusion (Section 6.3).

6.2.2.4 Site re-engineering

356. A site re-engineering/remediation scenario was included in the SNIFFER methodology to cover the situation where a site operator has no records of radioactive waste disposals or their location, possibly because they were disposed of under earlier VLLW authorisations, and excavates waste during final site restoration works. In the case of Port Clarence records would be maintained as a condition of the Permit. Any remediation work would be done with the knowledge that there was radioactive material on the site and it can be assumed that appropriate precautions against exposure would be adopted. Site rules also prevent any disposal of radioactive waste within 2 m of basal liners and within 1 m of the top of the cell. Hence this scenario is not considered in the ESC.

6.3 Human intrusion after the period of authorisation {R7}

357. The NS-GRA provides dose guidance levels to be used for assessments of human intrusion after the period of authorisation (Requirement 7):

> "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 its 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/year to around 20 mSv/year. 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)." (UK Environment Agencies, 2009), para 6.3.36

358. The NS-GRA defines human intrusion as any human action that accesses the waste or that damages a barrier providing an environmental safety function after the period of authorisation.

359. The NS-GRA (paragraph 6.3.41) requires assessment of future human intrusion into the facility, assuming that either the intruder does not have prior knowledge of the disposal facility or that the intruder has knowledge of the existence of underground workings but does not understand what they contain. It is not necessary to assess intrusions undertaken with full knowledge of the existence, location, nature and contents of the disposal facility; the environment agencies take the view that a society that preserves full knowledge of the disposal facility will be capable of exercising proper control over any intrusions into the disposal system. Therefore, the human actions that must be assessed are deliberate acts, for example, to excavate a void or recover materials, but where the intruder is uninformed or oblivious to the radiological hazard. The standard against which human intrusion into a near-surface disposal facility should be assessed is specified in terms of dose, not risk, because the environment agencies believe that the likelihood of human intrusion cannot reliably be assessed in terms of a probability (NS-GRA (UK Environment Agencies, 2009), para 6.3.38).

360. The NS-GRA dose guidance level of 3 mSv y^{-1} to 20 mSv y^{-1} indicates the standard of environmental safety to be achieved. The guidance levels should not be interpreted as limits and are the same as the levels given in advice issued by the HPA in their publication on the disposal of solid radioactive waste (HPA, 2009).

361. The lower dose criterion of 3 mSv y^{-1} is applied in this ESC for prolonged exposure resulting from human intrusion. Doses in this section are presented as mSv.

6.3.1 Dose assessments following intrusion after the period of authorisation

362. The results of the assessments relating to intrusion, after the period of authorisation (post-closure), are described in Appendix E.5. The radiological assessment has considered a range of potential scenarios and these are summarised in Table 24. The scenarios discussed below consider workers and site residents and farming families (adult, child and infant).

Table 24 Summary of radiological assessment scenarios following intrusion after the period of authorisation

Scenario	Exposed group	Time after closure
Drilling operative	Worker	60 years
Trial pit excavation	Worker	60 years
Informal scavenger	Worker	60 years
Material recovery worker	Worker	60 years
Excavation for a road	Worker	60 years
Gas release and external exposure	Site resident	60 years
Excavation for housing	Excavation worker and Resident	60 years
Excavation for smallholder	Farming family	60 years
Site re-engineering or removal	not quantitatively assessed	n/a

6.3.2 Dose to workers excavating the site

363. The exposure of any workers who might excavate waste at the site has been assessed over a single timeframe. It is assumed that all excavations occur at the site in the short term after closure (60 years). Whilst there are no active controls over events at the site, larger excavations, e.g. for housing or for smallholding, are more likely to occur in the longer term after closure if at all. However, LLW, other waste and cover material are assumed to be excavated. If the LLW is disposed of at a depth greater than 5 m, as most of the waste will be, then it would not be extracted or disturbed by the trial pits or large excavations and the resulting doses to workers excavating at the site would be zero.

364. The three scenarios summarised below give the greatest worker doses following site excavation. Doses presented are for a material recovery worker/user (see Appendix E.5.5) who is working at the site and uses excavated material for building works, for a drilling operative (see Appendix E.5.2) and a road excavator (see Appendix E.5.6). It is assumed that a single drilling operative is involved in 5 boreholes (Hicks & Baldwin, 2011), i.e. the potential dose arising from 5 intrusion events is calculated. The results for the 17 radionuclides giving the largest impacts are summarised in Table 25 alongside the potential dose arising from disposing of the maximum inventory. Whilst road construction may lead to the excavation of a larger amount of waste, it may also lead to exposure from contaminated waste at higher activity concentration and less contact with waste because a road construction worker will be using machinery.

365. The doses to a trial pit excavator (see full results in Appendix E, Table 151) and an informal scavenger (see full results in Appendix E, Table 153) are both always lower than for borehole drilling so these are not listed in Table 25 (see full results in Appendix E, Table 149). The doses to a worker excavating for housing are never greater than to the borehole drilling operative so these are also not listed in Table 25 (see full results in Appendix E, Table 157). The doses to a material recovery worker are included below as they are sometimes more restrictive than doses to the drilling operative.

366. The dose (and hence derived quantities such as the radiological capacity) to the worker in the human intrusion scenarios depends upon the duration of exposure and the activity concentration in the excavated waste.

Table 25 Highest doses to workers excavating at the site

Radionuclide	Maximum Inventory (MBq)	Borehole drilling (60y)		Material recovery worker/user (60y)		Excavation for Road (60y)	
		Dose per unit disposal (mSv MBq^{-1})	Dose at Maximum Inventory (mSv)	Dose per unit disposal (mSv MBq^{-1})	Dose at Maximum Inventory (mSv)	Max specific activity (Bq g^{-1})	Dose at Max specific activity (mSv)
Nb-94	$2.19\ 10^{7}$	$5.28\ 10^{-9}$	$1.16\ 10^{-1}$	$6.04\ 10^{-9}$	$1.33\ 10^{-1}$	100	$1.46\ 10^{-4}$
Ag-108m	$2.19\ 10^{7}$	$4.74\ 10^{-9}$	$1.04\ 10^{-1}$	$5.42\ 10^{-9}$	$1.19\ 10^{-1}$	100	$1.31\ 10^{-4}$
U-232	$1.10\ 10^{7}$	$8.45\ 10^{-9}$	$9.27\ 10^{-2}$	$9.36\ 10^{-9}$	$1.03\ 10^{-1}$	50	$1.13\ 10^{-4}$
Cm-246	$4.39\ 10^{7}$	$1.85\ 10^{-9}$	$8.14\ 10^{-2}$	$1.51\ 10^{-9}$	$6.64\ 10^{-2}$	200	$7.38\ 10^{-5}$
Eu-152	$4.39\ 10^{8}$	$1.84\ 10^{-10}$	$8.07\ 10^{-2}$	$2.10\ 10^{-10}$	$9.22\ 10^{-2}$	2000	$1.02\ 10^{-4}$
Sn-126	$1.10\ 10^{7}$	$6.59\ 10^{-9}$	$7.23\ 10^{-2}$	$7.53\ 10^{-9}$	$8.27\ 10^{-2}$	50	$9.10\ 10^{-5}$
Pu-241	$1.10\ 10^{9}$	$5.64\ 10^{-11}$	$6.18\ 10^{-2}$	$4.61\ 10^{-11}$	$5.06\ 10^{-2}$	5000	$3.46\ 10^{-6}$
Pu-238	$4.39\ 10^{7}$	$1.30\ 10^{-9}$	$5.69\ 10^{-2}$	$1.05\ 10^{-9}$	$4.63\ 10^{-2}$	200	$5.15\ 10^{-5}$
Am-242m	$2.19\ 10^{7}$	$2.35\ 10^{-9}$	$5.15\ 10^{-2}$	$1.92\ 10^{-9}$	$4.22\ 10^{-2}$	100	$6.02\ 10^{-5}$
Eu-154	$1.10\ 10^{9}$	$3.41\ 10^{-11}$	$3.75\ 10^{-2}$	$3.90\ 10^{-11}$	$4.28\ 10^{-2}$	5000	$4.72\ 10^{-5}$
Am-241	$2.19\ 10^{7}$	$1.67\ 10^{-9}$	$3.67\ 10^{-2}$	$1.37\ 10^{-9}$	$3.00\ 10^{-2}$	100	$3.34\ 10^{-5}$
Cm-245	$1.45\ 10^{7}$	$2.12\ 10^{-9}$	$3.06\ 10^{-2}$	$1.79\ 10^{-9}$	$2.59\ 10^{-2}$	200	$1.27\ 10^{-4}$
Ra-226	$1.39\ 10^{6}$	$2.01\ 10^{-8}$	$2.80\ 10^{-2}$	$1.89\ 10^{-8}$	$2.63\ 10^{-2}$	10	$4.66\ 10^{-5}$
Th-232	$2.16\ 10^{6}$	$1.20\ 10^{-8}$	$2.59\ 10^{-2}$	$1.25\ 10^{-8}$	$2.70\ 10^{-2}$	10	$3.05\ 10^{-5}$
Th-229	$4.27\ 10^{6}$	$5.81\ 10^{-9}$	$2.48\ 10^{-2}$	$5.04\ 10^{-9}$	$2.15\ 10^{-2}$	20	$2.46\ 10^{-5}$
Cs-137	$4.39\ 10^{7}$	$4.76\ 10^{-10}$	$2.09\ 10^{-2}$	$5.43\ 10^{-10}$	$2.38\ 10^{-2}$	200	$2.63\ 10^{-5}$
Pu-244	$1.80\ 10^{6}$	$3.40\ 10^{-9}$	$6.12\ 10^{-3}$	$3.20\ 10^{-9}$	$5.75\ 10^{-3}$	200	$1.55\ 10^{-4}$

367. The highest doses occur for Nb-94 with a dose of about 0.13 mSv to a material recovery worker/user from disposal of about 22 TBq at the site. These calculated doses are below the dose guidance level for intrusion. Other scenarios constrain the radiological capacity at the Port Clarence landfill.

368. The material recovery worker/user is one of the scenarios used to determine the proposed radionuclide activity concentration limits for packaged wastes (see Section 7.4.1.2 for further details).

6.3.3 Doses to site residents at 60 years (intact cap)

369. The scenario where housing is built on the site but leaves the cap intact is discussed here. The scenario where housing is built on the site but the cap and some waste has been excavated is discussed in Section 6.3.4. The complete results for site residents arising from gas released from the wastes and through external irradiation are presented in Appendix E (for example see Table 162). Note that these results include the effects of radioactive decay and ingrowth after 60 years (the assumed time between site closure and housing development on the site) upon the calculated doses. This is a very cautious assessment because housing is very unlikely to be constructed on reclaimed land that has been subjected to land raise in the estuary, particularly because it is clearly obvious that the landform is not natural.

370. The ten highest doses are shown below (Table 26) and are dominated by the gas pathway. In the case of Ra-226, the dominant pathway is inhalation of radon gas and results are given for wastes reflecting the emplacement strategy. Wastes containing up to 10 Bq g^{-1} of Ra-226 (labelled high content) are disposed of at a depth greater than 5 m and the resulting doses from radon are insignificant because the radon decays in the soil before it reaches the surface. Waste containing Ra-226 activity

concentrations of less than 5 Bq g^{-1} can be disposed of at any depth (labelled low content) and results in a dose from the radon gas that is generated from decay of Ra-226 in wastes within 5 m of the restored surface. The impact of disposing of Ra-226 at depth (below 5 m) is discussed further in Section 6.3.5.

371. The highest dose per unit disposal is from C-14 and all doses are below the dose guidance level for intrusion. The gas model is very conservative since it makes no allowance for the impact on gas migration of either an intact cap or the concrete raft on which the house is built. These physical barriers will reduce gas migration and doses significantly. This scenario does not constrain the radiological capacity.

Table 26 Site resident exposure – cap intact

Radionuclide	Maximum Inventory (MBq)	Dose (mSv y^{-1} MBq^{-1})			Dose from maximum inventory (mSv y^{-1})
		Gas*	External	Total	
C-14	$1.19\ 10^{8}$	$1.25\ 10^{-8}$	$9.84\ 10^{-67}$	$1.25\ 10^{-8}$	$1.48\ 10^{0}$
H-3	$1.88\ 10^{8}$	$2.50\ 10^{-11}$	$2.54\ 10^{-15}$	$2.50\ 10^{-11}$	$4.70\ 10^{-3}$
Zr-93	$1.10\ 10^{9}$	0	$1.05\ 10^{-11}$	$1.05\ 10^{-11}$	$1.16\ 10^{-2}$
Ni-63	$1.10\ 10^{9}$	0	$5.88\ 10^{-12}$	$5.88\ 10^{-12}$	$6.45\ 10^{-3}$
Mo-93	$5.95\ 10^{7}$	0	$3.66\ 10^{-12}$	$3.66\ 10^{-12}$	$2.18\ 10^{-4}$
Ni-59	$1.10\ 10^{9}$	0	$9.83\ 10^{-13}$	$9.83\ 10^{-13}$	$1.08\ 10^{-3}$
Ra-226** (high content)	$1.39\ 10^{6}$	$1.30\ 10^{-13}$	$7.71\ 10^{-33}$	$1.30\ 10^{-13}$	$1.81\ 10^{-7}$
Nb-93m	$1.10\ 10^{9}$	0	$5.02\ 10^{-14}$	$5.02\ 10^{-14}$	$5.51\ 10^{-5}$
Th-232	$2.16\ 10^{6}$	0	$8.57\ 10^{-18}$	$8.57\ 10^{-18}$	$1.85\ 10^{-11}$
U-232	$1.10\ 10^{7}$	0	$7.56\ 10^{-18}$	$7.56\ 10^{-18}$	$8.30\ 10^{-11}$

* Conservative estimate ignoring the effect of the cap.
**The gas dose shown for Ra-226 is from the release of Rn-222 at a depth of 5 m or greater.

6.3.4 Doses to site occupants at 60 years (cap excavated)

372. This section considers the doses to site occupants after excavation works have removed the cap and some of the waste. The dose rates to residents on the site following construction of houses 60 years after the period of authorisation (Appendix E.5.8) and to a smallholder on the site 60 years after the period of authorisation (Appendix E.5.10), are summarised in Table 27 for the 13 radionuclides giving rise to the highest doses at the maximum inventory for each scenario. It is assumed that wastes containing Ra-226 up to 5 Bq g^{-1} could be disposed of without restriction on the depth of disposal in the landfill. The sensitivity of the intrusion doses and radon release to the radium placement depth within the landfills is discussed below (see Section 6.3.5). The maximum activity concentration of Ra-226 in LLW consignments is only 10 Bq g^{-1} and the radiological capacity is limited by an erosion scenario.

Table 27 Doses to site residents or smallholders after 60 years

Radionuclide	Maximum Inventory (MBq)	Resident (60 y)		Smallholder (60 y)	
		Dose per MBq ($mSv\ y^{-1}\ MBq^{-1}$)	Dose from the maximum inventory ($mSv\ y^{-1}$)	Dose per MBq ($mSv\ y^{-1}\ MBq^{-1}$)	Dose from the maximum inventory ($mSv\ y^{-1}$)
C-14	$1.19\ 10^{8}$	$1.25\ 10^{-8}$	$1.48\ 10^{0}$	$1.06\ 10^{-8}$	$1.25\ 10^{0}$
Se-79	$4.39\ 10^{8}$	$5.18\ 10^{-10}$	$2.27\ 10^{-1}$	$2.11\ 10^{-9}$	$9.28\ 10^{-1}$
Ca-41	$1.05\ 10^{9}$	$8.86\ 10^{-12}$	$9.30\ 10^{-3}$	$3.82\ 10^{-11}$	$4.01\ 10^{-2}$
Tc-99	$1.73\ 10^{7}$	$8.87\ 10^{-10}$	$1.54\ 10^{-2}$	$1.78\ 10^{-9}$	$3.08\ 10^{-2}$
Mo-93	$5.95\ 10^{7}$	$1.17\ 10^{-11}$	$6.98\ 10^{-4}$	$4.62\ 10^{-10}$	$2.75\ 10^{-2}$
I-129	$4.39\ 10^{7}$	$1.04\ 10^{-10}$	$4.55\ 10^{-3}$	$3.36\ 10^{-10}$	$1.48\ 10^{-2}$
Nb-94	$2.19\ 10^{7}$	$4.22\ 10^{-10}$	$9.25\ 10^{-3}$	$5.50\ 10^{-10}$	$1.21\ 10^{-2}$
Ag-108m	$2.19\ 10^{7}$	$3.79\ 10^{-10}$	$8.32\ 10^{-3}$	$4.94\ 10^{-10}$	$1.08\ 10^{-2}$
U-232	$1.10\ 10^{7}$	$6.44\ 10^{-10}$	$7.06\ 10^{-3}$	$8.65\ 10^{-10}$	$9.49\ 10^{-3}$
Sr-90	$4.39\ 10^{7}$	$7.66\ 10^{-11}$	$3.36\ 10^{-3}$	$1.97\ 10^{-10}$	$8.66\ 10^{-3}$
Eu-152	$4.39\ 10^{8}$	$1.47\ 10^{-11}$	$6.43\ 10^{-3}$	$1.91\ 10^{-11}$	$8.40\ 10^{-3}$
Sn-126	$1.10\ 10^{7}$	$5.66\ 10^{-10}$	$6.21\ 10^{-3}$	$7.56\ 10^{-10}$	$8.30\ 10^{-3}$
H-3	$1.88\ 10^{8}$	$2.52\ 10^{-11}$	$4.74\ 10^{-3}$	$2.49\ 10^{-11}$	$4.68\ 10^{-3}$

373. For the smallholder, the calculations apply critical group consumption rates to the two foodstuffs that give the greatest contribution to the dose and mean consumption rates to all other foodstuffs. The two foodstuffs giving the highest dose rate vary from radionuclide to radionuclide; for example for Np-237 and the higher atomic number actinides, they are root vegetables and green vegetables. There are also a small number of radionuclides where animal products are included in the two foodstuffs resulting in the highest dose rates (e.g. Cl-36, Cs-134 and Cs-137). For the resident, the calculations assume that the consumption rate of root vegetables and green vegetables grown in the garden is 50% of the mean consumption rate, a conservative assumption for a household resident where most food is purchased rather than grown on-site.

374. The assessment calculations presented for the smallholding scenario also include a gas contribution based on gas migration from underlying waste and in the case of radon from excavated waste remaining directly under the house. The average timescale for gas release of H-3 and C-14 used were 50 y and 100 y, respectively.

6.3.5 Dose to site occupant from Radium when building on waste/spoil mix

375. The site occupant scenario was also evaluated assuming that there was no radium emplacement strategy placing higher content radium bearing wastes at a particular depth. Hence, it assumed that a house was built on Ra-226 contaminated waste in spoil excavated from the site. This scenario is described in Appendix E.5.9 and results are presented in Table 168. Specifying that wastes containing >5 Bq g^{-1} Ra-226 are disposed of below the excavation depth will ensure that the average activity concentration in any excavated wastes would meet the dose criterion. This scenario does not consider exposure to the wastes remaining in the site since this is addressed above. Hence, this scenario does not impose a restriction on the Ra-226 activity concentration in the waste below the excavated depth.

376. Since the scenario is only relevant if a dwelling is built on a spoil/waste mixture containing radium bearing waste, waste emplacement strategies within waste cells can be employed to ensure that waste containing >5 Bq g^{-1} radium is not excavated from the site. If it is cautiously assumed that the maximum depth of any human intrusion event is 5 m, then ensuring that waste containing >5 Bq g^{-1} (significant radium bearing waste) is placed at depths greater than this will prevent mixing of the waste with excavated spoil, and in these circumstances, this scenario is no longer credible. Hence waste emplacement strategies (i.e. placing significant radium bearing wastes no less than 5 m below the restored surface of the waste cells) are applied for radium bearing wastes at Port Clarence. This approach will apply to both NORM and LLW disposals.

377. The possibility of radon migration from buried radium bearing wastes through the remaining cell-filling material is also considered. This is the same type of calculation as considered in Appendix E.3.5, but considering migration of radon through cell-filling material (i.e. soil, soil-like waste and other non-radium bearing wastes) instead of considering radon migration through the intact cap. The assessment assumes that all the radon gas only has, on average, to migrate through 4 m of cover material and ignores the effect of house foundations and impermeable membranes designed to prevent radon ingress. If all radium bearing wastes were placed at depths of greater than 5 m, then this would result in radon migrating through at least 4 m of cell-filling material and as the thickness increases, i.e. the cover depth increases, the dose from radon declines due to radioactive decay during migration. Therefore, the assessment represents a very cautious estimate of the dose since higher content radium bearing wastes (>5 Bq g^{-1}) will be placed at various depths from 5 m below the restored surface.

6.4 Heterogeneity of waste

378. The waste that is expected to be sent to Port Clarence for disposal may not be uniformly distributed throughout the consignment. A series of scenarios have, therefore, been considered to look at the potential dose that could arise from different types of waste that may be sent to the site for disposal. These assessments are independent of whether disposal occurs to the hazardous or non-hazardous landfill and are uncertain to occur but have been assumed to have a probability of occurrence equal to unity. In this section the disposal of large items, discrete (smaller) items and particles are considered (see Table 28).

Table 28 Summary of radiological assessment scenarios for different waste forms

Scenario	Exposed group
Exposure to heterogeneously contaminated large objects following intrusion or erosion	Worker/ Member of public
Exposure to discrete items following erosion	Member of public
Exposure to particles following erosion	Member of public

379. The mixing assumptions that are applied in the ESC are shown below (Table 29). The baseline assumptions are:

- that exposure during the operational period following a dropped load or a fire considers waste as disposed;
- that a worker on-site is exposed to waste as disposed, whenever this occurs;

- that contaminated leachate/groundwater/floodwater/seepage considers the chemical interaction of liquids with the landfill mass and has therefore considered LLW to comprise 5% of the total landfill disposal;
- that disturbance of the site due to erosion or excavation that leads to exposure of a member of the public considers mixing of LLW with uncontaminated wastes and capping materials as appropriate; and,
- the inputs to Erica are taken from the contaminated leachate/groundwater model and has therefore considered LLW to comprise 5% of the total landfill disposal.

380. Mixing within a consignment is considered (see Section 7.4.1.2).

Table 29 Mixing assumptions for the radiological assessment scenarios

Relevance to ESC	Scenario description	Basis$
Radiological capacity calculations	Erosion - Dog walker (60y & 20,000y); Public	5%
	Erosion to coast - Fishing (60y); Public	5%
	Fire in non-hazardous cell - Operations; Public	no dilution
	WRP Treatment: Worker	5%
	Flooding; Public	5%
	Seepage/Bathtubbing - Residential; Public	5%
	Gas + External - Recreational user (0y) Ra-226 below 5m; Public	no dilution
	Leachate spillage - Operations; Public	5%
	ERICA - small-burrowing mammals	5%
Specific activity and other calculations	Dropped load (bag) - Operations; Worker	no dilution
	Dropped load (tipper)- Operations; Public	no dilution
	Dropped load (tipper)- Operations; Worker	no dilution
	Erosion - Dog walker (60y & 20,000y); Public	5%
	Material recovery user; Worker	5%
	Exposure to discrete items	no dilution
	Exposure to large objects	no dilution
	Exposure to particles	no dilution
	Intrusion - Trial pit excavator (60y) Ra-226 below 5m; Worker	no dilution
	Loose tipping - Operations; Worker	no dilution
	Waste emplacement - Operations; Worker	no dilution
Assessed but not restricting	Dropped load (bag) - Operations; Public	no dilution
	Waste handling - Operations; Worker	no dilution
	ERICA results for Estuary	5%
	ERICA results for Freshwater	5%
	ERICA results for Terrestrial	5%
	Gas - Operations; Public	n/a
	Gas - Operations; Worker	n/a
	Gas used for energy generation - Operations; Public	n/a
	Gas + External - Resident (60y) Ra-226 below 5m; Public	no dilution
	Gas + External - Smallholder (60y) Ra-226 below 5m; Public	no dilution
	Groundwater to estuary - Fishing; Public	5%
	Intrusion - Borehole excavator (60y) – worker	no dilution
	Intrusion - Excavator (For Housing 60y) Ra-226 below 5m; Worker	no dilution
	Intrusion - Smallholder (60y) Ra-226 below 5m; Public	5% + Cap
	Intrusion - Resident (60y) house over spoil; Public	5% + Cap
	Intrusion – Informal Scavenger (60y) – worker	no dilution
	Loose tipping - Operations; Public	no dilution
	Waste entering wound - Operations; Worker	no dilution
	Seepage/Bathtubbing - Leachate to freshwater; Public	5%
	Groundwater - Abstraction at boundary (100,000 y); Public	5%

Relevance to ESC	Scenario description	Basis$
Assessed but very low risk - what-if only	Groundwater – Fast to Estuary (100,000 y); Public	5%
	Leachate - Reed bed treatment (0y); Worker	5%
	Leachate - Sewage treatment/angling (0y); Public	5%
	Leachate - Sewage treatment/farming (0y); Public	5%
	Leachate - Sewage treatment (0y); Worker	5%

Note: $ The basis for the calculation is shown in this column. A value of 5% indicates that the scenario assumes that LLW disposal to the landfill is limited to 5% of the volume disposed to the landfills, where "+ Cap" indicates that the excavated waste is also diluted by the overlying capping materials and 1 m of uncontaminated waste that is placed over the LLW. No dilution indicates exposure to waste as disposed.

Large items

381. Concrete slabs or blocks from decommissioning buildings and rubble from demolition of buildings used for the storage or conditioning of radioactive wastes may become contaminated. Such contamination may be restricted to the surface layers of the concrete, but the depth of penetration will depend on the nature of the waste or conditioning process (e.g. wet or dry facilities), the period of time the facility was in use, the building material (and any surface treatment such as painting or other sealants) and the chemical properties of the radionuclide fingerprint. Best practice is to remove the contaminated surface layer of the building before demolition and dispose of it separately from the rest of the building material, so avoiding significant inhomogeneity in the waste.

382. Characterisation of wastes is always subject to some uncertainty. Wastes can be homogenised or representatively sampled to obtain an overall averaged activity concentration. To determine activity distributions within heterogeneously contaminated wastes, they can be sub-sampled or, for large items, cores can be extracted, and the depth of contamination, or depth profiles of contamination, can be determined. However, this can be a laborious and expensive undertaking, and considerable uncertainty may remain if there is spatial as well as penetrative heterogeneity in the activity distribution.

383. To consider the potential effects of a range of assumptions regarding the distribution of activity within wastes, the ESC considers some example heterogeneous large items and demolition rubble. This is the same approach used for the ENRMF ESC (Eden NE, 2023). A number of different cases are considered, including a hypothetical concrete block contaminated with Cs-137; concrete blocks from decommissioning (with different radionuclide fingerprints); and, rubble and crushed concrete from building demolition (with different radionuclide fingerprints). Details of the calculations are described in Appendix E.6.1. Sensitivity to assumed depth profiles for distribution of activity is explored.

384. Drilling through waste or exposure of waste (through natural processes of erosion or through deliberate human activity) could lead to exposure to heterogeneously contaminated material through external exposure or inhalation of dust or inadvertent ingestion of dust. The contamination is assumed to be in the exposed top surface 1 cm of the item.

385. The assessment considers the case where one or more boreholes drilled on the site after the end of the period of authorisation may penetrate the contaminated items and waste is retrieved for laboratory analysis. The driller may handle the retrieved core leading to both an organ dose (skin on the hand) and a whole-body effective dose. In

addition, dust from the core may be inhaled and inadvertent ingestion may occur. The principal considerations in determining the resulting dose are time spent handling or in proximity to the core and, for determining the whole-body effective dose, the averaged distance from the core.

386. The dose at 60 years after closure is compared to the human intrusion dose guidance values of 3 to 20 mSv (with the lower value being applicable for doses that may occur over extended periods). The doses from the example large items were all well below this.

387. An illustrative date for ‘natural’ erosion exposing the waste was used to illustrate the impact of delayed erosion followed by exposure of a site occupier to the contaminated surface. Erosion is not expected to happen in the near future and the illustrative date chosen was 1000 years post closure. Extrapolating the dose out to 1000 years gives a dose estimate of 0.14 mSv y^{-1} (dominated by the ingestion and inhalation of dust containing Pu-239 for the example waste item). This dose is equivalent to an annual risk of around 7 10^{-6}. Given the grossly conservative nature of the assumption that the contaminated surface 1 cm is uniformly exposed, it is considered that this risk is broadly consistent with the risk guidance criterion of 10^{-6} for the post-closure period.

6.4.1 Discrete items

388. This scenario is included due to the possibility that the site will be eroded by the sea, and walkers along the bank of the estuary near the site may then come into contact with discrete items of waste that have become exposed. Erosion is not expected to happen in the near future but an assessment is performed at 60 years post closure. This scenario is not used to constrain landfill capacity. However, it places limits on the radioactivity of specific discrete items within consignments. Details of the calculations are described in Appendix E.6.2.

389. LLW Repository Ltd (LLWR Ltd, 2013a) define ‘discrete items’ as “a distinct item of waste that, by its characteristics, is recognisable as unusual or not of natural origin and could be a focus of interest, out of curiosity or potential for recovery and recycling/re-use of materials should the waste item be exposed after repository closure.” This definition is adopted in this assessment.

390. Examples of discrete items given by LLWR (LLWR Ltd, 2013a) are hand tools, engineered items and equipment of durable materials (such as may be disposed with other wastes in drums for grouting or high-force compaction, or directly to a Disposal Container); grouted drums or pucks from high-force compaction; and large metal items, e.g. steel beams and plates, pipework, shielding, heavy equipment and flasks (but not general scrap metal) such as may be disposed directly to a Disposal Container.

391. A discrete item has the potential to modify the behaviour of a person that encounters it, i.e. it is visible and, therefore, an individual may deliberately go towards and inspect or (if small enough) pick up the item. This is different from the standard assessment calculations in which the estuary bank user carries out activities on the bank without regard to the presence of the waste or the radioactive hazard it may pose. Thus, two situations can be envisaged: a casual encounter with a single item and a situation where a person deliberately seeks out, collects, takes away or disrupts discrete items. However, the future behaviour of people that might lead to them encountering radioactive discrete items uncovered by natural disruptive processes cannot be

predicted, and so the probability of exposure cannot be quantified. In this respect, the exposure situation is similar to that of inadvertent human intrusion.

392. Exposure to discrete items exposed by natural processes is specifically addressed in Requirement R12 of the Environment agencies GRR (Environment Agencies, 2018), which specifies that the results of illustrative calculations are compared with the dose guidance level for inadvertent human intrusion (3 mSv to 20 mSv); however, this guidance relates to the clean-up of nuclear licensed sites, and does not apply to waste disposal sites.

393. The dose criteria used in this assessment is the effective dose of 20 µSv y^{-1}, which corresponds to the risk guidance level specified in the GRA, assuming a probability of unity. This is appropriate for an assessment of the dose as a result of a casual encounter with a single item. The results of the dose calculations are used to determine limits on the activity of discrete items that can be accepted for disposal at Port Clarence. The proposed Discrete Item Limits will provide adequate protection to a potential future estuary bank user. The radionuclide groups and discrete item limits for each group are given in Table 30 and Table 31, respectively.

Table 30 Radionuclide groups for Discrete Item Limits at Port Clarence

Parameter	Radionuclides
Group a	Nb-94, Ag-108m, Sn-126, Ra-226, Th-229, Th-232, Pa-231, U-232, Pu-244, Cm-248
Group b	I-129, Pb-210, Ac-227, Th-230, U-235, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-242, Am-241, Am-242m, Am-243, Cm-245, Cm-246
Group c	Cl-36, Se-79, Sr-90, Cs-137, Sm-147, Eu-152, U-233, U-234, U-236, Pu-241, Cm-243, Cm-244
Group d	C-14, Ca-41, Co-60, Mo-93, Zr-93, Tc-99, Ba-133, Cs-135, Eu-154, Ra-228, Cm-242
Group e	H-3, Mn-54, Fe-55, Ni-59, Ni-63, Zn-65, Nb-93m, Ru-106, Ag-110m, Cd-109, Sb-125, Sn-119m, Sn-123, Te-127m, Cs-134, Ce-144, Pm-147, Sm-151, Eu-155, Gd-153, Po-210, Th-228

Table 31 Discrete Item Limits for Port Clarence

	Weight 1 kg or less	Weight between 1 and 100 kg	Weight 100 kg or greater
Group a	0.00001 GBq	0.01 GBq t^{-1}	0.001 GBq
Group b	0.0001 GBq	0.1 GBq t^{-1}	0.01 GBq
Group c	0.001 GBq	1 GBq t^{-1}	0.1 GBq
Group d	0.01 GBq	10 GBq t^{-1}	1 GBq
Group e	0.1 GBq	100 GBq t^{-1}	10 GBq

Sum of fractions for discrete item limits

394. In the first instance, waste consignors should determine whether any items within a consignment should be classified as a discrete item. Waste items that meet the activity concentration limits for a package in a consignment, and the consignment concentration limit are accepted for disposal. Guidance on what can be classified as a discrete item can be obtained by consulting LLW Repository Ltd's Discrete Item Library (LLWR Ltd, 2019). Waste consignors would also contact Augean Ltd for guidance.

395. If the item concentration is less than the limits set out in Table 38 the consignment would be accepted for disposal. For other items, based on the activity of each radionuclide on the item and the Discrete Item Limits for the item, a Sum of Fractions approach to determine the acceptability of that item should then be used.

396. The Sum of Fractions is given by:

$$SoF = \frac{Q_a}{L_a} + \frac{Q_b}{L_b} + \frac{Q_c}{L_c} + \frac{Q_d}{L_d} + \frac{Q_e}{L_e},$$

where Q_n is the total activity of group n radionuclides on the item and L_n is the Port Clarence Discrete Item Limit for that group (given in Table 31).

397. If a radionuclide is known to be present on an item, is not listed in Table 30 and has a half-life greater than 200 years then the radionuclide should be cautiously assigned to Group a. Otherwise it should be assigned to Group e, unless it decays to an alpha-emitting daughter with a half-life a few tens to hundreds of times the parent half-life, in which it should be assigned to Group a.

398. If this Sum of Fraction is less than one, the item is acceptable for disposal within a consignment at Port Clarence, subject to meeting other Waste Acceptance Criteria. If a discrete item meets the discrete item sum of fractions limits but exceeds the consignment maximum activity concentrations that are given in Table 38 of the ESC, there are three potential outcomes:

- If the consignment as a whole meets the limits set out in Table 38 and the overall activity concentration of the discrete item meets the limits set out in Table 31 and is less than the upper bounds defining what constitutes LLW, the consignment would be accepted.
- If the consignment as a whole meets the limits set out in Table 38 and the overall activity concentration of the discrete item is more than the upper bounds defining what constitutes LLW or exceeds the limits set out in Table 31, the consignment would **not** be accepted due to the presence of the discrete item.
- If the consignment as a whole exceeds the limits set out in Table 38 the consignment would **not** be accepted.

6.4.2 Particles

399. Assessments have been undertaken to calculate the dose that could occur from the disposal of waste containing radioactive particles at Port Clarence. Radioactive particles are small items that could be as small as a grain of sand that could be incorporated in a radioactive waste stream or package. The possibility that future intrusion events could lead to unintentional recovery of, and exposure to, radioactive particles is considered. Migration of particles in groundwater or uptake from soil into the food chain is not considered credible.

400. The methodology for assessing the dose implications of exposure to waste materials that include particles following erosion is described in Appendix E.6.4.

401. It is not possible to determine generic waste acceptance criteria for waste containing particles as the characteristics of the particle (e.g. nuclides, size, solubility) will be

specific to the consignment. Therefore waste containing particles will be considered on a case by case basis.

402. The assessment approach is based on that applied in the ENRMF ESC (Eden NE, 2023). It draws on the work (Mobbs & Sumerling, 2012; Sumerling, 2013) undertaken for the LLWR ESC. The methodology can assess the dose arising from any radionuclide associated with a particle and has been implemented in an Excel workbook (PC Particle assessment tool v2.xlsx) for use by Augean on decisions regarding acceptability of waste at the ENRMF (Eden NE, 2018).

403. Decisions regarding acceptance for waste containing high activity particles can be made by comparison of the results of dose calculations for the activity on the particle with the NS-GRA intrusion dose guidance level. The ingestion dose and external (whole body) dose are therefore compared separately to the annual dose guidance level of 3 to 20 mSv. The doses from these pathways are not considered to be additive, i.e. it is unlikely that a particle giving a whole body dose is then ingested. The exposure is regarded as a 'one-off' event and hence the appropriate dose guidance value would lie towards the upper end of the range cited. The dose from contact with the skin is compared with the 50 mSv annual dose limit for the equivalent dose to skin for members of the public, as specified in the NS-GRA. Inhalation of particles is not considered as it is not relevant for particles of 1 mm in size and inhalation of particles up to 10 µm in size was found not to be an important pathway in other assessments of particles (Sumerling, 2013; HPA, 2005; HPA, 2011). Wastes that do not meet these dose guidance levels are not accepted without specific approval from the Environment Agency. Demonstration that the disposal route adopted represents BAT would also be required.

404. The waste acceptance procedure would follow the approach outlined below:

- Use the particle assessment spreadsheet tool to assess the dose from the type of particle in the waste.
- Identify the package and consignment activity concentration limits relevant to the nuclides in the package.
- For ESC radionuclides where the ingestion dose is less than 3 mSv, the external dose to whole body is less than 3 mSv, the skin dose due to external exposure is less than 50 mSv, and the package and consignment meet their respective activity concentration limits, a consignment of particles may be disposed of without consulting the Environment Agency.
- Where the ingestion dose is between 3 mSv and 20 mSv or the external dose to whole body is between 3 mSv and 20 mSv, then the Environment Agency should be consulted.
- Where the ingestion dose is above 20 mSv or the external dose to whole body is above 20 mSv or the skin dose due to external exposure is above 50 mSv the consignment would not be acceptable for disposal.
- For radionuclides not considered in the ESC or where alternative f1 values or low solubility are proposed then the Environment Agency should be consulted.

6.5 Optimisation {R8}

6.5.1 Introduction

405. The NS-GRA requires that radiological risks are as low as reasonably achievable (Requirement 8):

> The choice of waste acceptance criteria, how the selected site is used and the design, construction, operation, closure and post-closure management of the disposal facility should ensure that radiological risks to members of the public, both during the period of authorisation and afterwards, are as low as reasonably achievable (ALARA), taking into account economic and societal factors. (UK Environment Agencies, 2009), para 6.3.56

406. The principles of optimisation in the management and disposal of radioactive waste are discussed in guidance from the Environment Agency (Environment Agency, 2010) and apply to the disposals received at Port Clarence. The requirement for optimisation in relation to radiological risk may be considered at three levels:

- the design of the Port Clarence landfills, this is consistent with best practice and regulatory requirements for the disposal of hazardous and non-hazardous, as appropriate and may therefore be considered to be optimised and BAT for those waste types;
- we have considered a number of specific ways in which the operation of the site may be enhanced to achieve an optimised solution for the disposal of radioactive wastes; and,
- waste consignors are required to manage wastes in a manner consistent with BAT and must demonstrate that disposal to Port Clarence is an optimal solution and hence consistent with BAT.

407. The first two aspects are discussed below, noting that the third is a matter for consignors. We detail below the ways in which the design and operation of the disposal facility is optimal for the disposal of LLW. We have not carried out comparative assessments of the various design options because these are limited both in terms of the approach to landfill design/construction that follows prescribed standards and because the final inventory is unknown.

408. There is no requirement in current guidance to provide evidence that the disposal to landfill is the optimised approach for all LLW streams covered by the permit. It is the operator that generates the waste that is required to show that disposal to Port Clarence is BAT and waste generation is minimised. It is a requirement for Augean to show that the landfill operation is BAT (landfill design, management procedures, pre-acceptance evaluation, receipt of waste, acceptance of consignment, burial, discharges, landfill closure etc.) and that impacts of disposal are ALARA, as discussed below.

409. It is our contention, and that of the operators at other landfill sites receiving LLW, that compliance with the requirements of the Landfill Directive ensures that the facility is applying BAT. Whilst there are differences between the default BAT applied to a landfill receiving hazardous or non-hazardous waste, in design terms these largely concern the thickness of the clay basal liner, the default design criteria are then replaced by the findings of a site specific hydrogeological risk assessment (HRA) where this

demonstrates that the requirements of the EU Groundwater Directive are met. The approach to and the objectives of the site specific HRA are the same for both non-hazardous waste and hazardous waste landfill sites. It is this site specific HRA approach that is used to design the engineered containment system for the site. The design is therefore optimised for the site specific setting and circumstances rather than simply being based on the default criteria.

6.5.2 Design considerations

410. The landfill is designed and operated based on the principle of containment in accordance with modern standards and the use of Best Available Techniques in accordance with the Environmental Permitting Regulations (Schedule 7). These regulations, which are the basis of the implemented design and approach at the Port Clarence landfills, are the output of an extensive process. The choices for further design optimisation are constrained by past decisions and by legislation relating to the disposal of hazardous and non-hazardous waste. It is not possible to generate a record that shows how the NS-GRA requirement of optimisation influenced site design.

411. The design features and arrangements provide an appropriate strategy to limit the environmental impacts arising from non-radioactive contaminants. In the context of the assumed timescales and approach to landfill risk assessment, these measures will also be effective in limiting the environmental impacts arising from radioactive contaminants. In this sense, the design of the facility may be considered to have been optimised with respect to the release of radioactive contaminants and the arising radiological impacts.

412. The adopted landfill design features include:

- a leachate drainage system – a system is in place. The thickness, porosity and aggregate selection takes into account the need to minimise the potential for clogging and longevity of the material as well as including an element of redundancy. Accordingly there are no further decisions to optimise, leachate generation is reduced by phased capping and utilised on-site, monitoring ensures there is no transfer of radioactive leachate off-site;
- an engineered geological barrier, made of clay – construction is subject to quality assurance testing and the hydraulic conductivity and thickness of the layer is already optimal for restricting contaminant flow, further optimisation is not appropriate;
- a 2 mm HDPE liner and protective geotextile – the basal and side liner prevent leachate movement into the engineered clay barrier, it is cautiously assumed that this layer deteriorates over time, the standard of the membrane is already optimal for containment, further optimisation is not appropriate;
- a low permeability engineered cap covered by a surface water drainage layer and restoration materials – quantitative consideration has been given to the impact of different engineered caps on leachate generation and the impact that can result from the permeability of this barrier, there have been further discussions on optimisation for this barrier focussing largely on accumulation of leachate and barrier degradation. The combined provision of a low permeability capping layer and an overlying high permeability surface water drainage layer provides optimisation in terms of the minimisation of the rate of infiltration hence minimisation of the potential for the generation of leachate;

- optimisation of the vegetation cover will be undertaken prior to seeking agreement on the final restoration scheme to ensure that suitable coastal vegetation types will be encouraged and the potential for surface erosion is minimised;
- arrangements for the management of leachate – leachate is now primarily managed on-site, it is used in WRP treatment processes and treated wastes are then deposited in the landfill – this is an optimal approach for the management of leachate;
- arrangements for dealing with landfill gases – a system is in place and there are no decisions to optimise; and,
- a systematic approach to monitoring environmental impacts – the monitoring plan agreed with the Environment Agency and specified in the permit would be modified should any unexpected levels of radioactivity be discovered, UKHSA reviews all monitoring results and advises whether further investigation is required.

413. These design attributes accord with good practice for landfills and provide an appropriate strategy to limit the environmental impacts arising from contaminants present in waste. The design satisfies the requirements set out in the EU Landfill Directive and adopted in the Environmental Permitting Regulations. In the context of the assumed timescales and approach to landfill risk assessment, these measures will also be effective in limiting the environmental impacts arising from radioactive contaminants. In this sense, the design of the facility may already be considered to have been optimised.

414. A recent modification to the barrier between the two landfills considered whether LLW could be included in the engineered material used for the barrier. It was decided to exclude LLW from this part of the site thereby reducing the potential dose to operators from placing and working of materials in-situ. This decision also keeps potential doses to the public as low as reasonably achievable by preventing exposure of the public off-site to resuspended dusts contaminated with LLW. The commercial impact is not quantifiable but it reduces the available radiological capacity of the site and has a cost impact.

415. The maximum average activity concentration limits applied for at Port Clarence are based on the relative risk associated with each radionuclide. This was not the case at the ENRMF where the activity concentration was constrained by planning consent that adopted a nominal value of 200 Bq g^{-1}. The NS-GRA makes no mention of 'low activity LLW' being distinct from LLW or a requirement for additional engineering measures if waste is not considered to be 'low activity LLW'. The risk associated with disposal has been used to assign proposed specific activity concentration limits for the Port Clarence landfill to each radionuclide, for example, 20 Bq g^{-1} of Th-229 having a broadly equivalent risk to 100 Bq g^{-1} of Nb-94 in the ESC. The risks upon which these limits are based were derived based on the engineering and operational specification set out in the ESC. It is our view, therefore, that there is no requirement for additional engineering measures or optimisation beyond those already set out in the ESC. However, the upper activity concentration for consignment average concentrations is capped at 5000 Bq g^{-1} for an individual radionuclide and a limit of 2000 Bq g^{-1} is proposed for a consignment fingerprint.

416. The profiling of the restored surface will encourage surface runoff, preventing the development of puddles and reducing infiltration. Areas of the site will also be

developed as woodland and these areas will have a deeper soil layer over the cap. This will further reduce the chance of intrusion disturbing waste or the already relatively low prospect of housing development at the site. The profiling also ensures that any seepage from the joint between the cap and basal liners will occur at a depth (>1 m below the surface), reducing the potential impact of this event.

417. The seal between the cap and basal liner is resilient and constructed by keying the engineered capping layer into the previously constructed side liner. The works at these boundaries, as with all engineering works for the containment system, are subject to the preparation of design and a Construction Quality Assurance Plan (CQA Plan) which must be approved by the Environment Agency. The construction is subject to third party Quality Assurance in accordance with the CQA Plan and the preparation of a Verification Report. The Verification report must be submitted to the Environment Agency for approval before the works are accepted as complete. All engineering works are subject to ongoing monitoring for the duration that the Environmental Permit is in place. This design, construction, Quality Assurance and approval process limits water flow across these barriers reducing the potential for seepage as well as the impact of any seepage and the potential for flood water to mix with waste.

6.5.3 Waste location considerations

418. Most large scale human intrusion events (see Section 6.3) only disturb the ground to a limited depth of a few metres, and hence, if the radioactive waste is placed below that depth then such intrusion events will not disturb it. This is particularly important for radium-bearing wastes, which can give rise to doses from radon if buildings are constructed on waste that has been distributed on the surface as a result of a human intrusion event. Strategies that place the majority of the radioactive waste below the intrusion depth, e.g. below 5 m of the restored surface will reduce doses from intrusion. Intrusion doses are dependent on the activity concentration in the material that is excavated and, therefore, waste emplacement strategies that result in wastes with lower activity concentrations being placed within the top of the site (within the intrusion depth) or co-disposal of radioactive and non-radioactive wastes within this depth will also minimise doses from intrusion. The doses from the other scenarios depend on the total activity in the landfill site and are, therefore, not affected significantly by waste emplacement strategies relating to depth of disposal.

419. It is therefore proposed that wastes with significant radium content above 5 Bq/g should be emplaced under at least 5 m of cover. Waste emplacement strategies for other radioactive wastes would be considered if required, bearing in mind the current sequence of cell filling and the importance of intrusion scenarios compared with other exposure scenarios for the radionuclides in the wastes.

420. As the landfill is constructed, the areas of the landfill that are currently in the Flood Zone 2 area of the site will be built up to the same level as the rest of the site, which is in Flood Zone 1. As such, from a flood risk perspective, it is not appropriate to limit LLW disposals to a certain area of the landfill, because the whole landfill will be at a similar risk of flooding.

421. Local flooding or sea level rise may see saturation of soil/made ground rise to a level that is above the base of the landfill at some locations. The design includes an engineered clay barrier beneath each cell and an HDPE liner to minimise water entering waste cells. There are also coarse materials and drainage pipes on the base of the liner to assist with leachate collection. When the HDPE liner degrades (and

although still protected by the clay layer) there is the potential for saturation of the base of the landfill from floodwater for short periods and subsequent drainage to surrounding land. The design requires 2 m of waste, from which LLW will be excluded, to be emplaced on top of the base liner before LLW can be disposed. This 2 m of waste would also have to be saturated before the LLW begins to be saturated. The emplacement approach is intended to reduce the risk resulting from leachate build-up that can result from flooding or bathtubbing.

422. Waste emplacement 2 m above the drainage layer delays the time at which water could reach the base of LLW within the landfills. The relative height of the flood plain to the north and northwest (2.5 to 3 m AOD with some roads at 4 m AOD) will require flooding to a height of 8m AOD before LLW is impacted.

6.5.4 Operational considerations

423. A number of specific considerations have led to enhancements to the operational or emplacement approach to ensure that performance for radioactive waste receipt and disposal is optimised. Site operating procedures have been provided to the Environment Agency (see Item 9). Operational aspects in the procedures for reasons of optimisation include:

- the use of waste packages for the vast majority of LLW which reduces the probability of doses during operations, increases the prospect of the waste being recognised as potentially harmful during future human intrusion and reduces contact with non-human biota;
- while most waste packages will also reduce leaching post-closure (e.g. in the case of drums) the safety case does not rely on this claim to reduce contamination of leachate because all contaminants in waste are assumed to be chemically available for transport to and in leachate;
- a lower limit on the amount of LLW as a proportion of total waste disposed at the landfills, reduced from 20% (Eden NE, 2019) to 5% in this ESC.
- the implementation of a limit on putrescible materials accepted at Port Clarence hazardous landfill ensures that microbial activity is minimised and gaseous release from microbial action or the potential for fire is minimised, specific limits are assessed for the waste disposed in the non-hazardous landfill to account for potentially greater organic matter content;
- Augean places a constraint on the dose rate 1 m from the surface of waste packages (10 $\mu Sv\ h^{-1}$) to ensure packages do not present a hazard on-site;
- there will be no double handling of waste on-site, it will be offloaded directly to the landfill and placed where it will be buried, operational procedures detail placement at the foot of a prepared face so that subsequent burial is facilitated using material higher up the prepared face;
- Augean places a constraint on the level of dust on the surface of waste packages to ensure this does not represent a hazard. Wastes placed in the landfill are also covered daily to prevent dust suspension and hence the risk of impacts via the inhalation pathway during the operational period;
- Emergency plans detail the mitigation measures that would be taken, in the event that LLW is found to have escaped from a container. These include steps

to locate and avoid spreading contamination and monitoring after clean-up to ensure that no residual contamination exists;

- the activity concentration associated with loose tipped waste is limited to a low value so that disposals cannot result in unacceptable doses;
- dust suppression is also undertaken in the case of loose tipped waste that could produce suspended particles, practical suppression measures would include avoidance of tipping during windy conditions and use of water spray suppression as required;
- a check is also undertaken on dose measurements at 1 m above the surface of the covered LLW, to ensure exposure of less than 2 μSv hr^{-1}. The depth of cover will be increased if necessary to ensure that this limit is not exceeded. All operational staff involved in the LLW operations wear a TLD, despite expected doses not being high enough to require this. These precautions will provide additional confidence that no specific protective measures are needed for workers at the site who are closest to the LLW and will provide additional confidence that anyone off-site is also suitably protected;
- the depth of cover over emplaced LLW has been increased from 0.3 to 0.4 m in site operating procedures, further reducing the potential impact on workers traversing the landfill to be ALARA;
- operational constraints have been put in place to restrict the placement of waste in a landfill cell, placing non-radioactive waste to a specified depth at the base (2 m), distance from sides (2 m) and top (1 m) of a cell. This creates a barrier between the LLW and the side liner of a waste cell which will need to be located when the cell is capped – this ensures workers do not come into contact with LLW when the landfill is permanently capped; and,
- cell caps will be constructed once disposal cells are full, eliminating potential dust resuspension if LLW becomes exposed and reducing water ingress, hence reducing potential leachate generation.

6.5.5 Waste form considerations

424. The waste packages (drums and bags) used to transport LLW are constructed to high standards and are engineered to be durable. The waste form inside these packages is loose items of waste and the amount of voidage in the package is minimized as far as possible.

425. The current practice of grouting ISO containers at the LLWR is performed to improve structural integrity within a vault by limiting void space. This is important because ISO containers are the only waste form accepted and, therefore, the voidage is key to the stability of the site. Recent studies have identified there is also an associated benefit from grout chemistry reducing radionuclide release to the near field. The Port Clarence landfill will receive LLW wastes in other types of packages, and loose non-rad wastes (which form the majority of the waste). LLW will be only 5% by volume of the landfill content. The landfill design has been subject to stability risk assessments as part of the landfill permit applications and construction of the capping systems (MJCA, 2019c); construction is subject to *Construction Quality Assurance* (CQA) and Verification, and all processes are subject to approval by the Environment Agency. Accordingly, the stability and long-term integrity of the designed and constructed systems at Port Clarence have a high degree of reliability and confidence. Hence, grouting of LLW

packages is not needed to maintain the stability of the facility by reducing the void space. In fact, it is BAT not to add grout to the LLW waste for disposal unless there is a good reason to do so. Similarly, putting bags and drums of LLW into ISO containers and then grouting them would not be BAT as an outer ISO container is not required for safety case reasons and there is no benefit gained by the additional grout. We do not believe a discussion of waste form optimisation is proportional for the disposal of LLW waste to a landfill. It is proportional for HAW waste disposal in the Geological Disposal Facility.

426. Any disposal of LLW to the Port Clarence Landfills has to comply with the Conditions For Acceptance of waste (CfA; see Item 9) and the waste acceptance criteria and these are subject to agreement with the Environment Agency before waste disposal commences. If the consigning operator has established that disposal to landfill is BAT for the waste stream and it meets the CfA for Port Clarence, then the waste is considered acceptable for disposal. Although the requirement to demonstrate BAT for potential waste streams is not something the landfill operator is required to demonstrate and is not a requirement of the NS-GRA, the CfA requires the consigning operator to provide a BAT assessment for disposals and this is reviewed by Augean before waste is accepted for disposal. There is an expectation that, when disposing of radioactive waste, operators need to ensure that the radiological impacts on people are kept as low as reasonably achievable during the period of authorisation and afterwards. There is an expectation that this is achieved through the use of BAT in relation to the management of the generation and disposal of radioactive waste.

427. The Environment Agency requires use of BAT to help minimise impacts of LLW disposal to the public and on the environment. The design of the landfill sites at Port Clarence are consistent with best practice and regulatory requirements for the disposal of hazardous wastes and non-hazardous wastes and are therefore considered to be optimised landfill designs and are based on BAT. The procedures for receipt and burial of waste minimise the immediate radiological effects on the environment and members of the public (burial within 24 hours with non-radioactive cover materials). Environmental sampling and monitoring use a best practice approach for landfill sites and will be subject to independent verification monitoring by the Environment Agency. The radiological assessments supporting the ESC use cautious assumptions to limit disposals ensuring that actual doses will be substantially lower than the limits specified in the NS-GRA. The use of BAT by the consigning operator further helps to ensure that any radiation risks to the public and the environment will be as low as reasonably achievable.

6.6 Environmental radioactivity {R9}

428. The NS-GRA asks for an assessment of the impact on non-human species (Requirement 9):

> "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." NS-GRA (Environment Agencies, 2009), para 6.3.70

429. A radiological assessment of the potential effects on non-human biota (NHB) from the disposal of LLW at Port Clarence has been undertaken using the ERICA (Environmental Risk from Ionising Contaminants: Assessment and Management) Assessment Tool. The ERICA tool is a software system that has a structure based

upon the tiered ERICA Integrated Approach to assessing the radiological risk to terrestrial, freshwater and marine biota. The most recent update (v2.0) was uploaded in November 2021, and that is the version of the tool used in this assessment.

430. There are currently no internationally agreed criteria against which radiological dose assessments for non-human species can be evaluated and, as such, assessors are required to apply best available knowledge to draw conclusions on the potential effects of a facility on the environment (paras 6.3.73 & 6.3.74). Results in this ESC are therefore interpreted taking account of the following:

- the ERICA incremental screening value of 10 µGy h^{-1};
- the FREDERICA effects database; and
- the derived activity concentration reference levels provided in the ICRP Reference Animals and Plants approach (ICRP, 2008).

431. Consideration is also given to uncertainties inherent in the ERICA assessment approach when applied to sub-surface radioactive waste disposal facilities (see, e.g., the discussion in (Smith, et al., 2010)). We have also considered ongoing developments in the interpretation of screening values, knowledge quality and implied levels of protection at the species or population level (Jackson, et al., 2014).

432. The ERICA toolkit offers a tiered approach to assessment. Tier 1 assessments are based on media concentration and use pre-calculated environmental media concentration limits (EMCLs) to estimate risk quotients: if they are <1 the dose rate to the organism is less than the screening value of 10 µGy h^{-1}. Tier 2 assessments calculate dose rates but allows the user to examine and edit most of the parameters used in the calculation e.g. to add radionuclides or organisms. The results can then be used to derive risk quotients based on the screening dose rate. Tier 3 allows probabilistic calculations.

433. The ERICA toolkit allows consideration of three ecosystems: terrestrial, freshwater and marine. All these ecosystems are applicable to the environment surrounding the Port Clarence site and are considered in the ESC. Within these ecosystems, the ERICA tool considers a range of organisms and wildlife groups as shown in Table 32.

Table 32 Wildlife groups considered in the ERICA tool

Terrestrial	Freshwater	Marine
Amphibian	Amphibian	Benthic Fish
Annelid	Benthic fish	Bird
Arthropod – detritivorous	Bird	Crustacean
Bird	Crustacean	Macroalgae
Flying insects	Insect larvae	Mammal
Grasses and herbs	Mammal	Mollusc – bivalve
Lichen and bryophytes	Mollusc – bivalve	Pelagic fish
Mammal large	Mollusc – gastropod	Phytoplankton
Mammal small – burrowing	Pelagic fish	Polychaete Worm
Mollusc – gastropod	Phytoplankton	Reptile
Reptile	Reptile	Sea Anemones &True Coral
Shrub	Vascular plant	Vascular Plant
Tree	Zooplankton	Zooplankton

434. During the operational and active management phases, radioactivity could be released to the biosphere as gas (e.g. landfill gas production may result in C-14 labelled carbon dioxide or tritiated hydrogen gas), or in discharges from leachate treatment facilities. After the period of authorisation, the releases of radioactivity are assumed to be associated with groundwater, bathtubbing, erosion or as a result of intrusion into the waste.

435. Input data for the NHB dose assessment are radioactivity concentrations in soil and air (terrestrial ecosystem assessment) and water or sediment (freshwater and marine ecosystem assessment). The activity concentrations of radionuclides in soil and water are calculated using the same approaches underlying the dose calculations to the public.

436. The impact on burrowing animals that dig into the waste is also considered.

437. We note that within the regulatory framework the site operator has the obligation to protect a species rather than individual animals. The underlying philosophy of radioactive waste disposal to a landfill is to contain and protect the environment from the waste. This is done by isolating the waste from the many populations of non-human biota around the site. The landfill itself is not part of the environment that is to be protected.

6.6.1 Marine ecosystem

438. A marine ecosystem was considered to be representative of the estuary close to the Port Clarence site. The ERICA assessment considered the impacts of groundwater release to the estuary and the impacts of releases from coastal erosion to the estuary using the activity concentrations in the water in the estuary from these scenarios.

439. A Tier 2 ERICA assessment was used in both scenarios for release to the estuary. The assessment used the activity concentrations in the estuary given by the GoldSim model, scaled to the radiological capacity.

440. The risk quotients for the groundwater release to estuary were all well below 1 and therefore the marine ecosystem is considered to be sufficiently protected in this scenario.

441. There was a high risk quotient for Am-242m in the erosion to estuary scenario. This radionuclide was assessed using the ICRP BIOTA DC tool, which uses a conservative approach, because it is not included in the ERICA list of radionuclides.

6.6.2 Freshwater ecosystem

442. There is an existing freshwater pond at the north-west corner of the site and further ponds are planned, as shown in Figure 7. Radionuclides may be transferred to these bodies from the landfill by water that has become contaminated by leachate from the landfill that is assumed to overtop the liner (the bathtubbing scenario, see Section 6.2.2.2).

443. Although the GoldSim model showed that leachate overtopping the landfill would not reach a planned or existing freshwater pond, a ‘what-if’ case was considered where a hypothetical pond does become contaminated. The activity concentration in the

hypothetical pond was cautiously assumed to be equal to the peak activity in water in the GoldSim 'fast pathway' (flow overland) for the bathtubbing scenario for each radionuclide, calculated using the GoldSim model (see Appendix E.4.4.6), reduced by the same factor (1 10^{-3}) applied in the leachate spillage scenario (see Appendix E.3.10).

444. The risk quotients for the 'what-if' leachate breakout via the "bathtubbing" scenario were all well below 1 and therefore the freshwater ecosystem is considered to be sufficiently protected.

6.6.3 Terrestrial ecosystem

445. The scenarios considered in the assessments for the terrestrial ecosystem were gas release, and intrusion into the site. ERICA T2 assessments were used for the terrestrial ecosystem.

446. The assessment for the gas release (operational period) considered C-14 and H-3 activity concentrations in air (Bq m^{-3}) per MBq disposed taken from the gas release scenario assessment (see Appendix E.3.5.3). The air concentrations for each radionuclide were then scaled to account for the maximum inventory of each radionuclide.

447. The assessment for intrusion into the site was run using the radionuclide concentrations in waste cells at the end of the PoA (per MBq disposed), applying the same dilution factors used for the smallholder scenario (E.5.10) and assigning these values as soil concentrations in ERICA. The soil concentrations for each radionuclide were then scaled to account for the lowest radiological capacity of each radionuclide. Activity concentrations for radionuclides that were ingrown through radioactive decay were calculated separately.

448. The risk quotients for the gas release and exposure to waste cells at the end of the PoA due to erosion were all well below 1 except for Cm-243 and Cm-244 when the radiological capacity was used. When the maximum inventory was considered no radionuclides exceed a dose rate of 40 µGy h^{-1} and most were substantially below 1 µGy h^{-1}. Hence, based on a realistic waste composition, terrestrial non-human biota are sufficiently protected.

6.6.4 Animals burrowing into landfill

449. The assessment undertaken for burrowing animals using the ERICA model is generic and applies to burrowing species that could burrow deep enough to reach the LLW (at least 2.3 m below the surface). Badger tunnels can be 4 m deep, though most are less than 1 m deep. Rabbit warrens can be up to 3 m deep. Hence, it is appropriate to consider rabbits and badgers in the assessment, and the results calculated for rabbits are assumed to be applicable to badgers. Other burrowing animals (mice, voles, moles) have a maximum burrow depth that is less than 1 m and, therefore, will not burrow into the waste.

450. We note that in their review of the ENRMF ESC (Eden NE, 2015b), the EA commented that it would be precautionary to apply radiological capacity reduction factors based on the ERICA Tier 2 assessment for burrowing animals.

451. A Tier 2 assessment was carried out within ERICA to calculate a risk quotient for each radionuclide for burrowing mammals.

452. The assessment for impacts on burrowing mammals was run using the radionuclide concentrations in waste cells at the end of the PoA (per MBq disposed) and assigning them as soil concentrations in ERICA. The soil concentrations for each radionuclide were then scaled to account for the minimum radiological capacity of each radionuclide. Activity concentrations for radionuclides that were ingrown through radioactive decay were calculated separately.

453. There are four radionuclides for which the dose rate to the burrowing mammal is greater than 40 µGy h^{-1} (Sr-90, Ag-108m, Cs-135, Cs-137) some by up to an order of magnitude. Given the design of the landfill facility and the design of the cap, it seems very unlikely that burrowing animals will build their nesting chambers in the disposed waste. In addition, the purpose of the landfill site is to concentrate and contain the waste to protect the environment, so the environment in the actual landfill (the waste cell) is not the part of the environment that is being protected (it is not a conservation area). The radiological capacity without this reduction is considered as a sensitivity (see Appendix E.8).

7 Technical Requirements

454. In this section consideration is given to the technical requirements of the NS-GRA as follows: to protect against non-radiological hazards at the site (Section 7.1); to site investigations (Section 7.2); to the development of the site and the operational aspects of non-hazardous waste, hazardous waste and LLW disposal (Section 7.3); to waste acceptance criteria and conditions that would apply to LLW disposals (Section 7.4); and lastly, to details about site monitoring (Section 7.5).

7.1 Protection against non-radiological hazards {R10}

455. The NS-GRA includes a requirement that the ESC demonstrates that adequate protection against non-radiological hazards is achieved (Requirement 10):

> "The developer/operator of a disposal facility for solid radioactive waste should demonstrate that the disposal system provides adequate protection against non-radiological hazards." (UK Environment Agencies, 2009) para 6.4.1

456. Paragraph 6.4.2 of Requirement 10 states that:

> "Some waste disposed of at a facility receiving radioactive waste may be potentially harmful wholly or partly because of its non-radioactive properties. There are nationally acceptable standards for disposing of hazardous waste. However, these standards may not be suitable to apply directly to waste that presents both radiological and non-radiological hazards. Accordingly, these standards need not necessarily be applied, but a level of protection should be provided against the non-radiological hazards that is no less stringent than would be provided if the standards were applied."

457. The Port Clarence landfill sites are already the subject of Environmental Permits issued and regulated by the Environment Agency which will continue in force for the period over which radioactive waste is deposited. Accordingly, all the standards and controls that apply to the disposal of non-radioactive wastes will be applied to the radioactive wastes. The radioactive and non-radioactive wastes will be deposited in the same engineered cells within the boundaries of the currently consented Environmental Permits.

458. The landfill cells are designed to accept hazardous wastes and non-hazardous wastes and the adequacy of the designs is demonstrated through compliance with environmental protection legislation, stability risk assessments, hydrogeological risk assessments, landfill gas risk assessments and amenity impact risk assessments. The controls over the construction of the landfill engineering and landfill cells are specified in a Construction Quality Assurance Plan which is approved by the Environment Agency and construction works are subject to CQA Supervision with the provision of a CQA Verification Report to confirm that each aspect of the cell construction has been carried out in accordance with the specification. The operational procedures, including waste pre-acceptance and acceptance, waste placement, site monitoring and site completion and restoration, are all controlled through procedures which are implemented through the Augean Integrated Management System which is necessary as part of the Environmental Permits.

459. The site pre-acceptance and acceptance procedures ensure that no explosive, flammable, corrosive, oxidising or infectious wastes are accepted at the site. The

hazardous wastes accepted at the hazardous waste landfill site are largely hazardous due to harmful, toxic, carcinogenic, irritant or eco-toxic properties. The established procedures for the safe handling and disposal of the non-radioactive hazardous and non-hazardous wastes accepted at the site are similar to those necessary for the handling of LLW and enhance rather than conflict with them.

460. The arrangements for construction design, waste acceptance, groundwater protection, landfill gas management, leachate management, landfill stability, pollution prevention, nuisance prevention, construction quality assurance, maintenance, landfill capping, site restoration, operations, waste handling/placement, security, emergency and accident management plans, monitoring, closure, aftercare and surrender are all the subject of review and regulation by the Environment Agency under the existing Environmental Permits and will continue to be applied. The Environment Agency would not have issued the Environmental Permits for the existing landfill sites if they were not satisfied that suitable environmental management controls were designed and implemented at the site in order that there are no unacceptable impacts on the environment or human health as a result of the landfill disposal activities.

461. The characteristics of the radioactive wastes introduce no additional non-radiological hazards beyond those already assessed and controlled through the designs and procedures implemented through the existing Environmental Permits for the landfill sites. Disposed LLW will otherwise be compliant with Augean's waste acceptance procedure specified in site procedure LLW01 (see Section 7.4.2) relating to the non-radioactive properties of the waste (i.e. the proposal is for the disposal of radioactive wastes that would be classified as inert, non-hazardous or hazardous in terms of their content of non-radioactive materials). The impact of non-radioactive properties of the LLW waste is therefore covered by the HRA assessments.

462. An outline of the key landfill engineering features follows:

- A full containment landfill engineering system designed to meet the requirements of the EU Landfill Directive. For the basal liner and side wall liner, the non-hazardous landfill incorporates a 1 m thick layer of engineered low permeability clay with a maximum hydraulic conductivity of 1 10^{-9} ms^{-1} and a 2 mm HDPE synthetic liner. The engineered clay layer is 1.5 m thick for the hazardous waste cells.;
- A low permeability cap consisting of a 300 mm regulation layer, a geosynthetic clay liner, a geotextile protection layer and at least 1 m of restoration soil cover;
- Ancillary systems such as vehicle cleaning equipment;
- A surface water, groundwater, gas and environmental monitoring system;
- The landfill site will be restored to areas of grassland, scrub and woodland and the wider site will be restored to areas of open water, aquatic marginal vegetation, scrub, wet meadow and ruderal grassland with small hollows, banks and ridges suitable for nature conservation use and permissive public access; and,
- Operational arrangements for site construction, operation, closure, restoration and aftercare.

463. The features and arrangements are not described in detail in this document (see (MJCA, 2019a; MJCA, 2019b) and references therein).

7.2 Site investigation {R11}

464. The NS-GRA includes a requirement that a site investigation has been undertaken (Requirement 11):

> "The developer/operator of a disposal facility for solid radioactive waste should carry out a programme of site investigation and site characterisation to provide information for the environmental safety case and to support facility design and construction." (UK Environment Agencies, 2009) para 6.4.6

465. The site has been the subject of a number of site investigations to support environmental impact assessments and site permits. These have characterised the geological and hydrogeological setting of the site and associated development. A summary of the results of site investigations is presented in the HRA (MJCA, 2019a).

466. A baseline radiological survey has been undertaken for background levels of radioactivity in materials on the site. The results from that survey are presented in Appendix B.

7.3 Use of site and facility design, construction, operation and closure {R12}

467. The NS-GRA includes a requirement concerning the management of the facility from design through to closure (Requirement 12):

> "The developer/operator of a disposal facility for solid radioactive waste should make sure that the site is used and the facility is designed, constructed, operated and capable of closure so as to avoid unacceptable effects on the performance of the disposal system." (UK Environment Agencies, 2009) para 6.4.16

468. The design, construction and operation of the site is in accordance with the Landfill Directive as described in Section 2.4 of this report. The Landfill Directive requires that the site provides long term protection of the environment. The risk assessments reported in the HRA (MJCA, 2019b) show that the site will provide an appropriate level of containment for tens of thousands of years. The site uses conventional landfill rather than novel technologies, which provides confidence in the engineered solution.

469. The Environmental Permit for waste landfill sites cannot be surrendered until the Environment Agency is satisfied that:

- the site has ceased accepting waste;
- relevant closure procedures have been complied with;
- an appropriate period of aftercare has passed to allow the waste to stabilise and to gather evidence to demonstrate that the active pollution control measures are no longer necessary; and,
- the deposits of waste are in a satisfactory state that, if left undisturbed, will not cause pollution of the environment or harm to human health.

470. Following closure and into the aftercare phase Augean will continue to manage the site in accordance with the Permit. In accordance with the Landfill Directive and the Environmental Permitting Regulations Augean has agreed with the Environment

Agency an approach to providing funds for the aftercare of the site in the event that Augean ceases to exist.

7.3.1 LLW operations

471. Prior to agreement that each specific LLW consignment can be accepted at the site, Augean will require a range of information from the consignor, including detailed characterisation information regarding the physical nature, the chemistry and radioactive content of the waste together with information regarding the quantity, form, voidage in containers and proposed packaging of the material. Augean will need to be provided with a copy of the relevant Environment Agency Authorisation or Environmental Permit for the disposal of the waste from the source site. The information will be assessed by Augean Technical Assessors and the site management to determine if the material is suitable for disposal at the site and is consistent with the conditions of the Environmental Permit. On approval by the Technical Assessor and site management, the consignor will be permitted to make a booking to deliver the waste to the site. The consignor will be advised of the delivery requirements for the waste, including an external exposure limit of 10 μSv h^{-1} at a 1 m distance from each package.

472. Prior to the delivery of wastes, the timetable and details of the waste will be pre-notified to the site in accordance with the transportation regulations and pre-acceptance checks will be carried out to confirm the suitability of the waste for deposition at the site. Augean will audit the consigning facilities routinely to confirm that the characterisation and packaging procedures are followed. The detailed procedures will be consistent with the requirements of any Environmental Permit issued by the Environment Agency.

473. Most of the LLW that will be accepted at the site will be at a level of activity that can be transported without the need for any specified packaging or containment. Augean has determined that it will specify that all consignors should send LLW to Port Clarence in ISO containers, drums or double skinned bags except in special circumstances where BAT dictates otherwise. Articles that are too large to be placed in containers will be wrapped. It will be a requirement that the activity measured at 1 m from each package face must not exceed 10 μSv h^{-1}. Where loose tipping is proposed, the activity concentration must meet the more restrictive limits specified in the Permit, the waste must be covered and the 10 μSv h^{-1} dose rate at 1 m from the waste must be met.

474. The LLW will be transported to the site in accordance with relevant transport regulations that apply to the radioactive wastes. The regulations are established to control the risks to vehicle drivers and risks from, for example, transport accidents that could result in waste spillage. Due to the limited amount of radioactivity in the LLW that can be accepted at the site, most wastes will not need any form of special packaging or shielding during handling or transport. However, as noted above, for ease of handling and in order to minimise the potential for spillage, Augean will oblige waste producers to ensure that waste is transported in enclosed containers such as drums, bulk bags or other containers. Similarly, waste with very low activity concentrations (as specified in the permit) could be loose tipped and must be transported in enclosed skips or trucks. Some large items of waste such as metal sheeting or concrete slabs, may not be transported in containers but will be wrapped.

475. On arrival at the site and prior to acceptance onto a landfill cell, the RPS will confirm that the characterisation information which accompanies the waste load is adequate,

conforms to the pre-acceptance information and that the load is acceptable for deposition at the site. Wastes arriving at the landfill will be subject to a physical check on the integrity of packaging and monitoring to check that the external radiation dose is no more than 10 μSv h^{-1} at a distance of 1 m from the package. The packages will not be opened or sampled at the site in order to minimise unnecessary exposure. Waste that will be loose tipped will be subject to the external radiation dose check and a physical check to identify whether dust suppression measures will be required.

476. Procedures have been set out to cover the unlikely event that unacceptable wastes arrive at the site. If the unacceptable wastes can be returned safely to the consignor, they will be refused acceptance at the site and returned to their source. If they may not be safe to return to the sender, quarantine measures will be implemented and the Environment Agency will be notified immediately. The detailed procedures for quarantine are specified in accordance with the radiation protection plan for the site, which is established in accordance with the Environmental Permit and to meet the requirements of the Ionising Radiation Regulations. LLW will not be accumulated intentionally. Waste for disposal will be placed in a landfill cell as soon as practicable after inspection on arrival at Port Clarence and within a maximum of 24 hours following acceptance for disposal at the Port Clarence site.

477. Once the waste has been accepted and can be deposited, the delivery vehicle will travel along the internal haul roads to an unloading point adjacent to an active landfill area. The waste packages will be lifted from the delivery vehicles using mechanical handling machines such as fork-lift trucks and placed in the landfill. For waste that will be loose tipped into the landfill, the delivery vehicle will be positioned by the delivery driver as instructed by Augean staff and the driver will activate the tipping as instructed by Augean staff. The waste will be disposed of in the operational working cell or cells and will be placed alongside other waste. The disposal of radioactive waste will take place only under the supervision of an RPS who will be responsible for the operation of the plant at the disposal face.

478. LLW is not placed within 2 m from the base of the cell and the perimeter seal. No LLW is placed within the top metre of the waste in each cell. Wastes containing significant activity concentrations of Ra-226 (i.e.>5 Bq/g) will be placed at least 5 m below the final restored surface (see Appendix E.5.7.2). No LLW will be placed in the engineered separation bund.

479. Immediately after placement, the deposited LLW will be covered with a minimum thickness of 400 mm of suitable non-LLW cover material over all exposed surfaces. The radiation levels at 1 m above the top of the cover material will be measured to check conformance with the specified dose rate of 2 μSv h^{-1}. If the radiation level exceeds the specified dose rate, additional cover will be placed as necessary until the specified dose rate is achieved. These precautions will provide additional confidence that no specific protective measures are needed for workers at the site who are closest to the LLW and will provide additional confidence that anyone off-site is also suitably protected.

480. As the predicted doses of radiation to which workers at the site will be exposed are below those specified under the Ionising Radiation Regulations 1999 no workers will be defined as Classified Persons in accordance with the regulations. Specific personal protective equipment additional to the standard equipment used and worn by workers at a hazardous waste landfill site will not be necessary during normal site operations. Passive dosimeters will be worn by staff working in the LLW reception and disposal areas as reassurance to confirm that the exposures received are in accordance with

the predictions. The personal dosimeters used by workers at the ENRMF have never recorded a dose above background levels, all measurements being below detection limits.

NORM Acceptance

481. Port Clarence accepts Type 2 NORM waste under the provisions of the exemption from the requirement to have a permit in accordance with Section 6 of Part 6 to Schedule 23 of the EPR2016. Following confirmation that the characterisation information is in order, the NORM waste is loose tipped into the working cell. The exposed surface is covered at the end of the working day in accordance with normal landfill procedures.

482. Type 2 NORM waste will not be used as covering material for LLW accepted at Port Clarence under the Permit.

7.3.2 Leachate management

483. The WRP has three waste plants that use landfill leachate for processing liquid. As a result, in many years there is a shortfall in processing liquid for the stabilisation process and Augean has imported leachate from its Mark's Quarry site. In the event that there is excess leachate generated at the Port Clarence landfills, such as during periods of WRP maintenance, the leachate can be stored in tanks at the WRP.

484. We confirm that we understand that the Billigham Reed Beds (Scott Bros. Ltd)) are not the subject of an RSR permit hence the facility would only be used if the leachate quality was not in scope of radioactive substances regulation, suitable for treatment and subject to appropriate permitting. Similarly, leachate will only be disposed of at Brans Sands if the leachate quality and radionuclide content meet the terms of their permit. The likelihood that leachate will be unsuitable for disposal at the above facilities is very low. The radiological capacity of the site is lower than the ENRMF, for a larger volume and area of landfill site. To date the radionuclide concentrations recorded in leachate at the ENRMF site (RPA/RWA review of 2019 results of the ENRMF Environmental Monitoring Programme, PHE June 2020) are considered to be exempt from requirement for a permit under EPR 2016 (as amended 2018), i.e., LLW inputs to the ENRMF site have not resulted in leachate contamination of regulatory concern.

485. The primary limitation on processing capacity at the WRP will be availability of APCR which is used as a reagent (a substitute for cement) in the stabilisation process. In the unlikely event that excess leachate is generated and is not suitable for disposal at the Reed Beds or Bran Sands, Augean has the option to use cement, lime or other stabilisation medium and if necessary Augean can also increase operating hours taking advantage of the 24 h operating consent under planning. As cement and lime are readily available to purchase this removes any constraint on the ability to use the leachate for stabilisation on-site.

486. The radiological capacity of each radionuclide that could result in the leachate disposal requiring a permit under the radioactive substances regulations because the level is above the ELLs is shown below (Table 33). This information will be used when considering the suite of radionuclides for leachate monitoring (see Section 7.5.2). Shaded cells indicate radionuclides where the maximum inventory exceeds the radiological capacity that would bring leachate under radioactive substances regulation. The radionuclides with the lowest capacity were discussed earlier in

Section 6.1.1.4. Based on disposal of the ENRMF fingerprint up to the radiological capacity of Port Clarence the resultant dose to an exposed off-site treatment plant workers is less than 0.005 µSv y^{-1}. On-site treatment of all leachate results in a dose of less than 0.06 µSv y^{-1} to WRP workers. Augean will submit an updated Leachate Management Plan should leachate for future off-site treatment, or WRP use, exceed the ELLs.

Table 33 Radiological capacity producing leachate activity concentrations above the relevant exemption level (ELL)

Radionuclide	ELL (Bq l^{-1})	Radiological capacity producing in-scope leachate (MBq)	Radionuclide	ELL (Bq l^{-1})	Radiological capacity producing in-scope leachate (MBq)
H-3	1000	$1.80\ 10^{9}$	Eu-154	0.01	$1.44\ 10^{7}$
C-14	0.1	$5.54\ 10^{7}$	Eu-155	0.1	$1.53\ 10^{8}$
Cl-36	10	$2.81\ 10^{7}$	Gd-153	0.1	$6.86\ 10^{8}$
Ca-41(1)	0.01	$4.54\ 10^{5}$	Pb-210	0.001	$1.14\ 10^{7}$
Mn-54	0.01	$1.39\ 10^{8}$	Po-210	0.001	$5.24\ 10^{6}$
Fe-55	1	$6.22\ 10^{9}$	Ra-226	0.01	$1.38\ 10^{8}$
Co-60	0.01	$3.02\ 10^{7}$	Ra-228	0.01	$1.56\ 10^{8}$
Ni-59	1	$1.55\ 10^{9}$	Ac-227	0.1	$9.70\ 10^{8}$
Ni-63	100	$1.56\ 10^{11}$	Th-228	1	$1.49\ 10^{10}$
Zn-65	0.1	$1.32\ 10^{9}$	Th-229	0.01	$1.05\ 10^{8}$
Se-79(1)	0.01	$1.11\ 10^{7}$	Th-230	1	$1.05\ 10^{10}$
Sr-90	0.1	$2.96\ 10^{7}$	Th-232	1	$1.05\ 10^{10}$
Mo-93	1	$2.22\ 10^{8}$	Pa-231	0.01	$1.11\ 10^{8}$
Zr-93	10	$2.27\ 10^{10}$	U-232	0.1	$1.12\ 10^{8}$
Nb-93m	10	$8.66\ 10^{10}$	U-233	0.1	$1.11\ 10^{8}$
Nb-94	0.1	$8.29\ 10^{8}$	U-234	0.1	$1.11\ 10^{8}$
Tc-99	10	$1.02\ 10^{8}$	U-235	0.1	$1.11\ 10^{8}$
Ru-106	0.1	$2.79\ 10^{8}$	U-236	0.1	$1.11\ 10^{8}$
Ag-108m	0.1	$2.11\ 10^{8}$	U-238	0.1	$1.11\ 10^{8}$
Ag-110m	0.1	$5.19\ 10^{8}$	Np-237	0.1	$1.95\ 10^{7}$
Cd-109	1	$1.39\ 10^{9}$	Pu-238	0.1	$4.13\ 10^{8}$
Sb-125	1	$4.39\ 10^{8}$	Pu-239	0.1	$4.09\ 10^{8}$
Sn-119m(1)	0.01	$1.93\ 10^{8}$	Pu-240	0.1	$4.09\ 10^{8}$
Sn-123(1)	0.01	$4.36\ 10^{8}$	Pu-241	10	$4.29\ 10^{10}$
Sn-126(1)	0.01	$8.85\ 10^{7}$	Pu-242	0.1	$4.09\ 10^{8}$
Te-127m	1	$1.66\ 10^{10}$	Pu-244	0.1	$4.09\ 10^{8}$
I-129	0.1	$3.93\ 10^{6}$	Am-241	0.1	$1.44\ 10^{9}$
Ba-133(1)	0.01	$3.59\ 10^{4}$	Am-242m	0.1	$1.44\ 10^{9}$
Cs-134	0.01	$9.16\ 10^{7}$	Am-243	0.1	$1.44\ 10^{9}$

Radionuclide	ELL (Bq l^{-1})	Radiological capacity producing in-scope leachate (MBq)	Radionuclide	ELL (Bq l^{-1})	Radiological capacity producing in-scope leachate (MBq)
Cs-135	0.1	$6.64\ 10^{8}$	Cm-242	1	$1.91\ 10^{11}$
Cs-137	0.01	$6.79\ 10^{7}$	Cm-243	0.1	$5.27\ 10^{9}$
Ce-144	0.1	$1.48\ 10^{9}$	Cm-244	0.1	$5.34\ 10^{9}$
Pm-147	10	$3.22\ 10^{10}$	Cm-245	0.01	$5.14\ 10^{8}$
Sm-147(1)	0.01	$5.14\ 10^{7}$	Cm-246	0.1	$5.14\ 10^{9}$
Sm-151	100	$5.18\ 10^{11}$	Cm-248	0.1	$5.14\ 10^{9}$
Eu-152	0.01	$1.40\ 10^{7}$	Any other radionuclide	0.01	$1.95\ 10^{6}$

1) The default value of 0.001 applies to any radionuclide not listed
2) The radiological capacity of grey shaded cells is less than the maximum inventory.

7.4 Waste acceptance criteria {R13}

487. The NS-GRA includes a requirement that the developer/operator of the facility makes sure that the waste accepted for disposal is consistent with the ESC and demonstrates that there are procedures in place to make sure that these criteria are met before waste is emplaced in the facility (Requirement 13). The waste acceptance criteria are found in the CfA (Procedure PC LLW01) for Port Clarence.

> "The developer/operator of a disposal facility for solid radioactive waste should establish waste acceptance criteria consistent with the assumptions made in the environmental safety case and with the requirements for transport and handling, and demonstrate that these can be applied during operations at the facility." (UK Environment Agencies, 2009) para 6.4.26

7.4.1 Introduction

488. It is important that only wastes that meet regulatory criteria are accepted for disposal at the Port Clarence site. Calculations are presented in Appendix E that determine a set of radionuclide-specific limits and Section 7.4.2 discusses how these are used as part of a waste acceptance process. This includes the radiological capacity of the site and limits on the activity concentration in the wastes. Conditions that are placed on waste consignors and specific controls for waste receipt at the Port Clarence site are addressed in Section 7.4.3.

489. The total inventory in the site (the sum of the LLW disposed of in the hazardous landfill and the LLW disposed of in the non-hazardous landfill) needs to be controlled in order to ensure protection of humans and the environment from the combined effects of the two landfills. Early discussions with the Environment Agency determined that the two landfills would operate under the same permit for LLW disposal. However, the conditions and types of waste accepted at the two landfills are different and therefore a single limiting radiological capacity for each radionuclide is not appropriate. For example, landfill gas generated in the non-hazardous landfill is collected and used on-site for power generation (or power is sold back into the grid) releasing carbon and hydrogen to atmosphere and representing a future pathway for the release of C-14 and H-3. There is also a low risk of waste catching fire in the non-hazardous landfill due to higher organic matter content allowed in the wastes, however wastes with higher organic matter content will not be disposed to the hazardous waste landfill due to the restrictions placed on disposal of waste organic matter content. These two scenarios (landfill gas and fire) are relevant for the non-hazardous site but not relevant to the hazardous site.

490. For the other scenarios that are selected to limit radiological capacity from scenarios presented in the ESC there is little difference between the impact of the same scenario on either landfill. For example, the radiological capacity determined for an excavator 60 years after closure is not sensitive to the type of landfill and it can be assumed that the radiological capacity for this scenario applies to both landfills. It is therefore appropriate to calculate the sum of fractions for each scenario for each landfill separately and then combine the fractions for the scenarios common to the two landfills into a total sum of fractions for the two landfills together. Hence, the total sum of fractions for each scenario includes the contribution from the inventory in the hazardous landfill and the contribution from the inventory in the non-hazardous landfill

(in the case of the landfill gas and fire scenarios the contribution from the hazardous landfill will be zero).

491. If the sum of fractions for each scenario is less than 1 then the waste can be accepted.

492. NORM wastes are controlled by a limit on the total tonnage in the site.

493. Finally, to ensure that the dose constraint of 0.3 mSv/y is not exceeded during the period of authorization, the doses from the LLW wastes and NORM wastes disposed of in the site are calculated and summed.

494. A worked example of the approach is given in Appendix D.

7.4.1.1 Radiological Capacity

495. The radiological capacities of the Port Clarence landfills are presented in three tables showing the limiting scenarios:

- Table 34 Scenario radiological capacity calculations WRP workers, leachate spillage and recreational use
- Table 35 Scenario radiological capacity calculations for site erosion and bathtubbing
- Table 36 Scenario radiological capacity for inundation (flooding), landfill fire (non-hazardous landfill only) and for burrowing mammals

496. Each table lists scenarios with a dose per unit disposal (µSv MBq^{-1}) and the scenario radiological capacity ($L_{Rn,\ Scenario}$) calculated as shown above for each radionuclide. For the dose arising from a groundwater pathway, a cut-off at 10^{-13} µSv MBq^{-1} is applied and the capacity is shown as "greater than" indicating the dose per unit disposal is very small. Two values are given for Ra-226 where appropriate: one for wastes containing significant activity concentrations of Ra-226 (>5 Bq g^{-1}) that are buried 5 m below the restored surface, and one for wastes containing small activity concentrations of Ra-226 that could be buried within 5 m of the restored surface.

497. The radiological capacities for the limiting scenarios are not combined into a single column of values because each scenario is addressed in turn when using the sum of fractions to limit disposals. Applying the sum of fractions approach to each scenario in turn allows Augean to understand the radiological impact of the LLW proposed for disposal. The radiological capacities from the limiting scenarios are summarised in Table 37.

498. These scenario radiological capacity values are proposed for inclusion in the Environment Agency permit and would be applied using the sum of fractions approach to each scenario in turn. This approach will ensure that estimated radiation doses arising from the disposed inventory will never exceed the regulatory criteria whatever the radionuclide mix in the inventory of LLW disposed. The exact details of waste acceptance criteria would normally be prepared after issue of the permit or draft permit when it is clear what the Environment Agency accepts for disposal at the site. The proposed limits for activity concentrations in packaged waste are presented below in Table 38 and in loose tipped waste in Table 39. The scenarios and activities proposed for limiting radiological capacities in the hazardous landfill are presented in Table 41 and for the non-hazardous landfill in Table 42.

499. The screening value for dose to biota is not intended to represent a limit but they have been applied in this way in order to determine the scenario radiological capacity for burrowing mammals. A waste emplacement strategy would be employed to remove the need to determine the sum of fractions for burrowing mammals (the sum of fractions is not relevant if the waste is below the burrowing depth).It is noted that burrowing animals would not be impacted with waste disposed at the maximum inventory, and this basis a scenario radiological capacity for burrowing animals could be omitted.

500. The ESC proposal to limit LLW disposal to 5% of the available void space will limit LLW disposal to about 230,000 t LLW. This disposal at Port Clarence combined with a maximum specific activity proposed for each radionuclide constrains the maximum disposed inventory for each radionuclide.

501. In broad terms, the larger the radiological capacity for a radionuclide in Table 28, the less impact the radionuclide has on constraining inputs to Port Clarence. Considering a single radionuclide, the maximum input to the Port Clarence site will be controlled either by the calculated radiological capacity or by the limit of 230,000 t of LLW.

502. In addition to the limits set out in Table 37, it is proposed that a category of “Other radionuclides” is included. This category would correspond to radionuclides with half-lives greater than 3 months and that are not otherwise identified in Table 6.

503. It is proposed that there is a component comprising “Other radionuclides”. For the “other radionuclides” this category would be assigned a radiological capacity equal to the limiting capacity for Np-237 across all scenarios.

Table 34 Scenario radiological capacity calculations for WRP workers, leachate spillage and recreational use

Radionuclide	Sewage treatment - worker (0y) 20,158 m3 (WRP)		Leachate spillage (0y) All ages		Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth	
	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)
H-3	$5.61\ 10^{-11}$	$1.78\ 10^{13}$	$4.95\ 10^{-10}$	$6.06\ 10^{11}$	$5.23\ 10^{-9}$	$3.82\ 10^{9}$
C-14	$1.02\ 10^{-10}$	$9.82\ 10^{12}$	$5.49\ 10^{-9}$	$5.46\ 10^{10}$	$1.69\ 10^{-7}$	$1.19\ 10^{8}$
Cl-36	$2.65\ 10^{-7}$	$3.78\ 10^{9}$	$8.56\ 10^{-8}$	$3.50\ 10^{9}$	$2.22\ 10^{-27}$	$8.99\ 10^{27}$
Ca-41	$6.60\ 10^{-12}$	$1.52\ 10^{14}$	$3.18\ 10^{-9}$	$9.43\ 10^{10}$	0	nd
Mn-54	$3.23\ 10^{-9}$	$3.10\ 10^{11}$	$2.35\ 10^{-11}$	$1.28\ 10^{13}$	$8.99\ 10^{-19}$	$2.22\ 10^{19}$
Fe-55	$8.69\ 10^{-14}$	$1.15\ 10^{16}$	$1.53\ 10^{-11}$	$1.96\ 10^{13}$	$4.46\ 10^{-15}$	$4.49\ 10^{15}$
Co-60	$4.79\ 10^{-8}$	$2.09\ 10^{10}$	$8.44\ 10^{-10}$	$3.55\ 10^{11}$	$1.02\ 10^{-16}$	$1.96\ 10^{17}$
Ni-59	$5.90\ 10^{-13}$	$1.70\ 10^{15}$	$5.57\ 10^{-12}$	$5.39\ 10^{13}$	$5.82\ 10^{-10}$	$3.44\ 10^{10}$
Ni-63	$4.80\ 10^{-12}$	$2.08\ 10^{14}$	$1.37\ 10^{-11}$	$2.20\ 10^{13}$	$5.18\ 10^{-9}$	$3.86\ 10^{9}$
Zn-65	$2.43\ 10^{-9}$	$4.11\ 10^{11}$	$1.21\ 10^{-9}$	$2.48\ 10^{11}$	$6.40\ 10^{-18}$	$3.13\ 10^{18}$
Se-79	$5.98\ 10^{-11}$	$1.67\ 10^{13}$	$3.69\ 10^{-8}$	$8.12\ 10^{9}$	$5.30\ 10^{-62}$	$3.77\ 10^{62}$
Sr-90	$1.52\ 10^{-8}$	$6.58\ 10^{10}$	$1.62\ 10^{-8}$	$1.85\ 10^{10}$	$1.09\ 10^{-24}$	$1.84\ 10^{25}$
Mo-93	$3.53\ 10^{-11}$	$2.84\ 10^{13}$	$6.15\ 10^{-10}$	$4.88\ 10^{11}$	$5.37\ 10^{-9}$	$3.72\ 10^{9}$
Zr-93	$5.06\ 10^{-12}$	$1.98\ 10^{14}$	$3.97\ 10^{-11}$	$7.55\ 10^{12}$	$6.13\ 10^{-9}$	$3.27\ 10^{9}$
Nb-93m	$9.36\ 10^{-14}$	$1.07\ 10^{16}$	$7.71\ 10^{-12}$	$3.89\ 10^{13}$	$9.60\ 10^{-10}$	$2.08\ 10^{10}$
Nb-94	$1.02\ 10^{-8}$	$9.78\ 10^{10}$	$8.60\ 10^{-11}$	$3.49\ 10^{12}$	$9.27\ 10^{-19}$	$2.16\ 10^{19}$
Tc-99	$1.76\ 10^{-8}$	$5.67\ 10^{10}$	$7.96\ 10^{-9}$	$3.77\ 10^{10}$	$4.40\ 10^{-46}$	$4.55\ 10^{46}$
Ru-106	$6.27\ 10^{-9}$	$1.59\ 10^{11}$	$2.18\ 10^{-10}$	$1.38\ 10^{12}$	$2.57\ 10^{-20}$	$7.78\ 10^{20}$
Ag-108m	$3.98\ 10^{-8}$	$2.51\ 10^{10}$	$1.76\ 10^{-10}$	$1.71\ 10^{12}$	$7.55\ 10^{-20}$	$2.65\ 10^{20}$
Ag-110m	$2.88\ 10^{-8}$	$3.48\ 10^{10}$	$9.11\ 10^{-11}$	$3.29\ 10^{12}$	$6.46\ 10^{-18}$	$3.10\ 10^{18}$
Cd-109	$8.27\ 10^{-11}$	$1.21\ 10^{13}$	$2.16\ 10^{-10}$	$1.39\ 10^{12}$	$6.05\ 10^{-49}$	$3.31\ 10^{49}$
Sb-125	$4.91\ 10^{-8}$	$2.04\ 10^{10}$	$4.35\ 10^{-10}$	$6.90\ 10^{11}$	$6.55\ 10^{-21}$	$3.05\ 10^{21}$
Sn-119m	$1.06\ 10^{-12}$	$9.45\ 10^{14}$	$2.85\ 10^{-11}$	$1.05\ 10^{13}$	0	nd
Sn-123	$4.85\ 10^{-11}$	$2.06\ 10^{13}$	$8.09\ 10^{-11}$	$3.71\ 10^{12}$	$8.66\ 10^{-20}$	$2.31\ 10^{20}$
Sn-126	$1.19\ 10^{-8}$	$8.38\ 10^{10}$	$8.02\ 10^{-10}$	$3.74\ 10^{11}$	$2.16\ 10^{-19}$	$9.27\ 10^{19}$
Te-127m	$3.11\ 10^{-12}$	$3.22\ 10^{14}$	$1.07\ 10^{-10}$	$2.80\ 10^{12}$	$1.56\ 10^{-38}$	$1.28\ 10^{39}$
I-129	$7.85\ 10^{-9}$	$1.27\ 10^{11}$	$1.10\ 10^{-6}$	$2.73\ 10^{8}$	$2.81\ 10^{-138}$	$7.10\ 10^{138}$
Ba-133	$4.72\ 10^{-6}$	$2.12\ 10^{8}$	$4.17\ 10^{-8}$	$7.19\ 10^{9}$	$1.55\ 10^{-23}$	$1.29\ 10^{24}$

Radionuclide	Sewage treatment - worker (0y) 20,158 m3 (WRP)		Leachate spillage (0y) All ages		Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth	
	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)
Cs-134	$9.06\ 10^{-9}$	$1.10\ 10^{11}$	$3.55\ 10^{-9}$	$8.46\ 10^{10}$	$3.73\ 10^{-19}$	$5.36\ 10^{19}$
Cs-135	$2.28\ 10^{-11}$	$4.38\ 10^{13}$	$5.15\ 10^{-10}$	$5.82\ 10^{11}$	$3.41\ 10^{-54}$	$5.87\ 10^{54}$
Cs-137	$4.44\ 10^{-9}$	$2.25\ 10^{11}$	$3.27\ 10^{-9}$	$9.17\ 10^{10}$	$7.60\ 10^{-20}$	$2.63\ 10^{20}$
Ce-144	$4.98\ 10^{-11}$	$2.01\ 10^{13}$	$3.37\ 10^{-11}$	$8.89\ 10^{12}$	$1.13\ 10^{-34}$	$1.77\ 10^{35}$
Pm-147	$2.64\ 10^{-11}$	$3.79\ 10^{13}$	$9.83\ 10^{-12}$	$3.05\ 10^{13}$	$3.57\ 10^{-45}$	$5.60\ 10^{45}$
Sm-147	$1.11\ 10^{-10}$	$9.02\ 10^{12}$	$4.52\ 10^{-10}$	$6.64\ 10^{11}$	0	nd
Sm-151	$1.94\ 10^{-12}$	$5.14\ 10^{14}$	$2.05\ 10^{-12}$	$1.46\ 10^{14}$	0	nd
Eu-152	$4.54\ 10^{-8}$	$2.20\ 10^{10}$	$2.23\ 10^{-10}$	$1.35\ 10^{12}$	$4.27\ 10^{-18}$	$4.68\ 10^{18}$
Eu-154	$4.80\ 10^{-8}$	$2.08\ 10^{10}$	$3.50\ 10^{-10}$	$8.57\ 10^{11}$	$5.90\ 10^{-18}$	$3.39\ 10^{18}$
Eu-155	$1.08\ 10^{-9}$	$9.23\ 10^{11}$	$6.01\ 10^{-11}$	$4.99\ 10^{12}$	$2.96\ 10^{-40}$	$6.75\ 10^{40}$
Gd-153	$2.96\ 10^{-10}$	$3.38\ 10^{12}$	$4.37\ 10^{-12}$	$6.87\ 10^{13}$	$3.82\ 10^{-42}$	$5.24\ 10^{42}$
Pb-210	$4.06\ 10^{-10}$	$2.46\ 10^{12}$	$9.58\ 10^{-8}$	$3.13\ 10^{9}$	$1.26\ 10^{-20}$	$1.59\ 10^{21}$
Po-210	$3.77\ 10^{-10}$	$2.65\ 10^{12}$	$3.50\ 10^{-8}$	$8.57\ 10^{9}$	$5.44\ 10^{-24}$	$3.68\ 10^{24}$
Ra-226	$1.95\ 10^{-8}$	$5.13\ 10^{10}$	$5.27\ 10^{-8}$	$5.70\ 10^{9}$	$3.48\ 10^{-16}$	$5.75\ 10^{16}$
Ra-228	$9.09\ 10^{-9}$	$1.10\ 10^{11}$	$2.38\ 10^{-8}$	$1.26\ 10^{10}$	$4.91\ 10^{-15}$	$4.07\ 10^{15}$
Ac-227	$5.28\ 10^{-9}$	$1.89\ 10^{11}$	$7.34\ 10^{-9}$	$4.09\ 10^{10}$	$2.85\ 10^{-20}$	$7.01\ 10^{20}$
Th-228	$6.10\ 10^{-9}$	$1.64\ 10^{11}$	$3.70\ 10^{-9}$	$8.11\ 10^{10}$	$3.15\ 10^{-15}$	$6.34\ 10^{15}$
Th-229	$2.83\ 10^{-9}$	$3.53\ 10^{11}$	$1.14\ 10^{-8}$	$2.64\ 10^{10}$	$9.80\ 10^{-18}$	$2.04\ 10^{18}$
Th-230	$5.23\ 10^{-10}$	$1.91\ 10^{12}$	$2.70\ 10^{-9}$	$1.11\ 10^{11}$	$4.90\ 10^{-38}$	$4.08\ 10^{38}$
Th-232	$1.41\ 10^{-8}$	$7.10\ 10^{10}$	$3.46\ 10^{-8}$	$8.66\ 10^{9}$	$4.91\ 10^{-15}$	$4.07\ 10^{15}$
Pa-231	$8.86\ 10^{-10}$	$1.13\ 10^{12}$	$2.20\ 10^{-9}$	$1.36\ 10^{11}$	$8.90\ 10^{-26}$	$2.25\ 10^{26}$
U-232	$2.03\ 10^{-7}$	$4.93\ 10^{9}$	$1.88\ 10^{-8}$	$1.60\ 10^{10}$	$7.84\ 10^{-15}$	$2.55\ 10^{15}$
U-233	$5.26\ 10^{-10}$	$1.90\ 10^{12}$	$1.45\ 10^{-9}$	$2.07\ 10^{11}$	$8.45\ 10^{-32}$	$2.37\ 10^{32}$
U-234	$5.09\ 10^{-10}$	$1.97\ 10^{12}$	$1.39\ 10^{-9}$	$2.15\ 10^{11}$	$5.19\ 10^{-45}$	$3.85\ 10^{45}$
U-235	$6.87\ 10^{-9}$	$1.46\ 10^{11}$	$1.35\ 10^{-9}$	$2.23\ 10^{11}$	$3.53\ 10^{-29}$	$5.67\ 10^{29}$
U-236	$4.72\ 10^{-10}$	$2.12\ 10^{12}$	$1.34\ 10^{-9}$	$2.25\ 10^{11}$	$4.21\ 10^{-41}$	$4.75\ 10^{41}$
U-238	$4.61\ 10^{-9}$	$2.17\ 10^{11}$	$1.43\ 10^{-9}$	$2.09\ 10^{11}$	$8.03\ 10^{-20}$	$2.49\ 10^{20}$
Np-237	$6.68\ 10^{-8}$	$1.50\ 10^{10}$	$1.95\ 10^{-8}$	$1.54\ 10^{10}$	$3.62\ 10^{-25}$	$5.53\ 10^{25}$
Pu-238	$1.46\ 10^{-9}$	$6.84\ 10^{11}$	$1.77\ 10^{-9}$	$1.69\ 10^{11}$	$6.36\ 10^{-47}$	$3.14\ 10^{47}$
Pu-239	$1.61\ 10^{-9}$	$6.22\ 10^{11}$	$1.94\ 10^{-9}$	$1.55\ 10^{11}$	$3.58\ 10^{-31}$	$5.59\ 10^{31}$
Pu-240	$1.61\ 10^{-9}$	$6.23\ 10^{11}$	$1.94\ 10^{-9}$	$1.55\ 10^{11}$	$4.97\ 10^{-54}$	$4.02\ 10^{54}$

Radionuclide	Sewage treatment - worker (0y) 20,158 m3 (WRP)		Leachate spillage (0y) All ages		Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth	
	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)
Pu-241	$2.93\ 10^{-11}$	$3.41\ 10^{13}$	$3.55\ 10^{-11}$	$8.45\ 10^{12}$	$2.75\ 10^{-40}$	$7.28\ 10^{40}$
Pu-242	$1.48\ 10^{-9}$	$6.77\ 10^{11}$	$1.86\ 10^{-9}$	$1.61\ 10^{11}$	$7.23\ 10^{-65}$	$2.76\ 10^{65}$
Pu-244	$6.57\ 10^{-9}$	$1.52\ 10^{11}$	$1.87\ 10^{-9}$	$1.60\ 10^{11}$	$1.20\ 10^{-19}$	$1.66\ 10^{20}$
Am-241	$3.92\ 10^{-10}$	$2.55\ 10^{12}$	$6.32\ 10^{-10}$	$4.75\ 10^{11}$	$8.36\ 10^{-61}$	$2.39\ 10^{61}$
Am-242m	$5.06\ 10^{-10}$	$1.97\ 10^{12}$	$7.61\ 10^{-10}$	$3.94\ 10^{11}$	$6.70\ 10^{-20}$	$2.98\ 10^{20}$
Am-243	$9.49\ 10^{-10}$	$1.05\ 10^{12}$	$6.35\ 10^{-10}$	$4.72\ 10^{11}$	$8.56\ 10^{-29}$	$2.34\ 10^{29}$
Cm-242	$1.64\ 10^{-12}$	$6.11\ 10^{14}$	$7.08\ 10^{-11}$	$4.23\ 10^{12}$	$3.68\ 10^{-41}$	$5.44\ 10^{41}$
Cm-243	$1.68\ 10^{-10}$	$5.94\ 10^{12}$	$1.36\ 10^{-9}$	$2.20\ 10^{11}$	$4.62\ 10^{-29}$	$4.33\ 10^{29}$
Cm-244	$5.85\ 10^{-11}$	$1.71\ 10^{13}$	$1.07\ 10^{-9}$	$2.80\ 10^{11}$	0	nd
Cm-245	$1.72\ 10^{-10}$	$5.82\ 10^{12}$	$1.95\ 10^{-9}$	$1.54\ 10^{11}$	$3.13\ 10^{-34}$	$6.40\ 10^{34}$
Cm-246	$1.09\ 10^{-10}$	$9.19\ 10^{12}$	$1.95\ 10^{-9}$	$1.54\ 10^{11}$	$4.79\ 10^{-136}$	$4.18\ 10^{136}$
Cm-248	$1.94\ 10^{-9}$	$5.14\ 10^{11}$	$7.14\ 10^{-9}$	$4.20\ 10^{10}$	0	nd
Note: Where dose is effectively zero the radiological capacity is infinite, marked here as nd (not determined).						

Table 35 Scenario radiological capacity calculations for site erosion and bathtubbing

Radionuclide	Erosion to coast (60y) All ages (PC-Cream)		Erosion - Dog walker (60y & 20,000y) All ages		Bathtubbing	
	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)*	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)*	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)*
H-3	$3.60\ 10^{-16}$	$5.55\ 10^{16}$	$1.38\ 10^{-12}$	$1.45\ 10^{13}$	$6.33\ 10^{-9}$	$3.16\ 10^{9}$
C-14	$6.62\ 10^{-9}$	$3.02\ 10^{9}$	$1.33\ 10^{-9}$	$1.50\ 10^{10}$	$4.55\ 10^{-10}$	$4.40\ 10^{10}$
Cl-36	$7.00\ 10^{-14}$	$2.86\ 10^{14}$	$5.26\ 10^{-9}$	$3.80\ 10^{9}$	$1.16\ 10^{-5}$	$1.72\ 10^{6}$
Ca-41	$7.45\ 10^{-13}$	$2.68\ 10^{13}$	$4.33\ 10^{-10}$	$4.62\ 10^{10}$	$1.91\ 10^{-8}$	$1.05\ 10^{9}$
Mn-54	0	nd	$2.21\ 10^{-30}$	$9.06\ 10^{30}$	0	nd
Fe-55	$3.08\ 10^{-16}$	$6.49\ 10^{16}$	$5.03\ 10^{-16}$	$3.97\ 10^{16}$	0	nd
Co-60	$2.14\ 10^{-11}$	$9.34\ 10^{11}$	$8.90\ 10^{-12}$	$2.25\ 10^{12}$	0	nd

Radionuclide	Erosion to coast (60y) All ages (PC-Cream)		Erosion - Dog walker (60y & 20,000y) All ages		Bathtubbing	
	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)*	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)*	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)*
Ni-59	2.67 10^{-10}	7.48 10^{10}	2.84 10^{-10}	7.05 10^{10}	2.52 10^{-11}	7.94 10^{11}
Ni-63	3.53 10^{-11}	5.66 10^{11}	4.63 10^{-10}	4.32 10^{10}	3.55 10^{-13}	5.63 10^{13}
Zn-65	0	nd	1.23 10^{-35}	1.63 10^{36}	0	nd
Se-79	1.09 10^{-8}	1.84 10^{9}	2.33 10^{-8}	8.58 10^{8}	1.38 10^{-8}	1.44 10^{9}
Sr-90	2.13 10^{-11}	9.40 10^{11}	1.83 10^{-8}	1.09 10^{9}	2.57 10^{-10}	7.77 10^{10}
Mo-93	7.02 10^{-10}	2.85 10^{10}	5.69 10^{-9}	3.52 10^{9}	3.36 10^{-7}	5.95 10^{7}
Zr-93	4.45 10^{-10}	4.49 10^{10}	6.36 10^{-10}	3.15 10^{10}	1.36 10^{-9}	1.48 10^{10}
Nb-93m	7.70 10^{-12}	2.60 10^{12}	5.77 10^{-11}	3.46 10^{11}	0	nd
Nb-94	2.55 10^{-7}	7.83 10^{7}	8.86 10^{-9}	2.26 10^{9}	6.70 10^{-9}	2.99 10^{9}
Tc-99	3.02 10^{-10}	6.63 10^{10}	4.01 10^{-9}	4.98 10^{9}	2.98 10^{-7}	6.70 10^{7}
Ru-106	0	nd	9.07 10^{-26}	2.20 10^{26}	0	nd
Ag-108m	1.01 10^{-8}	1.99 10^{9}	9.00 10^{-9}	2.22 10^{9}	5.51 10^{-9}	3.63 10^{9}
Ag-110m	0	nd	5.11 10^{-35}	3.92 10^{35}	0	nd
Cd-109	1.48 10^{-22}	1.35 10^{23}	3.97 10^{-23}	5.04 10^{23}	0	nd
Sb-125	2.10 10^{-16}	9.54 10^{16}	1.84 10^{-15}	1.09 10^{16}	0	nd
Sn-119m	0	nd	6.47 10^{-32}	3.09 10^{32}	0	nd
Sn-123	0	nd	1.16 10^{-59}	1.72 10^{60}	0	nd
Sn-126	1.46 10^{-7}	1.37 10^{8}	2.78 10^{-8}	7.20 10^{8}	1.13 10^{-8}	1.77 10^{9}
Te-127m	0	nd	9.96 10^{-71}	2.01 10^{71}	0	nd
I-129	6.45 10^{-10}	3.10 10^{10}	1.83 10^{-7}	1.09 10^{8}	2.14 10^{-7}	9.36 10^{7}
Ba-133	3.37 10^{-11}	5.93 10^{11}	1.02 10^{-10}	1.96 10^{11}	2.22 10^{-12}	9.00 10^{12}
Cs-134	3.08 10^{-18}	6.50 10^{18}	2.52 10^{-17}	7.92 10^{17}	0	nd
Cs-135	5.72 10^{-11}	3.49 10^{11}	1.93 10^{-9}	1.04 10^{10}	5.36 10^{-10}	3.73 10^{10}
Cs-137	7.23 10^{-10}	2.77 10^{10}	2.60 10^{-9}	7.70 10^{9}	5.78 10^{-13}	3.46 10^{13}
Ce-144	0	nd	2.28 10^{-31}	8.76 10^{31}	0	nd
Pm-147	4.09 10^{-16}	4.89 10^{16}	2.07 10^{-16}	9.67 10^{16}	0	nd
Sm-147	3.12 10^{-9}	6.40 10^{9}	1.28 10^{-7}	1.56 10^{8}	5.22 10^{-7}	3.83 10^{7}
Sm-151	4.47 10^{-12}	4.47 10^{12}	3.39 10^{-10}	5.90 10^{10}	2.70 10^{-13}	7.40 10^{13}
Eu-152	2.99 10^{-9}	6.69 10^{9}	3.14 10^{-10}	6.38 10^{10}	2.58 10^{-13}	7.75 10^{13}
Eu-154	3.73 10^{-10}	5.36 10^{10}	8.44 10^{-11}	2.37 10^{11}	2.22 10^{-14}	9.00 10^{14}
Eu-155	2.29 10^{-13}	8.75 10^{13}	2.99 10^{-13}	6.69 10^{13}	0	nd

Radionuclide	Erosion to coast (60y) All ages (PC-Cream)		Erosion - Dog walker (60y & 20,000y) All ages		Bathtubbing	
	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)*	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)*	Dose per MBq (µSv y^{-1} MBq^{-1})	Scenario Radiological Capacity (MBq)*
Gd-153	0	nd	5.51 10^{-37}	3.63 10^{37}	0	nd
Pb-210	2.55 10^{-6}	7.84 10^{6}	1.59 10^{-6}	1.26 10^{7}	1.57 10^{-11}	1.27 10^{12}
Po-210	0	nd	1.57 10^{-53}	1.27 10^{54}	0	nd
Ra-226	1.44 10^{-5}	1.39 10^{6}	1.09 10^{-5}	1.84 10^{6}	7.73 10^{-8}	2.59 10^{8}
Ra-228	1.98 10^{-10}	1.01 10^{11}	4.17 10^{-9}	4.80 10^{9}	4.30 10^{-14}	4.65 10^{14}
Ac-227	1.17 10^{-8}	1.71 10^{9}	6.53 10^{-7}	3.06 10^{7}	8.95 10^{-10}	2.23 10^{10}
Th-228	2.11 10^{-18}	9.48 10^{18}	3.55 10^{-16}	5.63 10^{16}	0	nd
Th-229	7.15 10^{-8}	2.80 10^{8}	2.25 10^{-6}	8.88 10^{6}	4.68 10^{-6}	4.27 10^{6}
Th-230	4.08 10^{-7}	4.91 10^{7}	7.29 10^{-7}	2.74 10^{7}	5.40 10^{-6}	3.70 10^{6}
Th-232	7.15 10^{-7}	2.80 10^{7}	6.25 10^{-6}	3.20 10^{6}	9.24 10^{-6}	2.16 10^{6}
Pa-231	1.53 10^{-7}	1.31 10^{8}	4.95 10^{-6}	4.04 10^{6}	2.59 10^{-5}	7.73 10^{5}
U-232	5.31 10^{-9}	3.76 10^{9}	9.44 10^{-7}	2.12 10^{7}	1.60 10^{-7}	1.25 10^{8}
U-233	8.94 10^{-10}	2.24 10^{10}	1.45 10^{-7}	1.38 10^{8}	7.93 10^{-5}	2.52 10^{5}
U-234	6.29 10^{-10}	3.18 10^{10}	1.23 10^{-7}	1.62 10^{8}	1.29 10^{-5}	1.55 10^{6}
U-235	9.86 10^{-10}	2.03 10^{10}	1.25 10^{-7}	1.60 10^{8}	9.58 10^{-5}	2.09 10^{5}
U-236	4.47 10^{-10}	4.48 10^{10}	1.22 10^{-7}	1.64 10^{8}	4.71 10^{-6}	4.24 10^{6}
U-238	5.43 10^{-10}	3.69 10^{10}	1.34 10^{-7}	1.50 10^{8}	4.80 10^{-6}	4.17 10^{6}
Np-237	1.34 10^{-8}	1.50 10^{9}	2.28 10^{-7}	8.79 10^{7}	2.68 10^{-4}	7.47 10^{4}
Pu-238	4.71 10^{-8}	4.25 10^{8}	2.68 10^{-7}	7.47 10^{7}	9.37 10^{-9}	2.13 10^{9}
Pu-239	9.04 10^{-8}	2.21 10^{8}	4.51 10^{-7}	4.44 10^{7}	5.13 10^{-6}	3.89 10^{6}
Pu-240	8.99 10^{-8}	2.22 10^{8}	4.49 10^{-7}	4.46 10^{7}	3.34 10^{-6}	5.98 10^{6}
Pu-241	1.38 10^{-9}	1.45 10^{10}	1.21 10^{-8}	1.66 10^{9}	1.86 10^{-9}	1.07 10^{10}
Pu-242	8.69 10^{-8}	2.30 10^{8}	4.30 10^{-7}	4.65 10^{7}	5.87 10^{-6}	3.41 10^{6}
Pu-244	1.25 10^{-7}	1.60 10^{8}	4.48 10^{-7}	4.46 10^{7}	1.11 10^{-5}	1.80 10^{6}
Am-241	3.98 10^{-8}	5.03 10^{8}	3.63 10^{-7}	5.51 10^{7}	5.42 10^{-8}	3.69 10^{8}
Am-242m	6.16 10^{-8}	3.25 10^{8}	4.83 10^{-7}	4.14 10^{7}	3.08 10^{-8}	6.48 10^{8}
Am-243	8.46 10^{-8}	2.36 10^{8}	3.98 10^{-7}	5.02 10^{7}	2.59 10^{-6}	7.73 10^{6}
Cm-242	2.40 10^{-10}	8.32 10^{10}	1.37 10^{-9}	1.46 10^{10}	4.79 10^{-11}	4.18 10^{11}
Cm-243	1.06 10^{-8}	1.88 10^{9}	8.48 10^{-8}	2.36 10^{8}	6.26 10^{-9}	3.20 10^{9}
Cm-244	2.58 10^{-9}	7.76 10^{9}	3.20 10^{-8}	6.24 10^{8}	9.25 10^{-9}	2.16 10^{9}
Cm-245	8.87 10^{-8}	2.25 10^{8}	4.04 10^{-7}	4.95 10^{7}	1.38 10^{-6}	1.45 10^{7}

Radionuclide	Erosion to coast (60y) All ages (PC-Cream)		Erosion - Dog walker (60y & 20,000y) All ages		Bathtubbing	
	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)*	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)*	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)*
Cm-246	$6.45\ 10^{-8}$	$3.10\ 10^{8}$	$3.96\ 10^{-7}$	$5.05\ 10^{7}$	$4.19\ 10^{-7}$	$4.78\ 10^{7}$
Cm-248	$2.40\ 10^{-7}$	$8.33\ 10^{7}$	$1.50\ 10^{-6}$	$1.34\ 10^{7}$	$1.60\ 10^{-5}$	$1.25\ 10^{6}$
* Where dose is effectively zero the radiological capacity is infinite, marked here as nd (not determined).						

Table 36 Scenario radiological capacity calculated for inundation (flooding), landfill fire (non-hazardous landfill only) and for burrowing mammals

Radionuclide	Inundation (flooding)		Landfill fire		Burrowing mammals*	
	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)	Dose to NHB per MBq ($\mu Gy\ h^{-1}\ MBq^{-1}$)	Scenario radiological capacity (MBq)
H-3	$1.06\ 10^{-7}$	$1.88\ 10^{8}$	$7.82\ 10^{-9}$	$3.83\ 10^{10}$	$3.27\ 10^{-13}$	$1.22\ 10^{14}$
C-14	$1.65\ 10^{-12}$	$1.21\ 10^{13}$	$1.65\ 10^{-7}$	$1.82\ 10^{9}$	$2.48\ 10^{-10}$	$1.61\ 10^{11}$
Cl-36	$3.94\ 10^{-5}$	$5.08\ 10^{5}$	$2.08\ 10^{-7}$	$1.44\ 10^{9}$	$2.06\ 10^{-7}$	$1.94\ 10^{8}$
Ca-41	$1.25\ 10^{-9}$	$1.60\ 10^{10}$	$6.79\ 10^{-12}$	$4.42\ 10^{13}$	$3.12\ 10^{-8}$	$1.28\ 10^{9}$
Mn-54	0	0	$5.26\ 10^{-11}$	$5.70\ 10^{12}$	$2.12\ 10^{-18}$	$1.89\ 10^{19}$
Fe-55	0	0	$2.88\ 10^{-11}$	$1.04\ 10^{13}$	$3.78\ 10^{-17}$	$1.06\ 10^{18}$
Co-60	$4.05\ 10^{-14}$	$4.94\ 10^{14}$	$8.92\ 10^{-10}$	$3.36\ 10^{11}$	$9.91\ 10^{-11}$	$4.03\ 10^{11}$
Ni-59	$2.38\ 10^{-14}$	$8.41\ 10^{14}$	$1.25\ 10^{-11}$	$2.40\ 10^{13}$	$8.58\ 10^{-11}$	$4.66\ 10^{11}$
Ni-63	$4.55\ 10^{-14}$	$4.39\ 10^{14}$	$3.70\ 10^{-11}$	$8.11\ 10^{12}$	$6.05\ 10^{-11}$	$6.61\ 10^{11}$
Zn-65	0	0	$8.05\ 10^{-9}$	$3.73\ 10^{10}$	$1.10\ 10^{-18}$	$3.63\ 10^{19}$
Se-79	$2.43\ 10^{-11}$	$8.22\ 10^{11}$	$1.94\ 10^{-7}$	$1.55\ 10^{9}$	$3.74\ 10^{-9}$	$1.07\ 10^{10}$
Sr-90	$1.54\ 10^{-10}$	$1.30\ 10^{11}$	$4.60\ 10^{-9}$	$6.53\ 10^{10}$	$4.16\ 10^{-8}$	$9.61\ 10^{8}$
Mo-93	$3.70\ 10^{-9}$	$5.41\ 10^{9}$	$6.55\ 10^{-11}$	$4.58\ 10^{12}$	$2.32\ 10^{-10}$	$1.72\ 10^{11}$
Zr-93	$8.26\ 10^{-13}$	$2.42\ 10^{13}$	$7.12\ 10^{-10}$	$4.22\ 10^{11}$	$6.56\ 10^{-12}$	$6.10\ 10^{12}$
Nb-93m	$1.20\ 10^{-15}$	$1.67\ 10^{16}$	$5.15\ 10^{-11}$	$5.83\ 10^{12}$	$1.32\ 10^{-11}$	$3.02\ 10^{12}$
Nb-94	$2.30\ 10^{-12}$	$8.70\ 10^{12}$	$1.40\ 10^{-9}$	$2.14\ 10^{11}$	$1.49\ 10^{-7}$	$2.68\ 10^{8}$
Tc-99	$1.15\ 10^{-6}$	$1.73\ 10^{7}$	$3.70\ 10^{-10}$	$8.11\ 10^{11}$	$3.96\ 10^{-9}$	$1.01\ 10^{10}$
Ru-106	0	0	$1.88\ 10^{-7}$	$1.60\ 10^{9}$	$2.54\ 10^{-19}$	$1.58\ 10^{20}$
Ag-108m	$7.76\ 10^{-11}$	$2.58\ 10^{11}$	$1.06\ 10^{-8}$	$2.83\ 10^{10}$	$1.38\ 10^{-7}$	$2.89\ 10^{8}$
Ag-110m	0	0	$3.81\ 10^{-9}$	$7.87\ 10^{10}$	$2.73\ 10^{-18}$	$1.47\ 10^{19}$

Radionuclide	Inundation (flooding)		Landfill fire		Burrowing mammals*	
	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)	Dose to NHB per MBq ($\mu Gy\ h^{-1}\ MBq^{-1}$)	Scenario radiological capacity (MBq)
Cd-109	0	0	$2.88\ 10^{-10}$	$1.04\ 10^{12}$	$1.22\ 10^{-19}$	$3.28\ 10^{20}$
Sb-125	0	0	$3.70\ 10^{-8}$	$8.10\ 10^{9}$	$1.82\ 10^{-14}$	$2.20\ 10^{15}$
Sn-119m	0	0	$6.38\ 10^{-11}$	$4.70\ 10^{12}$	$8.76\ 10^{-21}$	$4.57\ 10^{21}$
Sn-123	0	0	$2.47\ 10^{-10}$	$1.21\ 10^{12}$	$1.96\ 10^{-20}$	$2.04\ 10^{21}$
Sn-126	$2.52\ 10^{-12}$	$7.93\ 10^{12}$	$8.67\ 10^{-10}$	$3.46\ 10^{11}$	$1.87\ 10^{-7}$	$2.13\ 10^{8}$
Te-127m	0	0	$2.88\ 10^{-8}$	$1.04\ 10^{10}$	$1.30\ 10^{-19}$	$3.09\ 10^{20}$
I-129	$1.51\ 10^{-8}$	$1.32\ 10^{9}$	$1.38\ 10^{-6}$	$2.17\ 10^{8}$	$6.36\ 10^{-10}$	$6.29\ 10^{10}$
Ba-133	$2.13\ 10^{-11}$	$9.38\ 10^{11}$	$2.86\ 10^{-10}$	$1.05\ 10^{12}$	$7.67\ 10^{-10}$	$5.22\ 10^{10}$
Cs-134	0	0	$5.82\ 10^{-8}$	$5.15\ 10^{9}$	$9.48\ 10^{-16}$	$4.22\ 10^{16}$
Cs-135	$1.18\ 10^{-13}$	$1.70\ 10^{14}$	$2.45\ 10^{-8}$	$1.23\ 10^{10}$	$2.79\ 10^{-8}$	$1.43\ 10^{9}$
Cs-137	$3.40\ 10^{-13}$	$5.88\ 10^{13}$	$1.11\ 10^{-7}$	$2.70\ 10^{9}$	$3.70\ 10^{-8}$	$1.08\ 10^{9}$
Ce-144	0	0	$1.95\ 10^{-9}$	$1.54\ 10^{11}$	$2.65\ 10^{-20}$	$1.51\ 10^{21}$
Pm-147	0	0	$1.44\ 10^{-10}$	$2.08\ 10^{12}$	$3.67\ 10^{-17}$	$1.09\ 10^{18}$
Sm-147	$1.40\ 10^{-10}$	$1.43\ 10^{11}$	$2.73\ 10^{-7}$	$1.10\ 10^{9}$	$6.47\ 10^{-8}$	$6.18\ 10^{8}$
Sm-151	$3.66\ 10^{-14}$	$5.46\ 10^{14}$	$1.14\ 10^{-10}$	$2.63\ 10^{12}$	$4.11\ 10^{-11}$	$9.74\ 10^{11}$
Eu-152	$4.98\ 10^{-13}$	$4.02\ 10^{13}$	$1.20\ 10^{-9}$	$2.50\ 10^{11}$	$5.02\ 10^{-9}$	$7.97\ 10^{9}$
Eu-154	$9.56\ 10^{-14}$	$2.09\ 10^{14}$	$1.51\ 10^{-9}$	$1.98\ 10^{11}$	$9.56\ 10^{-10}$	$4.18\ 10^{10}$
Eu-155	$1.00\ 10^{-16}$	$1.99\ 10^{17}$	$1.97\ 10^{-10}$	$1.53\ 10^{12}$	$5.76\ 10^{-13}$	$6.94\ 10^{13}$
Gd-153	0	0	$8.70\ 10^{-11}$	$3.45\ 10^{12}$	$5.73\ 10^{-20}$	$6.98\ 10^{20}$
Pb-210	$5.01\ 10^{-11}$	$3.99\ 10^{11}$	$1.42\ 10^{-4}$	$2.11\ 10^{6}$	$8.53\ 10^{-8}$	$4.69\ 10^{8}$
Po-210	0	0	$1.22\ 10^{-7}$	$2.45\ 10^{9}$	$3.18\ 10^{-18}$	$1.26\ 10^{19}$
Ra-226	$3.64\ 10^{-10}$	$5.50\ 10^{10}$	$5.56\ 10^{-7}$	$5.40\ 10^{8}$	$2.90\ 10^{-6}$	$1.38\ 10^{7}$
Ra-228	$3.97\ 10^{-13}$	$5.04\ 10^{13}$	$1.70\ 10^{-6}$	$1.77\ 10^{8}$	$6.94\ 10^{-10}$	$5.76\ 10^{10}$
Ac-227	$6.54\ 10^{-10}$	$3.06\ 10^{10}$	$1.62\ 10^{-5}$	$1.85\ 10^{7}$	$1.35\ 10^{-7}$	$2.96\ 10^{8}$
Th-228	0	0	$1.24\ 10^{-6}$	$2.42\ 10^{8}$	$1.53\ 10^{-16}$	$2.61\ 10^{17}$
Th-229	$1.81\ 10^{-9}$	$1.10\ 10^{10}$	$7.29\ 10^{-6}$	$4.11\ 10^{7}$	$5.85\ 10^{-8}$	$6.84\ 10^{8}$
Th-230	$1.05\ 10^{-9}$	$1.91\ 10^{10}$	$2.85\ 10^{-6}$	$1.05\ 10^{8}$	$7.80\ 10^{-8}$	$5.13\ 10^{8}$
Th-232	$1.18\ 10^{-9}$	$1.69\ 10^{10}$	$4.83\ 10^{-6}$	$6.21\ 10^{7}$	$7.90\ 10^{-7}$	$5.06\ 10^{7}$
Pa-231	$5.45\ 10^{-9}$	$3.67\ 10^{9}$	$3.99\ 10^{-6}$	$7.53\ 10^{7}$	$9.36\ 10^{-7}$	$4.27\ 10^{7}$
U-232	$1.54\ 10^{-8}$	$1.30\ 10^{9}$	$2.29\ 10^{-6}$	$1.31\ 10^{8}$	$1.23\ 10^{-7}$	$3.24\ 10^{8}$
U-233	$1.47\ 10^{-8}$	$1.36\ 10^{9}$	$2.73\ 10^{-7}$	$1.10\ 10^{9}$	$1.55\ 10^{-8}$	$2.58\ 10^{9}$
U-234	$7.44\ 10^{-9}$	$2.69\ 10^{9}$	$2.68\ 10^{-7}$	$1.12\ 10^{9}$	$1.50\ 10^{-8}$	$2.66\ 10^{9}$
U-235	$1.65\ 10^{-8}$	$1.21\ 10^{9}$	$2.42\ 10^{-7}$	$1.24\ 10^{9}$	$2.73\ 10^{-8}$	$1.47\ 10^{9}$

Radionuclide	Inundation (flooding)		Landfill fire		Burrowing mammals*	
	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario Radiological Capacity (MBq)	Dose to NHB per MBq ($\mu Gy\ h^{-1}\ MBq^{-1}$)	Scenario radiological capacity (MBq)
U-236	5.88 10^{-9}	3.40 10^{9}	2.48 10^{-7}	1.21 10^{9}	1.41 10^{-8}	2.83 10^{9}
U-238	5.58 10^{-9}	3.58 10^{9}	2.28 10^{-7}	1.32 10^{9}	1.54 10^{-8}	2.60 10^{9}
Np-237	1.92 10^{-6}	1.04 10^{7}	1.42 10^{-6}	2.11 10^{8}	1.62 10^{-7}	2.47 10^{8}
Pu-238	1.24 10^{-9}	1.61 10^{10}	3.13 10^{-6}	9.58 10^{7}	5.20 10^{-8}	7.69 10^{8}
Pu-239	2.19 10^{-9}	9.13 10^{9}	3.42 10^{-6}	8.78 10^{7}	7.83 10^{-8}	5.11 10^{8}
Pu-240	2.18 10^{-9}	9.18 10^{9}	3.42 10^{-6}	8.78 10^{7}	7.81 10^{-8}	5.12 10^{8}
Pu-241	1.71 10^{-11}	1.17 10^{12}	6.55 10^{-8}	4.58 10^{9}	4.90 10^{-9}	8.16 10^{9}
Pu-242	2.01 10^{-9}	9.95 10^{9}	3.13 10^{-6}	9.58 10^{7}	7.45 10^{-8}	5.37 10^{8}
Pu-244	3.44 10^{-9}	5.81 10^{9}	3.13 10^{-6}	9.58 10^{7}	1.07 10^{-7}	3.76 10^{8}
Am-241	4.56 10^{-10}	4.39 10^{10}	2.73 10^{-6}	1.10 10^{8}	1.52 10^{-7}	2.63 10^{8}
Am-242m	1.15 10^{-9}	1.73 10^{10}	3.30 10^{-6}	9.10 10^{7}	1.28 10^{-7}	3.13 10^{8}
Am-243	8.32 10^{-10}	2.40 10^{10}	2.73 10^{-6}	1.10 10^{8}	1.74 10^{-7}	2.29 10^{8}
Cm-242	6.35 10^{-12}	3.15 10^{12}	1.69 10^{-7}	1.78 10^{9}	2.66 10^{-10}	1.51 10^{11}
Cm-243	2.62 10^{-11}	7.63 10^{11}	1.97 10^{-6}	1.52 10^{8}	4.45 10^{-8}	8.99 10^{8}
Cm-244	1.41 10^{-11}	1.42 10^{12}	1.62 10^{-6}	1.85 10^{8}	1.80 10^{-8}	2.23 10^{9}
Cm-245	6.21 10^{-10}	3.22 10^{10}	2.82 10^{-6}	1.06 10^{8}	1.78 10^{-7}	2.24 10^{8}
Cm-246	1.60 10^{-10}	1.25 10^{11}	2.79 10^{-6}	1.08 10^{8}	1.63 10^{-7}	2.45 10^{8}
Cm-248	5.25 10^{-10}	3.81 10^{10}	1.02 10^{-5}	2.93 10^{7}	7.18 10^{-7}	5.57 10^{7}

*Only applies to waste disposed of within the burrowing depth

Note: Where dose is effectively zero the radiological capacity is infinite, marked here as nd (not determined).

Table 37 Port Clarence radiological capacities (MBq)

Radionuclide	Sewage treatment - worker (0y) 20,158 m3 (WRP)	Leachate spillage (0y) All ages	Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth	Erosion to coast (60y) All ages (PC-Cream)	Erosion - Dog walker (60y & 20,000y) All ages	Bathtubbing	Inundation (flooding)	Fire in non-hazardous landfill – All ages	Burrowing mammals*
H-3	1.78 10^{13}	6.06 10^{11}	3.82 10^{9}	5.55 10^{16}	1.45 10^{13}	3.16 10^{9}	1.88 10^{8}	3.83 10^{10}	1.22 10^{14}
C-14	9.82 10^{12}	5.46 10^{10}	1.19 10^{8}	3.02 10^{9}	1.50 10^{10}	4.40 10^{10}	1.21 10^{13}	1.82 10^{9}	1.61 10^{11}
Cl-36	3.78 10^{9}	3.50 10^{9}	8.99 10^{27}	2.86 10^{14}	3.80 10^{9}	1.72 10^{6}	5.08 10^{5}	1.44 10^{9}	1.94 10^{8}
Ca-41	1.52 10^{14}	9.43 10^{10}	nd	2.68 10^{13}	4.62 10^{10}	1.05 10^{9}	1.60 10^{10}	4.42 10^{13}	1.28 10^{9}

Radionuclide	Sewage treatment - worker (0y) 20,158 m3 (WRP)	Leachate spillage (0y) All ages	Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth	Erosion to coast (60y) All ages (PC-Cream)	Erosion - Dog walker (60y & 20,000y) All ages	Bathtubbing	Inundation (flooding)	Fire in non-hazardous landfill – All ages	Burrowing mammals*
Mn-54	3.10 10^{11}	1.28 10^{13}	2.22 10^{19}	nd	9.06 10^{30}	nd	nd	5.70 10^{12}	1.89 10^{19}
Fe-55	1.15 10^{16}	1.96 10^{13}	4.49 10^{15}	6.49 10^{16}	3.97 10^{16}	nd	nd	1.04 10^{13}	1.06 10^{18}
Co-60	2.09 10^{10}	3.55 10^{11}	1.96 10^{17}	9.34 10^{11}	2.25 10^{12}	nd	4.94 10^{14}	3.36 10^{11}	4.03 10^{11}
Ni-59	1.70 10^{15}	5.39 10^{13}	3.44 10^{10}	7.48 10^{10}	7.05 10^{10}	7.94 10^{11}	8.41 10^{14}	2.40 10^{13}	4.66 10^{11}
Ni-63	2.08 10^{14}	2.20 10^{13}	3.86 10^{9}	5.66 10^{11}	4.32 10^{10}	5.63 10^{13}	4.39 10^{14}	8.11 10^{12}	6.61 10^{11}
Zn-65	4.11 10^{11}	2.48 10^{11}	3.13 10^{18}	nd	1.63 10^{36}	nd	nd	3.73 10^{10}	3.63 10^{19}
Se-79	1.67 10^{13}	8.12 10^{9}	3.77 10^{62}	1.84 10^{9}	8.58 10^{8}	1.44 10^{9}	8.22 10^{11}	1.55 10^{9}	1.07 10^{10}
Sr-90	6.58 10^{10}	1.85 10^{10}	1.84 10^{25}	9.40 10^{11}	1.09 10^{9}	7.77 10^{10}	1.30 10^{11}	6.53 10^{10}	9.61 10^{8}
Mo-93	2.84 10^{13}	4.88 10^{11}	3.72 10^{9}	2.85 10^{10}	3.52 10^{9}	5.95 10^{7}	5.41 10^{9}	4.58 10^{12}	1.72 10^{11}
Zr-93	1.98 10^{14}	7.55 10^{12}	3.27 10^{9}	4.49 10^{10}	3.15 10^{10}	1.48 10^{10}	2.42 10^{13}	4.22 10^{11}	6.10 10^{12}
Nb-93m	1.07 10^{16}	3.89 10^{13}	2.08 10^{10}	2.60 10^{12}	3.46 10^{11}	nd	1.67 10^{16}	5.83 10^{12}	3.02 10^{12}
Nb-94	9.78 10^{10}	3.49 10^{12}	2.16 10^{19}	7.83 10^{7}	2.26 10^{9}	2.99 10^{9}	8.70 10^{12}	2.14 10^{11}	2.68 10^{8}
Tc-99	5.67 10^{10}	3.77 10^{10}	4.55 10^{46}	6.63 10^{10}	4.98 10^{9}	6.70 10^{7}	1.73 10^{7}	8.11 10^{11}	1.01 10^{10}
Ru-106	1.59 10^{11}	1.38 10^{12}	7.78 10^{20}	nd	2.20 10^{26}	nd	nd	1.60 10^{9}	1.58 10^{20}
Ag-108m	2.51 10^{10}	1.71 10^{12}	2.65 10^{20}	1.99 10^{9}	2.22 10^{9}	3.63 10^{9}	2.58 10^{11}	2.83 10^{10}	2.89 10^{8}
Ag-110m	3.48 10^{10}	3.29 10^{12}	3.10 10^{18}	nd	3.92 10^{35}	nd	nd	7.87 10^{10}	1.47 10^{19}
Cd-109	1.21 10^{13}	1.39 10^{12}	3.31 10^{49}	1.35 10^{23}	5.04 10^{23}	nd	nd	1.04 10^{12}	3.28 10^{20}
Sb-125	2.04 10^{10}	6.90 10^{11}	3.05 10^{21}	9.54 10^{16}	1.09 10^{16}	nd	nd	8.10 10^{9}	2.20 10^{15}
Sn-119m	9.45 10^{14}	1.05 10^{13}	nd	nd	3.09 10^{32}	nd	nd	4.70 10^{12}	4.57 10^{21}
Sn-123	2.06 10^{13}	3.71 10^{12}	2.31 10^{20}	nd	1.72 10^{60}	nd	nd	1.21 10^{12}	2.04 10^{21}
Sn-126	8.38 10^{10}	3.74 10^{11}	9.27 10^{19}	1.37 10^{8}	7.20 10^{8}	1.77 10^{9}	7.93 10^{12}	3.46 10^{11}	2.13 10^{8}
Te-127m	3.22 10^{14}	2.80 10^{12}	1.28 10^{39}	nd	2.01 10^{71}	nd	nd	1.04 10^{10}	3.09 10^{20}
I-129	1.27 10^{11}	2.73 10^{8}	7.10 10^{138}	3.10 10^{10}	1.09 10^{8}	9.36 10^{7}	1.32 10^{9}	2.17 10^{8}	6.29 10^{10}
Ba-133	2.12 10^{8}	7.19 10^{9}	1.29 10^{24}	5.93 10^{11}	1.96 10^{11}	9.00 10^{12}	9.38 10^{11}	1.05 10^{12}	5.22 10^{10}
Cs-134	1.10 10^{11}	8.46 10^{10}	5.36 10^{19}	6.50 10^{18}	7.92 10^{17}	nd	nd	5.15 10^{9}	4.22 10^{16}
Cs-135	4.38 10^{13}	5.82 10^{11}	5.87 10^{54}	3.49 10^{11}	1.04 10^{10}	3.73 10^{10}	1.70 10^{14}	1.23 10^{10}	1.43 10^{9}
Cs-137	2.25 10^{11}	9.17 10^{10}	2.63 10^{20}	2.77 10^{10}	7.70 10^{9}	3.46 10^{13}	5.88 10^{13}	2.70 10^{9}	1.08 10^{9}
Ce-144	2.01 10^{13}	8.89 10^{12}	1.77 10^{35}	nd	8.76 10^{31}	nd	nd	1.54 10^{11}	1.51 10^{21}
Pm-147	3.79 10^{13}	3.05 10^{13}	5.60 10^{45}	4.89 10^{16}	9.67 10^{16}	nd	nd	2.08 10^{12}	1.09 10^{18}
Sm-147	9.02 10^{12}	6.64 10^{11}	nd	6.40 10^{9}	1.56 10^{8}	3.83 10^{7}	1.43 10^{11}	1.10 10^{9}	6.18 10^{8}
Sm-151	5.14 10^{14}	1.46 10^{14}	nd	4.47 10^{12}	5.90 10^{10}	7.40 10^{13}	5.46 10^{14}	2.63 10^{12}	9.74 10^{11}
Eu-152	2.20 10^{10}	1.35 10^{12}	4.68 10^{18}	6.69 10^{9}	6.38 10^{10}	7.75 10^{13}	4.02 10^{13}	2.50 10^{11}	7.97 10^{9}

Radionuclide	Sewage treatment - worker (0y) 20,158 m3 (WRP)	Leachate spillage (0y) All ages	Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth	Erosion to coast (60y) All ages (PC-Cream)	Erosion - Dog walker (60y & 20,000y) All ages	Bathtubbing	Inundation (flooding)	Fire in non-hazardous landfill – All ages	Burrowing mammals*
Eu-154	2.08 10^{10}	8.57 10^{11}	3.39 10^{18}	5.36 10^{10}	2.37 10^{11}	9.00 10^{14}	2.09 10^{14}	1.98 10^{11}	4.18 10^{10}
Eu-155	9.23 10^{11}	4.99 10^{12}	6.75 10^{40}	8.75 10^{13}	6.69 10^{13}	nd	1.99 10^{17}	1.53 10^{12}	6.94 10^{13}
Gd-153	3.38 10^{12}	6.87 10^{13}	5.24 10^{42}	nd	3.63 10^{37}	nd	nd	3.45 10^{12}	6.98 10^{20}
Pb-210	2.46 10^{12}	3.13 10^{9}	1.59 10^{21}	7.84 10^{6}	1.26 10^{7}	1.27 10^{12}	3.99 10^{11}	2.11 10^{6}	4.69 10^{8}
Po-210	2.65 10^{12}	8.57 10^{9}	3.68 10^{24}	nd	1.27 10^{54}	nd	nd	2.45 10^{9}	1.26 10^{19}
Ra-226	5.13 10^{10}	5.70 10^{9}	5.75 10^{16}	1.39 10^{6}	1.84 10^{6}	2.59 10^{8}	5.50 10^{10}	5.40 10^{8}	1.38 10^{7}
Ra-228	1.10 10^{11}	1.26 10^{10}	4.07 10^{15}	1.01 10^{11}	4.80 10^{9}	4.65 10^{14}	5.04 10^{13}	1.77 10^{8}	5.76 10^{10}
Ac-227	1.89 10^{11}	4.09 10^{10}	7.01 10^{20}	1.71 10^{9}	3.06 10^{7}	2.23 10^{10}	3.06 10^{10}	1.85 10^{7}	2.96 10^{8}
Th-228	1.64 10^{11}	8.11 10^{10}	6.34 10^{15}	9.48 10^{18}	5.63 10^{16}	nd	nd	2.42 10^{8}	2.61 10^{17}
Th-229	3.53 10^{11}	2.64 10^{10}	2.04 10^{18}	2.80 10^{8}	8.88 10^{6}	4.27 10^{6}	1.10 10^{10}	4.11 10^{7}	6.84 10^{8}
Th-230	1.91 10^{12}	1.11 10^{11}	4.08 10^{38}	4.91 10^{7}	2.03 10^{6}	3.70 10^{6}	1.91 10^{10}	1.05 10^{8}	5.13 10^{8}
Th-232	7.10 10^{10}	8.66 10^{9}	4.07 10^{15}	2.80 10^{7}	3.20 10^{6}	2.16 10^{6}	1.69 10^{10}	6.21 10^{7}	5.06 10^{7}
Pa-231	1.13 10^{12}	1.36 10^{11}	2.25 10^{26}	1.31 10^{8}	4.04 10^{6}	7.73 10^{5}	3.67 10^{9}	7.53 10^{7}	4.27 10^{7}
U-232	4.93 10^{9}	1.60 10^{10}	2.55 10^{15}	3.76 10^{9}	2.12 10^{7}	1.25 10^{8}	1.30 10^{9}	1.31 10^{8}	3.24 10^{8}
U-233	1.90 10^{12}	2.07 10^{11}	2.37 10^{32}	2.24 10^{10}	1.03 10^{7}	2.52 10^{5}	1.36 10^{9}	1.10 10^{9}	2.58 10^{9}
U-234	1.97 10^{12}	2.15 10^{11}	3.85 10^{45}	3.18 10^{10}	1.06 10^{8}	1.55 10^{6}	2.69 10^{9}	1.12 10^{9}	2.66 10^{9}
U-235	1.46 10^{11}	2.23 10^{11}	5.67 10^{29}	2.03 10^{10}	3.72 10^{7}	2.09 10^{5}	1.21 10^{9}	1.24 10^{9}	1.47 10^{9}
U-236	2.12 10^{12}	2.25 10^{11}	4.75 10^{41}	4.48 10^{10}	1.64 10^{8}	4.24 10^{6}	3.40 10^{9}	1.21 10^{9}	2.83 10^{9}
U-238	2.17 10^{11}	2.09 10^{11}	2.49 10^{20}	3.69 10^{10}	1.43 10^{8}	4.17 10^{6}	3.58 10^{9}	1.32 10^{9}	2.60 10^{9}
Np-237	1.50 10^{10}	1.54 10^{10}	5.53 10^{25}	1.50 10^{9}	8.44 10^{7}	7.47 10^{4}	1.04 10^{7}	2.11 10^{8}	2.47 10^{8}
Pu-238	6.84 10^{11}	1.69 10^{11}	3.14 10^{47}	4.25 10^{8}	7.47 10^{7}	2.13 10^{9}	1.61 10^{10}	9.58 10^{7}	7.69 10^{8}
Pu-239	6.22 10^{11}	1.55 10^{11}	5.59 10^{31}	2.21 10^{8}	4.44 10^{7}	3.89 10^{6}	9.13 10^{9}	8.78 10^{7}	5.11 10^{8}
Pu-240	6.23 10^{11}	1.55 10^{11}	4.02 10^{54}	2.22 10^{8}	4.46 10^{7}	5.98 10^{6}	9.18 10^{9}	8.78 10^{7}	5.12 10^{8}
Pu-241	3.41 10^{13}	8.45 10^{12}	7.28 10^{40}	1.45 10^{10}	1.66 10^{9}	1.07 10^{10}	1.17 10^{12}	4.58 10^{9}	8.16 10^{9}
Pu-242	6.77 10^{11}	1.61 10^{11}	2.76 10^{65}	2.30 10^{8}	4.65 10^{7}	3.41 10^{6}	9.95 10^{9}	9.58 10^{7}	5.37 10^{8}
Pu-244	1.52 10^{11}	1.60 10^{11}	1.66 10^{20}	1.60 10^{8}	2.38 10^{7}	1.80 10^{6}	5.81 10^{9}	9.58 10^{7}	3.76 10^{8}
Am-241	2.55 10^{12}	4.75 10^{11}	2.39 10^{61}	5.03 10^{8}	5.51 10^{7}	3.69 10^{8}	4.39 10^{10}	1.10 10^{8}	2.63 10^{8}
Am-242m	1.97 10^{12}	3.94 10^{11}	2.98 10^{20}	3.25 10^{8}	4.14 10^{7}	6.48 10^{8}	1.73 10^{10}	9.10 10^{7}	3.13 10^{8}
Am-243	1.05 10^{12}	4.72 10^{11}	2.34 10^{29}	2.36 10^{8}	5.02 10^{7}	7.73 10^{6}	2.40 10^{10}	1.10 10^{8}	2.29 10^{8}
Cm-242	6.11 10^{14}	4.23 10^{12}	5.44 10^{41}	8.32 10^{10}	1.46 10^{10}	4.18 10^{11}	3.15 10^{12}	1.78 10^{9}	1.51 10^{11}
Cm-243	5.94 10^{12}	2.20 10^{11}	4.33 10^{29}	1.88 10^{9}	2.36 10^{8}	3.20 10^{9}	7.63 10^{11}	1.52 10^{8}	8.99 10^{8}
Cm-244	1.71 10^{13}	2.80 10^{11}	nd	7.76 10^{9}	6.24 10^{8}	2.16 10^{9}	1.42 10^{12}	1.85 10^{8}	2.23 10^{9}

Radionuclide	Sewage treatment - worker (0y) 20,158 m3 (WRP)	Leachate spillage (0y) All ages	Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth	Erosion to coast (60y) All ages (PC-Cream)	Erosion - Dog walker (60y & 20,000y) All ages	Bathtubbing	Inundation (flooding)	Fire in non-hazardous landfill – All ages	Burrowing mammals*
Cm-245	$5.82\ 10^{12}$	$1.54\ 10^{11}$	$6.40\ 10^{34}$	$2.25\ 10^{8}$	$4.95\ 10^{7}$	$1.45\ 10^{7}$	$3.22\ 10^{10}$	$1.06\ 10^{8}$	$2.24\ 10^{8}$
Cm-246	$9.19\ 10^{12}$	$1.54\ 10^{11}$	$4.18\ 10^{136}$	$3.10\ 10^{8}$	$5.05\ 10^{7}$	$4.78\ 10^{7}$	$1.25\ 10^{11}$	$1.08\ 10^{8}$	$2.45\ 10^{8}$
Cm-248	$5.14\ 10^{11}$	$4.20\ 10^{10}$	nd	$8.33\ 10^{7}$	$1.34\ 10^{7}$	$1.25\ 10^{6}$	$3.81\ 10^{10}$	$2.93\ 10^{7}$	$5.57\ 10^{7}$

Note *Only applies to waste disposed of within the burrowing depth.
Where dose is effectively zero the radiological capacity is infinite, marked here as nd (not determined).

7.4.1.2 Sum of fraction for activity concentration

504. For the disposal of radioactive waste containing more than one radionuclide (n) the activity concentration of the different radionuclides (A_i) must also meet the following criterion:

$$\sum_{i=1\ to\ n} \frac{A_i}{A_{i\ Lim}} \leq 1$$

where $A_{i\ Lim}$ is the activity concentration limit for radionuclide *i*.

505. This sum of fractions approach for activity concentration is the approach that is used to control disposals of the radionuclides shown in Table 4 under the Paris Convention on Third Party Liability (NEA, 2017) and out of scope activities under UK legislation (UK Government SI, 2018).

506. Four scenarios have been used to calculate the limits to be applied to the activity concentrations of waste disposed at Port Clarence. These considered the exposure of a worker during emplacement, exposure of a material recovery worker, exposure of a worker if a load is dropped and exposure of a coastal walker after site erosion. The limiting concentrations have then been determined based on the dose criteria for the public and workers for these scenarios. The values take into account the limits specified in the Paris convention (NEA, 2017).

507. Waste concentrations have then been banded as shown in Table 38. Eight bands have been used to cover radionuclide specific limits from 10 Bq g^{-1} to an upper limit of 5,000 Bq g^{-1}. A sum of fractions approach is used to limit the activity concentration of consignments (and packages that are part of a consignment) containing more than one radionuclide. Furthermore, an upper limit of 2000 Bq g^{-1} is proposed for a consignment fingerprint.

508. Radionuclides where maximum inventory is more limiting than the radiological capacity are identified in Table 40.

Table 38 Activity concentrations used to limit disposal of packaged LLW at Port Clarence

Radionuclide specific activity concentration per consignment (Bq g^{-1})	Radionuclide specific activity concentration per package that is part of a consignment (Bq g^{-1})	Radionuclides (* = listed in the Paris convention)
10	50	Ra-226, Th-232, Pa-231
20	100	Th-229
50	250	Sn-126, Pb-210, Ac-227, U-232, Cm-248
100	500	Nb-94, Ag-108m, Th-230, Pu-239*, Am-241*, Am-242m
200	1,000	Co-60*, Sr-90*, Tc-99*, I-129, Cs-137*, Sm-147, Ra-228, Th-228, U-233, U-234, U-235, U-236, U-238*, Np-237, Pu-238, Pu-240, Pu-242, Pu-244, Am-243, Cm-242, Cm-243, Cm-244, Cm-245, Cm-246, Any other radionuclides
1,000	2,000	none assigned
2,000	3,000	Se-79, Ag-110m, Eu-152, Po-210
5,000	5,000	H-3*, C-14*, Cl-36, Ca-41, Mn-54, Fe-55, Ni-59, Ni-63, Zn-65, Mo-93, Zr-93, Nb-93m, Ru-106, Cd-109, Sb-125, Sn-119m, Sn-123, Te-127m, Ba-133, Cs-134, Cs-135, Ce-144, Pm-147, Sm-151, Eu-154, Eu-155, Gd-153, Pu-241

509. Typical waste fingerprints show that the maximum activity concentration that would be accepted for disposal at Port Clarence ranges from 138 Bq g^{-1} for a high alpha waste type (Pu-239, Pu-241 and Am-241) to 347 Bq g^{-1} for a decommissioning waste containing (a mixture of Cs-137, Ni-63 and Co-60).

510. The activity limits for loose tipping wastes are calculated based on worker exposure (see Appendix E.3.4.1) and the risk to the public from a dropped load (see Appendix 0). The activity concentration of all radionuclides is limited by worker exposure during loose tipping. The activity concentrations have been banded using four concentration limits from 5 Bq g^{-1} to 100 Bq g^{-1}. (see Table 39). A sum of fractions approach is used to limit the total activity concentration of loose tipped consignments.

Table 39 Activity concentrations used to limit disposal of LLW at Port Clarence by loose tipping

Radionuclide specific activity concentration in the consignment (Bq g^{-1})	Radionuclides
5	Ac-227, Th-229, Th-230, Th-232, Pa-231, Pu-238, Pu-239, Pu-240, Pu-242, Pu-244, Am-241, Am-242m, Am-243, Cm-245, Cm-246, Cm-248
10	Ra-226, Ra-228, Th-228, U-232, Np-237, Cm-243, Cm-244
50	Sn-126, Sm-147, Pb-210, U-233, U-234, U-235, U-236, Cm-242, Any other radionuclides
100	H-3, C-14, Cl-36, Ca-41, Mn-54, Fe-55, Co-60, Ni-59, Ni-63, Zn-65, Se-79, Sr-90, Mo-93, Zr-93, Nb-93m, Nb-94, Tc-99, Ru-106, Ag-108m, Ag-110m, Cd-109, Sb-125, Sn-119m, Sn-123, Te-127m, I-129, Ba-133, Cs-134, Cs-135, Cs-137, Ce-144, Pm-147, Sm-151, Eu-152, Eu-154, Eu-155, Gd-153, Po-210, U-238, Pu-241

Table 40 Radionuclides where maximum inventory is more limiting than the radiological capacity

Radionuclide	Radiological capacity (MBq)	Scenario	Maximum Inventory[1] (MBq)	Limitation on activity concentration
Mn-54	$3.10\ 10^{11}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)	$1.10\ 10^{9}$	Worker emplacement (0.4m cover)
Fe-55	$1.96\ 10^{13}$	Leachate spillage (0y) All ages	$1.10\ 10^{9}$	Upper band in ESC
Co-60	$2.09\ 10^{10}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)	$4.39\ 10^{7}$	Paris Convention
Ni-59	$3.44\ 10^{10}$	Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth	$1.10\ 10^{9}$	Upper band in ESC
Ni-63	$3.86\ 10^{9}$	Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth	$1.10\ 10^{9}$	Upper band in ESC
Zn-65	$2.48\ 10^{11}$	Leachate spillage (0y) All ages	$1.10\ 10^{9}$	Worker emplacement (0.4m cover)
Se-79	$8.58\ 10^{8}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$4.39\ 10^{8}$	Erosion (60y)
Sr-90	$9.61\ 10^{8}$	ERICA results for Mammals - small-burrowing	$4.39\ 10^{7}$	Paris Convention
Zr-93	$3.27\ 10^{9}$	Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth	$1.10\ 10^{9}$	Upper band in ESC
Nb-93m	$2.08\ 10^{10}$	Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth	$1.10\ 10^{9}$	Upper band in ESC
Nb-94	$7.83\ 10^{7}$	Erosion to coast (60y) All ages (PC-Cream: 0.21)	$2.19\ 10^{7}$	Material recovery user (60y)
Ru-106	$1.59\ 10^{11}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)	$1.10\ 10^{9}$	Upper band in ESC
Ag-108m	$2.89\ 10^{8}$	ERICA results for Mammals - small-burrowing	$2.19\ 10^{7}$	Material recovery user (60y)
Ag-110m	$3.48\ 10^{10}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)	$4.39\ 10^{8}$	Worker emplacement (0.4m cover)
Cd-109	$1.39\ 10^{12}$	Leachate spillage (0y) All ages	$1.10\ 10^{9}$	Upper band in ESC
Sb-125	$2.04\ 10^{10}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)	$1.10\ 10^{9}$	Upper band in ESC
Sn-119m	$1.05\ 10^{13}$	Leachate spillage (0y) All ages	$1.10\ 10^{9}$	Upper band in ESC
Sn-123	$3.71\ 10^{12}$	Leachate spillage (0y) All ages	$1.10\ 10^{9}$	Upper band in ESC
Sn-126	$1.37\ 10^{8}$	Erosion to coast (60y) All ages (PC-Cream: 0.21)	$1.10\ 10^{7}$	Material recovery user (60y)
Te-127m	$2.80\ 10^{12}$	Leachate spillage (0y) All ages	$1.10\ 10^{9}$	Upper band in ESC
I-129	$9.36\ 10^{7}$	Seepage Default (bypass, standard cap) All ages - Residential	$4.39\ 10^{7}$	Erosion (60y)
Cs-134	$8.46\ 10^{10}$	Leachate spillage (0y) All ages	$1.10\ 10^{9}$	Worker emplacement (0.4m cover)
Cs-135	$1.43\ 10^{9}$	ERICA results for Mammals - small-burrowing	$1.10\ 10^{9}$	Upper band in ESC
Cs-137	$1.08\ 10^{9}$	ERICA results for Mammals - small-burrowing	$4.39\ 10^{7}$	Paris Convention
Ce-144	$8.89\ 10^{12}$	Leachate spillage (0y) All ages	$1.10\ 10^{9}$	Upper band in ESC
Pm-147	$3.05\ 10^{13}$	Leachate spillage (0y) All ages	$1.10\ 10^{9}$	Upper band in ESC
Sm-151	$5.90\ 10^{10}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$1.10\ 10^{9}$	Upper band in ESC
Eu-152	$6.69\ 10^{9}$	Erosion to coast (60y) All ages (PC-Cream: 0.21)	$4.39\ 10^{8}$	Material recovery user (60y)
Eu-154	$2.08\ 10^{10}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)	$1.10\ 10^{9}$	Worker emplacement (0.4m cover)
Eu-155	$9.23\ 10^{11}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)	$1.10\ 10^{9}$	Upper band in ESC

Radionuclide	Radiological capacity (MBq)	Scenario	Maximum Inventory[1] (MBq)	Limitation on activity concentration
Gd-153	$3.38\ 10^{12}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)	$1.10\ 10^{9}$	Upper band in ESC
Po-210	$8.57\ 10^{9}$	Leachate spillage (0y) All ages	$4.39\ 10^{8}$	Upper band in ESC
Ra-228	$4.80\ 10^{9}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$4.39\ 10^{7}$	Dropped load (Bag) worker
Ac-227	$3.06\ 10^{7}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$1.10\ 10^{7}$	Dropped load (Bag) worker
Th-228	$8.11\ 10^{10}$	Leachate spillage (0y) All ages	$4.39\ 10^{7}$	Dropped load (Bag) worker
U-232	$2.12\ 10^{7}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$1.10\ 10^{7}$	Material recovery user (60y)
Pu-238	$7.47\ 10^{7}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$4.39\ 10^{7}$	Erosion (60y)
Pu-241	$1.66\ 10^{9}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$1.10\ 10^{9}$	Erosion (60y)
Am-241	$5.51\ 10^{7}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$2.19\ 10^{7}$	Paris Convention
Am-242m	$4.14\ 10^{7}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$2.19\ 10^{7}$	Erosion (60y)
Cm-242	$1.46\ 10^{10}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$4.39\ 10^{8}$	Upper band in ESC
Cm-243	$2.36\ 10^{8}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$4.39\ 10^{7}$	Dropped load (Bag) worker
Cm-244	$6.24\ 10^{8}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages	$4.39\ 10^{7}$	Dropped load (Bag) worker
Cm-246	$4.78\ 10^{7}$	Seepage Default (bypass, standard cap) All ages - Residential	$4.39\ 10^{7}$	Erosion (60y)

Note: 1) Maximum inventory is the minimum of the radiological capacity and "tonnage x activity concentration limit"

7.4.1.3 Discussion

511. The sum of fractions approach is an internationally recognised approach (US NRC, 2014) and is considered to be best practice. The sum of fractions methodology described above takes account of the cumulative impact of disposal using the most restrictive scenario for each radionuclide. It is also proposed by the NEA (NEA, 2017) for the control of the activity concentration in the disposed waste. This sum of fractions approach is the approach proposed by Augean to control both the inventory disposed of at the site and the activity concentration of the waste that is accepted for disposal. Steps must be taken to ensure that the accumulated inventory at any time does not result in a sum of fractions exceeding one. Similarly, that the activity concentration in the waste proposed for disposal does not result in a sum of fraction exceeding one for the consignment or package. Furthermore, Augean propose a limit of 5% of the void for LLW, further limiting the inventory disposed at the site, and an upper limit of 2000 Bq g^{-1} on the activity concentration for a consignment fingerprint, further limiting the activity concentration of some radionuclides. This sum of fractions plus additional limits is the approach proposed by Augean for the permit application for disposal of LLW.

512. An alternative approach for the control of the inventory at the site would be to attempt to forecast what the disposal inventory will be when the landfill closes and demonstrate that this assumed inventory is consistent with meeting regulatory guidance. For some disposal facilities, such estimates may be possible based on the National Waste Inventory and market projections. However, this approach is not desirable for Port Clarence landfills because the future inventory is very uncertain and subject to future commercial agreements.

513. Port Clarence also accepts Type 2 NORM under the provisions of the exemption from the requirement for a permit described in EPR. The radiological assessment that supported the Type 2 NORM exemption submission assumed that the Port Clarence site accepts about 85,000 t of Type 2 NORM per year. The calculated total capacity for the non-hazardous and hazardous landfill sites was 2.8 10^5 t and 1.5 10^6 t of NORM waste (Jones, et al., 2014), respectively, based on allocated void space and a disposal activity of 10 Bq g^{-1}. For NORM disposals, we propose using a lower dose criterion of 300 µSv y^{-1} for the period after authorisation (Jones et al. used 1 mSv) with the observed disposal activity (<2 Bq g^{-1}) of the disposed NORM to recalculate the tonnage capacity for the site. On this basis the adjusted site capacity is 4.9 10^6 t of exempt NORM waste split between the two landfills pro-rata to void space. We propose to control the disposal of the Type 2 NORM according to the adjusted tonnage capacity, as is currently the case.

514. A record will be maintained showing the combined dose impacts from both waste streams for relevant exposure scenarios covering both the period of authorisation of the landfill and after the period of authorisation. The combined impacts to members of the public during the period of authorisation will not exceed a maximum dose limit of 300 µSv y^{-1}. After the period of authorisation, constraining combined doses to the dose equivalent of the risk guidance level in the situation where there is a probability of the scenario occurring of 1 (i.e. the lower of the relevant dose constraints) would be unnecessarily restrictive for the management of NORM disposals and outside the requirements of the NORM exemption. It is therefore appropriate to manage NORM and LLW post-closure impacts separately, in accordance with their respective dose and risk constraints. We will use a cautious dose criterion of 300 µSv y^{-1} for the NORM disposals.

515. We have chosen to limit the LLW disposals by specifying radiological capacities for a set of scenarios for each radionuclide, rather than a single capacity for each radionuclide. This is because we have 2 landfills and different scenarios produce limits for different timescales: for example, C-14 might be limited by exposure immediately after site closure, and Th-230 by erosion of the site when sea level rise impacts disposed waste. In this way we avoid over-conservatism and optimise use of the site. The scheme is straightforward to apply using a spreadsheet.

516. The different assessment scenarios proposed for the Permit and listed below:

- Recreational (0y);
- Erosion - Dog walker (Combining 60 y and 20,000 y);
- Erosion to coast (60 y);
- WRP treatment worker;
- Seepage;
- Flooding;
- Leachate spillage;
- ERICA (Mammals - small-burrowing); and,
- Landfill fire (non-hazardous only).

517. We provide a spreadsheet for review (Monitoring Tool Blank +examples (draft4).xlsx), it is very similar to that used at the ENRMF to monitor the sum of fractions for cumulative disposals.

7.4.2 Conditions for acceptance of LLW

518. Procedure LLW01 lists the conditions for acceptance (CfA) of LLW at the Port Clarence site that are part of the contract between the consignor and Augean. The conditions are in two parts: Part A being the “Specification” for the waste and Part B being the “Procedures” associated with the receipt and acceptance of the waste. Part A has four sections dealing with general requirements, radiological waste characteristics, hazardous waste and other conditions. Part B deals with the procedures that are applied. Those aspects that relate to the ESC are summarised below. The CfA is used in the contractual arrangements with consignors and is designed to provide information to Augean that will ensure that disposals at Port Clarence meet permit conditions. The decision process leading to receipt of waste at the Port Clarence site is detailed in Section 7.3.1.

519. The working procedures that will apply to radioactive waste accepted for disposal at the Port Clarence site also include the following:

- A procedure for the pre-acceptance of waste by the central technical team (LLW02).
- A procedure for the receipt of waste, assay, quarantine, waste emplacement, coverage, record keeping and general LLW disposal operations (LLW03).
- A procedure for the quarantine of non-compliant waste packages received at the Port Clarence site (LLW04).

- A procedure for monitoring employee doses and instructions for measuring X-Ray and Gamma Radiation dose rates during acceptance of LLW waste at the Port Clarence site (LLW05).
- A procedure for handling asbestos bearing packages.
- Local rules in accordance with the Ionising Radiations Regulations
- A procedure for routine and periodic health surveillance monitoring for contamination and exposure. An emergency plan including response arrangements to identified fault scenarios including:
    - Dropped load or spillage;
    - Fire;
    - Loss or theft of LLW;
    - Contamination discovery;
    - Non-compliant or un-fit load;
    - Dose above threshold discovery; and,
    - Potentially contaminated person or wound.
- Procedures for environmental monitoring incorporated into the Monitoring and Action Plans (MAPs).
- A procedure outlining actions to be taken if consignments are unable to reach the site entrance in order to minimise risks to staff, the site and wider community (LLW06).

7.4.2.1 LLW01 Part A Conditions – Specification for Acceptance

General conditions

520. Consignors handling third party wastes are required to provide details of the organisation generating the waste and quality assurance to show the CfA have been applied at the point waste was produced.

521. Arrangements should be put in place by the consignor for the immediate return of non-compliant consignments delivered to the Port Clarence site.

Non-radiological characteristics

522. Non-radiological characteristics must be characterised for the waste to be assessed for acceptance.

523. Port Clarence landfill sites will not accept any of the following types of waste at the facility (definitions are from the Environmental Permitting Regulations):

- any waste in liquid form;
- waste which, in the conditions of landfill, is explosive, corrosive, oxidising, flammable or highly flammable;
- hospital and other clinical wastes which arise from medical or veterinary establishments and which are infectious;
- pressurised gas vessels; or,

- chemical substances arising from research and development or teaching activities, such as laboratory residues, which are not identified or which are new, and whose effects on man or on the environment are not known.

524. In addition, the Port Clarence landfills will not accept waste with any of the following characteristics:

- ion exchange materials (any material, whether synthetic or naturally occurring, that has the capability of interchanging ions from one substance to another by means of a reversible chemical or physical process);
- complexing agents (either chelating agents or monodentate organic ligands);
- waste which would otherwise present a danger to the facility operators during handling; or
- packages where the outer surface of the package is chemically contaminated.

525. All hazardous wastes deposited except asbestos must meet the specified leaching and other waste acceptance criteria in accordance with the Environmental Permitting Regulations.

526. All hazardous wastes disposed of at the site must meet the organic waste acceptance criteria; ≤10% Loss on ignition or ≤6% Total organic carbon.

Radiological acceptance criteria

527. The specific activity of radionuclides in any LLW consignment to Port Clarence is not greater than specified in Table 38 based on a sum of fractions.

528. The maximum mass of each waste/package/pallet combination to be received at Port Clarence is normally limited to 2 t (arrangements can be made for heavier loads if necessary). The radioactive materials transport container used for transporting the waste to Port Clarence is the package that will be used for handling and final disposal. The container will be disposed directly to the final disposal position by careful offloading and will not be tipped. Packages should contain no void spaces and not be over-packed. Large surface contaminated objects or large items must be fully wrapped and sealed.

529. Port Clarence will accept unpackaged LLW waste for disposal by loose tipping if it is broadly homogeneous in physical form and activity concentration and meets the radiological acceptance criteria for unpackaged waste. Concentration limits for unpackaged waste are presented in Table 39, above which Environment Agency permission will be sought.

530. The consignor needs to characterise the radionuclides in each package using good practice methods and provide details of quality assurance arrangements. The characterisation must be representative of the contents of the packages and not averaged over more than 10 t. Detection limits must be lower than Basic Safety Standards (BSS) exemption levels (European Commission, 2014). The activity of the radionuclides indicated in Table 6 where these are present at levels above the limit of detection must be reported. “Other radionuclides” need to be identified by name and activity, where reasonably practicable.

531. The total activity for the LLW in the package is the total activity of the radionuclides identified in column 1 of Table 6 (plus ‘Other radionuclides’, if present). Where the radionuclide is shown to have daughters in secular equilibrium (column 3), only the head of the chain should be reported. Where the activity of a daughter that is listed in column 1 (i.e. Pb-210 or Ra-228) exceeds the parent, the excess (i.e. the unsupported activity) of that daughter should also be reported. The risk assessments which underpin the ESC assume that the listed daughters always exist and appropriate dose conversion factors take this into account.

532. Radionuclides of less than a 3 month half-life are not normally included in the “Other radionuclides” category. However, if such nuclides are present in significant quantities (>5 MBq t^{-1} or a high percentage relative to the overall activity content) this must be reported.

533. The sum of fractions of the radionuclides in the waste added to the sum of fractions of radionuclides already disposed of at Port Clarence is less than unity.

534. The specific activity for radionuclides in the consignment shall be such that the waste is defined as low level or very low level radioactive waste in accordance with current policy, except where wastes of less than a relevant exemption or exclusion order are mixed in with the LLW/VLLW as an inevitable result of the production such that separation is not reasonably practicable. No waste above LLW as defined by radioactive content will be accepted for disposal.

535. The consignor shall ensure that external non-fixed contamination levels on waste packages is as low as reasonably practicable throughout the process, complies with transport regulations and not more than 4 Bq cm^{-2} beta/gamma and 0.4 Bq cm^{-2} alpha averaged over an area of 300 cm^2. The consignment is to be accompanied by monitoring certificates demonstrating compliance with this requirement.

536. External dose rates from packages are to be as low as reasonably practicable, in accordance with the transport regulations and will not exceed 0.01 mSv h^{-1} at 1 m from the waste package on all sides. Monitoring certificates are required to demonstrate compliance.

537. It is not acceptable to purposely dilute waste or add shielding materials for the sole purpose of achieving compliance with the CfA.

538. Packages and unpackaged wastes should comply with the requirements of the current transport regulations, all the way through to the “as-disposed” condition. Additional shielding should not be used to ensure compliance. LLW waste for disposal by loose tipping should comply with the requirements for LSA 1 waste, be transported in such a manner that under routine conditions of transport, there will be no escape of the radioactive contents from the conveyance, and each conveyance shall be under exclusive use of the consignor.

Other conditions

539. Waste characterisation shall be on a package by package basis unless a case can be made that characterisation of a waste stream of several packages can be justified for some or all determinants.

540. Waste to be received at the Port Clarence site will be provided with a full description including:

- Source and origin of the waste;
- The process producing the waste;
- The composition of the waste and an assessment against relevant CfA values (including activity in consignment, mass of consignment and specific activity of consignment);
- The appearance of the waste and a physical description;
- A description of any non-radiological hazardous properties/classifications;
- The mass of each package and the waste mass in each package, and for waste for loose tipping, the mass of waste in each vehicle;
- Unique identification labelling of each waste package as required under the transport regulations;
- An estimate of the void space in the package, where relevant;
- Details of any pre-conditioning/treatment of the wastes that has been utilised; and,
- Information relating to the safe transport of the waste as required under the transport regulations and details of the container/package to be used.

7.4.2.2 LLW01 Part B – Acceptance Procedures

541. All wastes must arise in the UK and the consigning site must have an appropriate transfer authorisation issued under EPR2016. As part of the pre-acceptance process applied by Augean, details of the methodology by which the waste was produced and characterised, the justification for the methodology and BAT reports, the quality assurance arrangements, container specifications including intermediate bulk containers (for waste exempt or excepted under radioactive materials transport regulations) and wrapping of large objects, the waste description and the results are required. Samples used in waste characterisation should be retained for one year after waste is received at the Port Clarence site and be available to Augean if requested. Pallet design is specified by Augean. Waste can only be shipped by the consignor once approval in writing is obtained from Augean, this will detail date for delivery and transport routing. Waste is to be transported by a carrier approved as competent by the consignor.

542. The pre-acceptance information supplied by the consignor is reviewed by the central technical assessment team (Procedure LLW02), and a decision is taken in principle on whether to approve or decline the consignment.

543. Wastes arriving at the landfill will be subject to the following on-site verification:

- The shipment will be checked while still on the vehicle against the pre-notified characterisation information for consistency and correctness.
- The external dose rate at 1 m will be checked (limit of 10 μSv h^{-1}).
- The packages will be visually checked for integrity.

- The transport documentation will be checked for compliance with the transport regulations.
- The characterisation documentation will be checked to ensure the waste has been pre-accepted and is compliant.
- Receipt records will be generated.
- The waste packages will not be opened or sampled at the landfill in order to minimise unnecessary exposure.

7.4.3 Radioactive waste disposal proposed permit conditions

544. A permit is sought to allow receipt and disposal of low level radioactive waste to the Port Clarence landfills covering all phases.

545. Schedule 3 of the permit includes Table 3.1 which is reproduced as Table 41 and Table 42 below for the hazardous and non-hazardous landfills, respectively. It is proposed to include a condition requiring the operator of the disposal site to calculate, for each radionuclide or group of radionuclides listed, the ratio of each radionuclide's activity of the radioactive waste disposed of at Port Clarence, to the relevant value in Table 3.1 in the permit for each column in turn. The permit will include the condition that the sum of these ratios shall be less than 1 and the maximum activity concentration for a consignment will be less than 2000 Bq g^{-1}. The table includes several columns containing a "Relevant value (TBq)" for each radionuclide for a particular scenario and these are the radiological capacities for the scenarios referred to throughout this ESC.

546. Radioactive waste consignments will be limited to a maximum specific activity (Bq g^{-1}) using the sum of fractions approach (values in Table 38 and Table 39) and an overall limit of 2000 Bq g^{-1}. The permit will include these tables and the condition that the sum of the ratios for a consignment shall be less than 1. The wastes will otherwise be compliant with the non-radioactive properties specified in the CfA (i.e. the proposal is for the disposal of radioactive wastes that would be classified as inert, non-hazardous or hazardous in terms of their content of non-radioactive materials). The radioactive waste disposals would not be segregated from other, non-radioactive wastes disposed at Port Clarence. It is proposed that the limit on the maximum specific activity applies to a consignment of up to 10 t.

547. The minimum depth of non-radioactive waste or material covering LLW and the constraining time periods for cover to be in place are 0.4 m and 8 h, respectively. The constraining time period for disposal to occur would be 24 h, to allow flexible management of delayed delivery when it is not possible to offload the consignment.

548. Constraints are suggested on the placement of waste in a landfill cell, placing non-radioactive waste to a specified depth at the base (2 m), distance from sides (2 m) and top (1 m) of a cell. An additional limitation is proposed for wastes containing a significant activity concentration of Ra-226 (>5 Bq g^{-1}) with a requirement to bury these wastes at least 5 m below the restored surface of the site.

549. Augean will maintain records of LLW disposal tonnage and compare this to total landfill disposal tonnage. This record will show what proportion of total disposal is LLW and will trigger either a reassessment of the ESC or a halt to disposals following consultation with the Environment Agency.

Table 41 Suggested Schedule 3 – Disposals of radioactive waste in hazardous landfill (Permit Table 3.1)

Table 3.1 Disposal by burial on the premises (hazardous landfill)										
Waste type	Disposal route	Radionuclide	Sum of fractions limits							
			Intrusion – Smallholder (60y) scenario – relevant value (TBq)	Gas + External (Recreational 0y) scenario – relevant value (TBq)	Erosion to coast (60y) scenario – relevant value (TBq)	Erosion – Dog walker (60y) scenario – relevant value (TBq)	Leachate spillage (0y) scenario – relevant value (TBq)	Bathtubbing (TBq)	Inundation (flooding) (TBq)	Burrowing mammals* (TBq)
Solid waste with a maximum total activity concentration specified in Table 3.2	Burial on the premises in the hazardous waste landfill at Port Clarence.	H-3	$1.78\ 10^{7}$	$6.06\ 10^{5}$	$3.82\ 10^{3}$	$5.55\ 10^{10}$	$1.45\ 10^{7}$	$3.16\ 10^{3}$	$1.88\ 10^{2}$	$1.22\ 10^{8}$
		C-14	$9.82\ 10^{6}$	$5.46\ 10^{4}$	$1.19\ 10^{2}$	$3.02\ 10^{3}$	$1.50\ 10^{4}$	$4.40\ 10^{4}$	$1.21\ 10^{7}$	$1.61\ 10^{5}$
		Cl-36	$3.78\ 10^{3}$	$3.50\ 10^{3}$	$8.99\ 10^{21}$	$2.86\ 10^{8}$	$3.80\ 10^{3}$	$1.72\ 10^{0}$	$5.08\ 10^{-1}$	$1.94\ 10^{2}$
		Ca-41	$1.52\ 10^{8}$	$9.43\ 10^{4}$	nd	$2.68\ 10^{7}$	$4.62\ 10^{4}$	$1.05\ 10^{3}$	$1.60\ 10^{4}$	$1.28\ 10^{3}$
		Mn-54	$3.10\ 10^{5}$	$1.28\ 10^{7}$	$2.22\ 10^{13}$	nd	$9.06\ 10^{24}$	nd	nd	$1.89\ 10^{13}$
		Fe-55	$1.15\ 10^{10}$	$1.96\ 10^{7}$	$4.49\ 10^{9}$	$6.49\ 10^{10}$	$3.97\ 10^{10}$	nd	nd	$1.06\ 10^{12}$
		Co-60	$2.09\ 10^{4}$	$3.55\ 10^{5}$	$1.96\ 10^{11}$	$9.34\ 10^{5}$	$2.25\ 10^{6}$	nd	$4.94\ 10^{8}$	$4.03\ 10^{5}$
		Ni-59	$1.70\ 10^{9}$	$5.39\ 10^{7}$	$3.44\ 10^{4}$	$7.48\ 10^{4}$	$7.05\ 10^{4}$	$7.94\ 10^{5}$	$8.41\ 10^{8}$	$4.66\ 10^{5}$
		Ni-63	$2.08\ 10^{8}$	$2.20\ 10^{7}$	$3.86\ 10^{3}$	$5.66\ 10^{5}$	$4.32\ 10^{4}$	$5.63\ 10^{7}$	$4.39\ 10^{8}$	$6.61\ 10^{5}$
		Zn-65	$4.11\ 10^{5}$	$2.48\ 10^{5}$	$3.13\ 10^{12}$	nd	$1.63\ 10^{30}$	nd	nd	$3.63\ 10^{13}$
		Se-79	$1.67\ 10^{7}$	$8.12\ 10^{3}$	$3.77\ 10^{56}$	$1.84\ 10^{3}$	$8.58\ 10^{2}$	$1.44\ 10^{3}$	$8.22\ 10^{5}$	$1.07\ 10^{4}$
		Sr-90	$6.58\ 10^{4}$	$1.85\ 10^{4}$	$1.84\ 10^{19}$	$9.40\ 10^{5}$	$1.09\ 10^{3}$	$7.77\ 10^{4}$	$1.30\ 10^{5}$	$9.61\ 10^{2}$
		Mo-93	$2.84\ 10^{7}$	$4.88\ 10^{5}$	$3.72\ 10^{3}$	$2.85\ 10^{4}$	$3.52\ 10^{3}$	$5.95\ 10^{1}$	$5.41\ 10^{3}$	$1.72\ 10^{5}$
		Zr-93	$1.98\ 10^{8}$	$7.55\ 10^{6}$	$3.27\ 10^{3}$	$4.49\ 10^{4}$	$3.15\ 10^{4}$	$1.48\ 10^{4}$	$2.42\ 10^{7}$	$6.10\ 10^{6}$
		Nb-93m	$1.07\ 10^{10}$	$3.89\ 10^{7}$	$2.08\ 10^{4}$	$2.60\ 10^{6}$	$3.46\ 10^{5}$	nd	$1.67\ 10^{10}$	$3.02\ 10^{6}$
		Nb-94	$9.78\ 10^{4}$	$3.49\ 10^{6}$	$2.16\ 10^{13}$	$7.83\ 10^{1}$	$2.26\ 10^{3}$	$2.99\ 10^{3}$	$8.70\ 10^{6}$	$2.68\ 10^{2}$
		Tc-99	$5.67\ 10^{4}$	$3.77\ 10^{4}$	$4.55\ 10^{40}$	$6.63\ 10^{4}$	$4.98\ 10^{3}$	$6.70\ 10^{1}$	$1.73\ 10^{1}$	$1.01\ 10^{4}$
		Ru-106	$1.59\ 10^{5}$	$1.38\ 10^{6}$	$7.78\ 10^{14}$	nd	$2.20\ 10^{20}$	nd	nd	$1.58\ 10^{14}$
		Ag-108m	$2.51\ 10^{4}$	$1.71\ 10^{6}$	$2.65\ 10^{14}$	$1.99\ 10^{3}$	$2.22\ 10^{3}$	$3.63\ 10^{3}$	$2.58\ 10^{5}$	$2.89\ 10^{2}$
		Ag-110m	$3.48\ 10^{4}$	$3.29\ 10^{6}$	$3.10\ 10^{12}$	nd	$3.92\ 10^{29}$	nd	nd	$1.47\ 10^{13}$
		Cd-109	$1.21\ 10^{7}$	$1.39\ 10^{6}$	$3.31\ 10^{43}$	$1.35\ 10^{17}$	$5.04\ 10^{17}$	nd	nd	$3.28\ 10^{14}$
		Sb-125	$2.04\ 10^{4}$	$6.90\ 10^{5}$	$3.05\ 10^{15}$	$9.54\ 10^{10}$	$1.09\ 10^{10}$	nd	nd	$2.20\ 10^{9}$
		Sn-119m	$9.45\ 10^{8}$	$1.05\ 10^{7}$	nd	nd	$3.09\ 10^{26}$	nd	nd	$4.57\ 10^{15}$
		Sn-123	$2.06\ 10^{7}$	$3.71\ 10^{6}$	$2.31\ 10^{14}$	nd	$1.72\ 10^{54}$	nd	nd	$2.04\ 10^{15}$
		Sn-126	$8.38\ 10^{4}$	$3.74\ 10^{5}$	$9.27\ 10^{13}$	$1.37\ 10^{2}$	$7.20\ 10^{2}$	$1.77\ 10^{3}$	$7.93\ 10^{6}$	$2.13\ 10^{2}$
		Te-127m	$3.22\ 10^{8}$	$2.80\ 10^{6}$	$1.28\ 10^{33}$	nd	$2.01\ 10^{65}$	nd	nd	$3.09\ 10^{14}$

Table 3.1 Disposal by burial on the premises (hazardous landfill)										
Waste type	Disposal route	Radionuclide	Sum of fractions limits							
			Intrusion – Smallholder (60y) scenario – relevant value (TBq)	Gas + External (Recreational 0y) scenario – relevant value (TBq)	Erosion to coast (60y) scenario – relevant value (TBq)	Erosion – Dog walker (60y) scenario – relevant value (TBq)	Leachate spillage (0y) scenario – relevant value (TBq)	Bathtubbing (TBq)	Inundation (flooding) (TBq)	Burrowing mammals* (TBq)
		I-129	1.27 10^{5}	2.73 10^{2}	7.10 10^{132}	3.10 10^{4}	1.09 10^{2}	9.36 10^{1}	1.32 10^{3}	6.29 10^{4}
		Ba-133	2.12 10^{2}	7.19 10^{3}	1.29 10^{18}	5.93 10^{5}	1.96 10^{5}	9.00 10^{6}	9.38 10^{5}	5.22 10^{4}
		Cs-134	1.10 10^{5}	8.46 10^{4}	5.36 10^{13}	6.50 10^{12}	7.92 10^{11}	nd	nd	4.22 10^{10}
		Cs-135	4.38 10^{7}	5.82 10^{5}	5.87 10^{48}	3.49 10^{5}	1.04 10^{4}	3.73 10^{4}	1.70 10^{8}	1.43 10^{3}
		Cs-137	2.25 10^{5}	9.17 10^{4}	2.63 10^{14}	2.77 10^{4}	7.70 10^{3}	3.46 10^{7}	5.88 10^{7}	1.08 10^{3}
		Ce-144	2.01 10^{7}	8.89 10^{6}	1.77 10^{29}	nd	8.76 10^{25}	nd	nd	1.51 10^{15}
		Pm-147	3.79 10^{7}	3.05 10^{7}	5.60 10^{39}	4.89 10^{10}	9.67 10^{10}	nd	nd	1.09 10^{12}
		Sm-147	9.02 10^{6}	6.64 10^{5}	nd	6.40 10^{3}	1.56 10^{2}	3.83 10^{1}	1.43 10^{5}	6.18 10^{2}
		Sm-151	5.14 10^{8}	1.46 10^{8}	nd	4.47 10^{6}	5.90 10^{4}	7.40 10^{7}	5.46 10^{8}	9.74 10^{5}
		Eu-152	2.20 10^{4}	1.35 10^{6}	4.68 10^{12}	6.69 10^{3}	6.38 10^{4}	7.75 10^{7}	4.02 10^{7}	7.97 10^{3}
		Eu-154	2.08 10^{4}	8.57 10^{5}	3.39 10^{12}	5.36 10^{4}	2.37 10^{5}	9.00 10^{8}	2.09 10^{8}	4.18 10^{4}
		Eu-155	9.23 10^{5}	4.99 10^{6}	6.75 10^{34}	8.75 10^{7}	6.69 10^{7}	nd	1.99 10^{11}	6.94 10^{7}
		Gd-153	3.38 10^{6}	6.87 10^{7}	5.24 10^{36}	nd	3.63 10^{31}	nd	nd	6.98 10^{14}
		Pb-210	2.46 10^{6}	3.13 10^{3}	1.59 10^{15}	7.84 10^{0}	1.26 10^{1}	1.27 10^{6}	3.99 10^{5}	4.69 10^{2}
		Po-210	2.65 10^{6}	8.57 10^{3}	3.68 10^{18}	nd	1.27 10^{48}	nd	nd	1.26 10^{13}
		Ra-226	5.13 10^{4}	5.70 10^{3}	5.75 10^{10}	1.39 10^{0}	1.84 10^{0}	2.59 10^{2}	5.50 10^{4}	1.38 10^{1}
		Ra-228	1.10 10^{5}	1.26 10^{4}	4.07 10^{9}	1.01 10^{5}	4.80 10^{3}	4.65 10^{8}	5.04 10^{7}	5.76 10^{4}
		Ac-227	1.89 10^{5}	4.09 10^{4}	7.01 10^{14}	1.71 10^{3}	3.06 10^{1}	2.23 10^{4}	3.06 10^{4}	2.96 10^{2}
		Th-228	1.64 10^{5}	8.11 10^{4}	6.34 10^{9}	9.48 10^{12}	5.63 10^{10}	nd	nd	2.61 10^{11}
		Th-229	3.53 10^{5}	2.64 10^{4}	2.04 10^{12}	2.80 10^{2}	8.88 10^{0}	4.27 10^{0}	1.10 10^{4}	6.84 10^{2}
		Th-230	1.91 10^{6}	1.11 10^{5}	4.08 10^{32}	4.91 10^{1}	2.74 10^{1}	3.70 10^{0}	1.91 10^{4}	5.13 10^{2}
		Th-232	7.10 10^{4}	8.66 10^{3}	4.07 10^{9}	2.80 10^{1}	3.20 10^{0}	2.16 10^{0}	1.69 10^{4}	5.06 10^{1}
		Pa-231	1.13 10^{6}	1.36 10^{5}	2.25 10^{20}	1.31 10^{2}	4.04 10^{0}	7.73 10^{-1}	3.67 10^{3}	4.27 10^{1}
		U-232	4.93 10^{3}	1.60 10^{4}	2.55 10^{9}	3.76 10^{3}	2.12 10^{1}	1.25 10^{2}	1.30 10^{3}	3.24 10^{2}
		U-233	1.90 10^{6}	2.07 10^{5}	2.37 10^{26}	2.24 10^{4}	1.38 10^{2}	2.52 10^{-1}	1.36 10^{3}	2.58 10^{3}
		U-234	1.97 10^{6}	2.15 10^{5}	3.85 10^{39}	3.18 10^{4}	1.62 10^{2}	1.55 10^{0}	2.69 10^{3}	2.66 10^{3}
		U-235	1.46 10^{5}	2.23 10^{5}	5.67 10^{23}	2.03 10^{4}	1.60 10^{2}	2.09 10^{-1}	1.21 10^{3}	1.47 10^{3}
		U-236	2.12 10^{6}	2.25 10^{5}	4.75 10^{35}	4.48 10^{4}	1.64 10^{2}	4.24 10^{0}	3.40 10^{3}	2.83 10^{3}
		U-238	2.17 10^{5}	2.09 10^{5}	2.49 10^{14}	3.69 10^{4}	1.50 10^{2}	4.17 10^{0}	3.58 10^{3}	2.60 10^{3}

Table 3.1 Disposal by burial on the premises (hazardous landfill)										
Waste type	Disposal route	Radionuclide	Sum of fractions limits							
			Intrusion – Smallholder (60y) scenario – relevant value (TBq)	Gas + External (Recreational 0y) scenario – relevant value (TBq)	Erosion to coast (60y) scenario – relevant value (TBq)	Erosion – Dog walker (60y) scenario – relevant value (TBq)	Leachate spillage (0y) scenario – relevant value (TBq)	Bathtubbing (TBq)	Inundation (flooding) (TBq)	Burrowing mammals* (TBq)
		Np-237	$1.50\ 10^{4}$	$1.54\ 10^{4}$	$5.53\ 10^{19}$	$1.50\ 10^{3}$	$8.79\ 10^{1}$	$7.47\ 10^{-2}$	$1.04\ 10^{1}$	$2.47\ 10^{2}$
		Pu-238	$6.84\ 10^{5}$	$1.69\ 10^{5}$	$3.14\ 10^{41}$	$4.25\ 10^{2}$	$7.47\ 10^{1}$	$2.13\ 10^{3}$	$1.61\ 10^{4}$	$7.69\ 10^{2}$
		Pu-239	$6.22\ 10^{5}$	$1.55\ 10^{5}$	$5.59\ 10^{25}$	$2.21\ 10^{2}$	$4.44\ 10^{1}$	$3.89\ 10^{0}$	$9.13\ 10^{3}$	$5.11\ 10^{2}$
		Pu-240	$6.23\ 10^{5}$	$1.55\ 10^{5}$	$4.02\ 10^{48}$	$2.22\ 10^{2}$	$4.46\ 10^{1}$	$5.98\ 10^{0}$	$9.18\ 10^{3}$	$5.12\ 10^{2}$
		Pu-241	$3.41\ 10^{7}$	$8.45\ 10^{6}$	$7.28\ 10^{34}$	$1.45\ 10^{4}$	$1.66\ 10^{3}$	$1.07\ 10^{4}$	$1.17\ 10^{6}$	$8.16\ 10^{3}$
		Pu-242	$6.77\ 10^{5}$	$1.61\ 10^{5}$	$2.76\ 10^{59}$	$2.30\ 10^{2}$	$4.65\ 10^{1}$	$3.41\ 10^{0}$	$9.95\ 10^{3}$	$5.37\ 10^{2}$
		Pu-244	$1.52\ 10^{5}$	$1.60\ 10^{5}$	$1.66\ 10^{14}$	$1.60\ 10^{2}$	$4.46\ 10^{1}$	$1.80\ 10^{0}$	$5.81\ 10^{3}$	$3.76\ 10^{2}$
		Am-241	$2.55\ 10^{6}$	$4.75\ 10^{5}$	$2.39\ 10^{55}$	$5.03\ 10^{2}$	$5.51\ 10^{1}$	$3.69\ 10^{2}$	$4.39\ 10^{4}$	$2.63\ 10^{2}$
		Am-242m	$1.97\ 10^{6}$	$3.94\ 10^{5}$	$2.98\ 10^{14}$	$3.25\ 10^{2}$	$4.14\ 10^{1}$	$6.48\ 10^{2}$	$1.73\ 10^{4}$	$3.13\ 10^{2}$
		Am-243	$1.05\ 10^{6}$	$4.72\ 10^{5}$	$2.34\ 10^{23}$	$2.36\ 10^{2}$	$5.02\ 10^{1}$	$7.73\ 10^{0}$	$2.40\ 10^{4}$	$2.29\ 10^{2}$
		Cm-242	$6.11\ 10^{8}$	$4.23\ 10^{6}$	$5.44\ 10^{35}$	$8.32\ 10^{4}$	$1.46\ 10^{4}$	$4.18\ 10^{5}$	$3.15\ 10^{6}$	$1.51\ 10^{5}$
		Cm-243	$5.94\ 10^{6}$	$2.20\ 10^{5}$	$4.33\ 10^{23}$	$1.88\ 10^{3}$	$2.36\ 10^{2}$	$3.20\ 10^{3}$	$7.63\ 10^{5}$	$8.99\ 10^{2}$
		Cm-244	$1.71\ 10^{7}$	$2.80\ 10^{5}$	nd	$7.76\ 10^{3}$	$6.24\ 10^{2}$	$2.16\ 10^{3}$	$1.42\ 10^{6}$	$2.23\ 10^{3}$
		Cm-245	$5.82\ 10^{6}$	$1.54\ 10^{5}$	$6.40\ 10^{28}$	$2.25\ 10^{2}$	$4.95\ 10^{1}$	$1.45\ 10^{1}$	$3.22\ 10^{4}$	$2.24\ 10^{2}$
		Cm-246	$9.19\ 10^{6}$	$1.54\ 10^{5}$	$4.18\ 10^{130}$	$3.10\ 10^{2}$	$5.05\ 10^{1}$	$4.78\ 10^{1}$	$1.25\ 10^{5}$	$2.45\ 10^{2}$
		Cm-248	$5.14\ 10^{5}$	$4.20\ 10^{4}$	nd	$8.33\ 10^{1}$	$1.34\ 10^{1}$	$1.25\ 10^{0}$	$3.81\ 10^{4}$	$5.57\ 10^{1}$
		Any other radionuclide	$1.50\ 10^{4}$	$1.54\ 10^{4}$	$5.53\ 10^{19}$	$1.50\ 10^{3}$	$8.79\ 10^{1}$	$7.47\ 10^{-2}$	$1.04\ 10^{1}$	$2.47\ 10^{2}$

*Only applies to waste disposed of within the burrowing depth.

Note: Where dose is effectively zero the radiological capacity is infinite, marked here as nd (not determined).

Table 42 Suggested Schedule 3 – Disposals of radioactive waste in non-hazardous landfill (Permit Table 3.1)

Table 3.1 Disposal by burial on the premises (non-hazardous landfill)											
Waste type	Disposal route	Radionuclide	Sum of fractions limits								
			Intrusion – Smallholder (60y) scenario – relevant value (TBq)	Gas + External (Recreational 0y) scenario – relevant value (TBq)	Erosion to coast (60y) scenario – relevant value (TBq)	Erosion – Dog walker (60y) scenario – relevant value (TBq)	Leachate spillage (0y) scenario – relevant value (TBq)	Bathtubbing – relevant value (TBq)	Inundation (flooding) – relevant value (TBq)	Fire in non-hazardous landfill– relevant value (TBq)	Burrowing mammals* – relevant value (TBq)
Solid waste with a maximum total activity concentration specified in Table 3.2	Burial on the premises in the hazardous waste landfill at Port Clarence.	H-3	$1.78\ 10^{7}$	$6.06\ 10^{5}$	$3.82\ 10^{3}$	$5.55\ 10^{10}$	$1.45\ 10^{7}$	$3.16\ 10^{3}$	$1.88\ 10^{2}$	$3.83\ 10^{4}$	$1.22\ 10^{8}$
		C-14	$9.82\ 10^{6}$	$5.46\ 10^{4}$	$1.19\ 10^{2}$	$3.02\ 10^{3}$	$1.50\ 10^{4}$	$4.40\ 10^{4}$	$1.21\ 10^{7}$	$1.82\ 10^{3}$	$1.61\ 10^{5}$
		Cl-36	$3.78\ 10^{3}$	$3.50\ 10^{3}$	$8.99\ 10^{21}$	$2.86\ 10^{8}$	$3.80\ 10^{3}$	$1.72\ 10^{0}$	$5.08\ 10^{-1}$	$1.44\ 10^{3}$	$1.94\ 10^{2}$
		Ca-41	$1.52\ 10^{8}$	$9.43\ 10^{4}$	nd	$2.68\ 10^{7}$	$4.62\ 10^{4}$	$1.05\ 10^{3}$	$1.60\ 10^{4}$	$4.42\ 10^{7}$	$1.28\ 10^{3}$
		Mn-54	$3.10\ 10^{5}$	$1.28\ 10^{7}$	$2.22\ 10^{13}$	nd	$9.06\ 10^{24}$	nd	nd	$5.70\ 10^{6}$	$1.89\ 10^{13}$
		Fe-55	$1.15\ 10^{10}$	$1.96\ 10^{7}$	$4.49\ 10^{9}$	$6.49\ 10^{10}$	$3.97\ 10^{10}$	nd	nd	$1.04\ 10^{7}$	$1.06\ 10^{12}$
		Co-60	$2.09\ 10^{4}$	$3.55\ 10^{5}$	$1.96\ 10^{11}$	$9.34\ 10^{5}$	$2.25\ 10^{6}$	nd	$4.94\ 10^{8}$	$3.36\ 10^{5}$	$4.03\ 10^{5}$
		Ni-59	$1.70\ 10^{9}$	$5.39\ 10^{7}$	$3.44\ 10^{4}$	$7.48\ 10^{4}$	$7.05\ 10^{4}$	$7.94\ 10^{5}$	$8.41\ 10^{8}$	$2.40\ 10^{7}$	$4.66\ 10^{5}$
		Ni-63	$2.08\ 10^{8}$	$2.20\ 10^{7}$	$3.86\ 10^{3}$	$5.66\ 10^{5}$	$4.32\ 10^{4}$	$5.63\ 10^{7}$	$4.39\ 10^{8}$	$8.11\ 10^{6}$	$6.61\ 10^{5}$
		Zn-65	$4.11\ 10^{5}$	$2.48\ 10^{5}$	$3.13\ 10^{12}$	nd	$1.63\ 10^{30}$	nd	nd	$3.73\ 10^{4}$	$3.63\ 10^{13}$
		Se-79	$1.67\ 10^{7}$	$8.12\ 10^{3}$	$3.77\ 10^{56}$	$1.84\ 10^{3}$	$8.58\ 10^{2}$	$1.44\ 10^{3}$	$8.22\ 10^{5}$	$1.55\ 10^{3}$	$1.07\ 10^{4}$
		Sr-90	$6.58\ 10^{4}$	$1.85\ 10^{4}$	$1.84\ 10^{19}$	$9.40\ 10^{5}$	$1.09\ 10^{3}$	$7.77\ 10^{4}$	$1.30\ 10^{5}$	$6.53\ 10^{4}$	$9.61\ 10^{2}$
		Mo-93	$2.84\ 10^{7}$	$4.88\ 10^{5}$	$3.72\ 10^{3}$	$2.85\ 10^{4}$	$3.52\ 10^{3}$	$5.95\ 10^{1}$	$5.41\ 10^{3}$	$4.58\ 10^{6}$	$1.72\ 10^{5}$
		Zr-93	$1.98\ 10^{8}$	$7.55\ 10^{6}$	$3.27\ 10^{3}$	$4.49\ 10^{4}$	$3.15\ 10^{4}$	$1.48\ 10^{4}$	$2.42\ 10^{7}$	$4.22\ 10^{5}$	$6.10\ 10^{6}$
		Nb-93m	$1.07\ 10^{10}$	$3.89\ 10^{7}$	$2.08\ 10^{4}$	$2.60\ 10^{6}$	$3.46\ 10^{5}$	nd	$1.67\ 10^{10}$	$5.83\ 10^{6}$	$3.02\ 10^{6}$
		Nb-94	$9.78\ 10^{4}$	$3.49\ 10^{6}$	$2.16\ 10^{13}$	$7.83\ 10^{1}$	$2.26\ 10^{3}$	$2.99\ 10^{3}$	$8.70\ 10^{6}$	$2.14\ 10^{5}$	$2.68\ 10^{2}$
		Tc-99	$5.67\ 10^{4}$	$3.77\ 10^{4}$	$4.55\ 10^{40}$	$6.63\ 10^{4}$	$4.98\ 10^{3}$	$6.70\ 10^{1}$	$1.73\ 10^{1}$	$8.11\ 10^{5}$	$1.01\ 10^{4}$
		Ru-106	$1.59\ 10^{5}$	$1.38\ 10^{6}$	$7.78\ 10^{14}$	nd	$2.20\ 10^{20}$	nd	nd	$1.60\ 10^{3}$	$1.58\ 10^{14}$
		Ag-108m	$2.51\ 10^{4}$	$1.71\ 10^{6}$	$2.65\ 10^{14}$	$1.99\ 10^{3}$	$2.22\ 10^{3}$	$3.63\ 10^{3}$	$2.58\ 10^{5}$	$2.83\ 10^{4}$	$2.89\ 10^{2}$
		Ag-110m	$3.48\ 10^{4}$	$3.29\ 10^{6}$	$3.10\ 10^{12}$	nd	$3.92\ 10^{29}$	nd	nd	$7.87\ 10^{4}$	$1.47\ 10^{13}$
		Cd-109	$1.21\ 10^{7}$	$1.39\ 10^{6}$	$3.31\ 10^{43}$	$1.35\ 10^{17}$	$5.04\ 10^{17}$	nd	nd	$1.04\ 10^{6}$	$3.28\ 10^{14}$
		Sb-125	$2.04\ 10^{4}$	$6.90\ 10^{5}$	$3.05\ 10^{15}$	$9.54\ 10^{10}$	$1.09\ 10^{10}$	nd	nd	$8.10\ 10^{3}$	$2.20\ 10^{9}$
		Sn-119m	$9.45\ 10^{8}$	$1.05\ 10^{7}$	nd	nd	$3.09\ 10^{26}$	nd	nd	$4.70\ 10^{6}$	$4.57\ 10^{15}$
		Sn-123	$2.06\ 10^{7}$	$3.71\ 10^{6}$	$2.31\ 10^{14}$	nd	$1.72\ 10^{54}$	nd	nd	$1.21\ 10^{6}$	$2.04\ 10^{15}$
		Sn-126	$8.38\ 10^{4}$	$3.74\ 10^{5}$	$9.27\ 10^{13}$	$1.37\ 10^{2}$	$7.20\ 10^{2}$	$1.77\ 10^{3}$	$7.93\ 10^{6}$	$3.46\ 10^{5}$	$2.13\ 10^{2}$
		Te-127m	$3.22\ 10^{8}$	$2.80\ 10^{6}$	$1.28\ 10^{33}$	nd	$2.01\ 10^{65}$	nd	nd	$1.04\ 10^{4}$	$3.09\ 10^{14}$
		I-129	$1.27\ 10^{5}$	$2.73\ 10^{2}$	$7.10\ 10^{132}$	$3.10\ 10^{4}$	$1.09\ 10^{2}$	$9.36\ 10^{1}$	$1.32\ 10^{3}$	$2.17\ 10^{2}$	$6.29\ 10^{4}$

Table 3.1 Disposal by burial on the premises (non-hazardous landfill)

Waste type	Disposal route	Radionuclide	Sum of fractions limits								
			Intrusion – Smallholder (60y) scenario – relevant value (TBq)	Gas + External (Recreational 0y) scenario – relevant value (TBq)	Erosion to coast (60y) scenario – relevant value (TBq)	Erosion – Dog walker (60y) scenario – relevant value (TBq)	Leachate spillage (0y) scenario – relevant value (TBq)	Bathtubbing – relevant value (TBq)	Inundation (flooding) – relevant value (TBq)	Fire in non-hazardous landfill– relevant value (TBq)	Burrowing mammals* – relevant value (TBq)
		Ba-133	2.12 10^{2}	7.19 10^{3}	1.29 10^{18}	5.93 10^{5}	1.96 10^{5}	9.00 10^{6}	9.38 10^{5}	1.05 10^{6}	5.22 10^{4}
		Cs-134	1.10 10^{5}	8.46 10^{4}	5.36 10^{13}	6.50 10^{12}	7.92 10^{11}	nd	nd	5.15 10^{3}	4.22 10^{10}
		Cs-135	4.38 10^{7}	5.82 10^{5}	5.87 10^{48}	3.49 10^{5}	1.04 10^{4}	3.73 10^{4}	1.70 10^{8}	1.23 10^{4}	1.43 10^{3}
		Cs-137	2.25 10^{5}	9.17 10^{4}	2.63 10^{14}	2.77 10^{4}	7.70 10^{3}	3.46 10^{7}	5.88 10^{7}	2.70 10^{3}	1.08 10^{3}
		Ce-144	2.01 10^{7}	8.89 10^{6}	1.77 10^{29}	nd	8.76 10^{25}	nd	nd	1.54 10^{5}	1.51 10^{15}
		Pm-147	3.79 10^{7}	3.05 10^{7}	5.60 10^{39}	4.89 10^{10}	9.67 10^{10}	nd	nd	2.08 10^{6}	1.09 10^{12}
		Sm-147	9.02 10^{6}	6.64 10^{5}	nd	6.40 10^{3}	1.56 10^{2}	3.83 10^{1}	1.43 10^{5}	1.10 10^{3}	6.18 10^{2}
		Sm-151	5.14 10^{8}	1.46 10^{8}	nd	4.47 10^{6}	5.90 10^{4}	7.40 10^{7}	5.46 10^{8}	2.63 10^{6}	9.74 10^{5}
		Eu-152	2.20 10^{4}	1.35 10^{6}	4.68 10^{12}	6.69 10^{3}	6.38 10^{4}	7.75 10^{7}	4.02 10^{7}	2.50 10^{5}	7.97 10^{3}
		Eu-154	2.08 10^{4}	8.57 10^{5}	3.39 10^{12}	5.36 10^{4}	2.37 10^{5}	9.00 10^{8}	2.09 10^{8}	1.98 10^{5}	4.18 10^{4}
		Eu-155	9.23 10^{5}	4.99 10^{6}	6.75 10^{34}	8.75 10^{7}	6.69 10^{7}	nd	1.99 10^{11}	1.53 10^{6}	6.94 10^{7}
		Gd-153	3.38 10^{6}	6.87 10^{7}	5.24 10^{36}	nd	3.63 10^{31}	nd	nd	3.45 10^{6}	6.98 10^{14}
		Pb-210	2.46 10^{6}	3.13 10^{3}	1.59 10^{15}	7.84 10^{0}	1.26 10^{1}	1.27 10^{6}	3.99 10^{5}	2.11 10^{0}	4.69 10^{2}
		Po-210	2.65 10^{6}	8.57 10^{3}	3.68 10^{18}	nd	1.27 10^{48}	nd	nd	2.45 10^{3}	1.26 10^{13}
		Ra-226	5.13 10^{4}	5.70 10^{3}	5.75 10^{10}	1.39 10^{0}	1.84 10^{0}	2.59 10^{2}	5.50 10^{4}	5.40 10^{2}	1.38 10^{1}
		Ra-228	1.10 10^{5}	1.26 10^{4}	4.07 10^{9}	1.01 10^{5}	4.80 10^{3}	4.65 10^{8}	5.04 10^{7}	1.77 10^{2}	5.76 10^{4}
		Ac-227	1.89 10^{5}	4.09 10^{4}	7.01 10^{14}	1.71 10^{3}	3.06 10^{1}	2.23 10^{4}	3.06 10^{4}	1.85 10^{1}	2.96 10^{2}
		Th-228	1.64 10^{5}	8.11 10^{4}	6.34 10^{9}	9.48 10^{12}	5.63 10^{10}	nd	nd	2.42 10^{2}	2.61 10^{11}
		Th-229	3.53 10^{5}	2.64 10^{4}	2.04 10^{12}	2.80 10^{2}	8.88 10^{0}	4.27 10^{0}	1.10 10^{4}	4.11 10^{1}	6.84 10^{2}
		Th-230	1.91 10^{6}	1.11 10^{5}	4.08 10^{32}	4.91 10^{1}	2.74 10^{1}	3.70 10^{0}	1.91 10^{4}	1.05 10^{2}	5.13 10^{2}
		Th-232	7.10 10^{4}	8.66 10^{3}	4.07 10^{9}	2.80 10^{1}	3.20 10^{0}	2.16 10^{0}	1.69 10^{4}	6.21 10^{1}	5.06 10^{1}
		Pa-231	1.13 10^{6}	1.36 10^{5}	2.25 10^{20}	1.31 10^{2}	4.04 10^{0}	7.73 10^{-1}	3.67 10^{3}	7.53 10^{1}	4.27 10^{1}
		U-232	4.93 10^{3}	1.60 10^{4}	2.55 10^{9}	3.76 10^{3}	2.12 10^{1}	1.25 10^{2}	1.30 10^{3}	1.31 10^{2}	3.24 10^{2}
		U-233	1.90 10^{6}	2.07 10^{5}	2.37 10^{26}	2.24 10^{4}	1.38 10^{2}	2.52 10^{-1}	1.36 10^{3}	1.10 10^{3}	2.58 10^{3}
		U-234	1.97 10^{6}	2.15 10^{5}	3.85 10^{39}	3.18 10^{4}	1.62 10^{2}	1.55 10^{0}	2.69 10^{3}	1.12 10^{3}	2.66 10^{3}
		U-235	1.46 10^{5}	2.23 10^{5}	5.67 10^{23}	2.03 10^{4}	1.60 10^{2}	2.09 10^{-1}	1.21 10^{3}	1.24 10^{3}	1.47 10^{3}
		U-236	2.12 10^{6}	2.25 10^{5}	4.75 10^{35}	4.48 10^{4}	1.64 10^{2}	4.24 10^{0}	3.40 10^{3}	1.21 10^{3}	2.83 10^{3}
		U-238	2.17 10^{5}	2.09 10^{5}	2.49 10^{14}	3.69 10^{4}	1.50 10^{2}	4.17 10^{0}	3.58 10^{3}	1.32 10^{3}	2.60 10^{3}
		Np-237	1.50 10^{4}	1.54 10^{4}	5.53 10^{19}	1.50 10^{3}	8.79 10^{1}	7.47 10^{-2}	1.04 10^{1}	2.11 10^{2}	2.47 10^{2}

Table 3.1 Disposal by burial on the premises (non-hazardous landfill)											
Waste type	Disposal route	Radionuclide	Sum of fractions limits								
			Intrusion – Smallholder (60y) scenario – relevant value (TBq)	Gas + External (Recreational 0y) scenario – relevant value (TBq)	Erosion to coast (60y) scenario – relevant value (TBq)	Erosion – Dog walker (60y) scenario – relevant value (TBq)	Leachate spillage (0y) scenario – relevant value (TBq)	Bathtubbing – relevant value (TBq)	Inundation (flooding) – relevant value (TBq)	Fire in non-hazardous landfill– relevant value (TBq)	Burrowing mammals* – relevant value (TBq)
		Pu-238	6.84 10^{5}	1.69 10^{5}	3.14 10^{41}	4.25 10^{2}	7.47 10^{1}	2.13 10^{3}	1.61 10^{4}	9.58 10^{1}	7.69 10^{2}
		Pu-239	6.22 10^{5}	1.55 10^{5}	5.59 10^{25}	2.21 10^{2}	4.44 10^{1}	3.89 10^{0}	9.13 10^{3}	8.78 10^{1}	5.11 10^{2}
		Pu-240	6.23 10^{5}	1.55 10^{5}	4.02 10^{48}	2.22 10^{2}	4.46 10^{1}	5.98 10^{0}	9.18 10^{3}	8.78 10^{1}	5.12 10^{2}
		Pu-241	3.41 10^{7}	8.45 10^{6}	7.28 10^{34}	1.45 10^{4}	1.66 10^{3}	1.07 10^{4}	1.17 10^{6}	4.58 10^{3}	8.16 10^{3}
		Pu-242	6.77 10^{5}	1.61 10^{5}	2.76 10^{59}	2.30 10^{2}	4.65 10^{1}	3.41 10^{0}	9.95 10^{3}	9.58 10^{1}	5.37 10^{2}
		Pu-244	1.52 10^{5}	1.60 10^{5}	1.66 10^{14}	1.60 10^{2}	4.46 10^{1}	1.80 10^{0}	5.81 10^{3}	9.58 10^{1}	3.76 10^{2}
		Am-241	2.55 10^{6}	4.75 10^{5}	2.39 10^{55}	5.03 10^{2}	5.51 10^{1}	3.69 10^{2}	4.39 10^{4}	1.10 10^{2}	2.63 10^{2}
		Am-242m	1.97 10^{6}	3.94 10^{5}	2.98 10^{14}	3.25 10^{2}	4.14 10^{1}	6.48 10^{2}	1.73 10^{4}	9.10 10^{1}	3.13 10^{2}
		Am-243	1.05 10^{6}	4.72 10^{5}	2.34 10^{23}	2.36 10^{2}	5.02 10^{1}	7.73 10^{0}	2.40 10^{4}	1.10 10^{2}	2.29 10^{2}
		Cm-242	6.11 10^{8}	4.23 10^{6}	5.44 10^{35}	8.32 10^{4}	1.46 10^{4}	4.18 10^{5}	3.15 10^{6}	1.78 10^{3}	1.51 10^{5}
		Cm-243	5.94 10^{6}	2.20 10^{5}	4.33 10^{23}	1.88 10^{3}	2.36 10^{2}	3.20 10^{3}	7.63 10^{5}	1.52 10^{2}	8.99 10^{2}
		Cm-244	1.71 10^{7}	2.80 10^{5}	nd	7.76 10^{3}	6.24 10^{2}	2.16 10^{3}	1.42 10^{6}	1.85 10^{2}	2.23 10^{3}
		Cm-245	5.82 10^{6}	1.54 10^{5}	6.40 10^{28}	2.25 10^{2}	4.95 10^{1}	1.45 10^{1}	3.22 10^{4}	1.06 10^{2}	2.24 10^{2}
		Cm-246	9.19 10^{6}	1.54 10^{5}	4.18 10^{130}	3.10 10^{2}	5.05 10^{1}	4.78 10^{1}	1.25 10^{5}	1.08 10^{2}	2.45 10^{2}
		Cm-248	5.14 10^{5}	4.20 10^{4}	nd	8.33 10^{1}	1.34 10^{1}	1.25 10^{0}	3.81 10^{4}	2.93 10^{1}	5.57 10^{1}
		Any other radionuclide	1.50 10^{4}	1.54 10^{4}	5.53 10^{19}	1.50 10^{3}	8.79 10^{1}	7.47 10^{-2}	1.04 10^{1}	2.11 10^{2}	2.47 10^{2}

*Only applies to waste disposed of within the burrowing depth.

Note: Where dose is effectively zero the radiological capacity is infinite, marked here as nd (not determined).

Table 43 Suggested Schedule 3 – Disposals of radioactive waste at Port Clarence (Permit Table 3.2)

Radionuclide	Radionuclide specific consignment average activity concentration (Bq g^{-1})	Radionuclide specific peak package concentration in 10 % of consignment (Bq g^{-1})	Radionuclide	Radionuclide specific consignment average activity concentration (Bq g^{-1})	Radionuclide specific peak package concentration in 10 % of consignment (Bq g^{-1})
H-3	5000	5000	Eu-154	5000	5000
C-14	5000	5000	Eu-155	5000	5000
Cl-36	5000	5000	Gd-153	5000	5000
Ca-41	5000	5000	Pb-210	50	250
Mn-54	5000	5000	Po-210	2000	3000
Fe-55	5000	5000	Ra-226	10	50
Co-60	200	1000	Ra-228	200	1000
Ni-59	5000	5000	Ac-227	50	250
Ni-63	5000	5000	Th-228	200	1000
Zn-65	5000	5000	Th-229	20	100
Se-79	2000	3000	Th-230	100	500
Sr-90	200	1000	Th-232	10	50
Mo-93	5000	5000	Pa-231	10	50
Zr-93	5000	5000	U-232	50	250
Nb-93m	5000	5000	U-233	200	1000
Nb-94	100	500	U-234	200	1000
Tc-99	200	1000	U-235	200	1000
Ru-106	5000	5000	U-236	200	1000
Ag-108m	100	500	U-238	200	1000
Ag-110m	2000	3000	Np-237	200	1000
Cd-109	5000	5000	Pu-238	200	1000
Sb-125	5000	5000	Pu-239	100	500
Sn-119m	5000	5000	Pu-240	200	1000
Sn-123	5000	5000	Pu-241	5000	5000
Sn-126	50	250	Pu-242	200	1000
Te-127m	5000	5000	Pu-244	200	1000
I-129	200	1000	Am-241	100	500
Ba-133	5000	5000	Am-242m	100	500

Radionuclide	Radionuclide specific consignment average activity concentration (Bq g^{-1})	Radionuclide specific peak package concentration in 10 % of consignment (Bq g^{-1})	Radionuclide	Radionuclide specific consignment average activity concentration (Bq g^{-1})	Radionuclide specific peak package concentration in 10 % of consignment (Bq g^{-1})
Cs-134	5000	5000	Am-243	200	1000
Cs-135	5000	5000	Cm-242	200	1000
Cs-137	200	1000	Cm-243	200	1000
Ce-144	5000	5000	Cm-244	200	1000
Pm-147	5000	5000	Cm-245	200	1000
Sm-147	200	1000	Cm-246	200	1000
Sm-151	5000	5000	Cm-248	50	250
Eu-152	2000	3000	Any other radionuclide	200	1000

7.5 Monitoring {R14}

550. The NS-GRA outlines the requirement for the operator to undertake a monitoring programme to support the environmental safety case (Requirement 14):

> "In support of the environmental safety case, the developer/operator of a disposal facility for solid radioactive waste should carry out a programme to monitor for changes caused by construction, operation and closure of the facility.
>
> The developer/operator should establish a reasoned and proportionate approach to a programme for monitoring the site and facility. This monitoring will provide data during the period of authorisation to ensure that the facility is operating within the parameters set out in the environmental safety case. However, the monitoring must not itself compromise the environmental safety of the facility.
>
> (UK Environment Agencies, 2009), para 6.4.31 and 6.4.32."

551. There are two main reasons for a monitoring programme at the site:

- Demonstration of compliance with stated regulatory requirements; and,
- Reassurance of stakeholders that disposal at Port Clarence is safe and being managed appropriately.

7.5.1 Existing monitoring programme

552. Augean currently operates a monitoring programme at Port Clarence in connection with the hazardous waste and non-hazardous waste disposal permits.

7.5.2 Proposed monitoring programme in relation to the LLW permit

553. Augean currently operates a LLW permit monitoring programme at the ENRMF. Augean propose using a similar LLW permit monitoring programme and reporting arrangements at Port Clarence with minor modifications. The key aspects are:

- bi-annual radiochemical analysis of groundwater for several existing boreholes close to the site, analysis would be for gamma spectrometry, gross alpha / beta in waters and H-3 in aqueous samples;
- annual radiochemical analysis of bulked leachate, analysis would be for gamma spectrometry, gross alpha / beta in waters and H-3 in aqueous samples;
- quarterly radiochemical analysis of leachate treated off-site, analysis would be for gamma spectrometry, gross alpha / beta in waters and H-3 in aqueous samples;
- bi-annual radiochemical analysis of surface water, analysis would be for gamma spectrometry, gross alpha/beta in waters and H-3 in aqueous samples;
- quarterly radiochemical analysis of the landfill gas generator input for the radioactive gases identified in the risk assessment;

- quarterly radiochemical analysis for dust deposited on a powered static air sampler paper at one predominantly downwind location on the site boundary to include gamma spectrometry and gross alpha/beta;
- quarterly site perimeter dose rate at four locations; and,
- annual analysis of randomly selected surface soils from four points around the site boundary to include gamma spectrometry and gross alpha/beta.

554. The radionuclides that will be disposed at Port Clarence has not yet been determined and it is not possible to state what the monitoring regime will need to detect. This results in a reliance on total alpha, beta and gamma to indicate any variance from the background samples that would then be the subject of further analysis. The analytical detection limits of initial samples were: total alpha <0.00085 Bq g^{-1}; total beta <0.0053 Bq g^{-1}; and, total gamma <0.31 Bq g^{-1}.

555. All equipment used for environmental monitoring purposes is calibrated in line with the manufacturer's recommendations. The equipment used for dose rate monitoring is approved by the UKHSA for monitoring purposes and the UKHSA undertake re-assurance monitoring at other Augean sites to confirm the data collected. This approach will be undertaken at Port Clarence as part of the RPA provision for Port Clarence.

556. Sample analysis is undertaken by UKHSA and the laboratory detection limits are detailed in Table 44 below.

Table 44 UKHSA Laboratory detection limits

Radiochemical analysis	HPA-CRCE Scotland	UK Drinking Water Quality Standards (Anglian Water Guidance)
	Generic LoD (Bq/l and Bq/g)	
Gross alpha	Water – 0.1 Bq/l Soil – 0.05 Bq/g	0.1 Bq/l
Gross beta	Water – 1.0 Bq/l Soil – 0.05 Bq/g	1 Bq/l
Gamma spectrometry	Water – 0.001 Bq/l Soil – 0.001 Bq/g	n/a
H-3 (Tritium) by distillation	Water – 5 Bq/l Gas – not tested at this lab	100 Bq/l
H-3 (Tritium) by combustion (solid samples)	Leachate/Soil- 0.005 Bq/g	n/a

557. The monitoring action plans (MAP) for Port Clarence are detailed in the following documents:

- Port Clarence Landfill Gas MAP LLW 2022;
- Port Clarence Leachate MAP LLW 2022;
- Port Clarence Particulates Asbestos MAP LLW 2022;
- Port Clarence Surface Soil MAP LLW 2022;
- Port Clarence Surface Water MAP LLW 2022;
- Port Clarence Groundwater MAP LLW 2022; and,
- Port Clarence Site Perimeter Dose Rate MAP LLW 2022.

558. Augean will undertake re-assurance monitoring. The groundwater monitoring regime at Port Clarence will include spectrometry on an annual basis including the radionuclides of interest:

- Alpha emitters (Pb-210, Th alphas, U alphas, Pu-238, Pu-239+240 and Am-241);
- Beta emitters (H-3, Sr-90 and Pu-241);
- Gamma emitters (K-40, Co-60, Cs-134 and Cs-137); and,
- C-14.

559. The suite of radionuclides considered in the analyses includes markers for NORM, these are Ra-224, Ra-226, U-234 and U-235, indicative of their respective decay chains.

560. Bulked leachate samples will be taken from each cell receiving LLW (hazardous and non-hazardous) on a quarterly basis, see the accompanying Leachate MAP LLW. Monthly sampling will be undertaken where leachate is being transported off site, where leachate is not being removed from site then the frequency will be Quarterly. If cumulative disposal reaches the radiological capacity estimated to produce leachate at the relevant exemption level [ELL, (see Table 33)] the suite of radionuclides used for leachate monitoring of leachate will be reviewed.

561. The analysis of radioactive gas in the landfill gas generator input will occur. Analyses will include tritium, C-14 and radon, monitoring will be undertaken on a quarterly basis.

562. The following surface water locations are monitored under the current landfill EPR permits and it is proposed that radiological monitoring will be undertaken at these locations:

- PCSWPC09 This is an existing sampling point of standing surface water approximately 50m east of PC09 at approximate National Grid Reference 451280, 522610
- PCSWWBLAG This is a body of surface water directly adjacent to the drum compound at approximate National Grid Reference 451380, 522450
- PCSWGATE This is a body of surface water south of cell 1A, next to the gate adjacent to the weighbridge, located at grid reference 451420, 522380
- PCRTEES The River Tees lies adjacent to the southeastern boundary. When appropriate and during periods of high water a sample will be collected at grid reference 452200, 521800

563. The site permitter dose rate monitoring was undertaken at the following locations (shown on plan auus23115.pdf):

- Site office;
- Site office car park;
- Adjacent to groundwater borehole PC22;
- Adjacent to groundwater borehole PC16a;
- Adjacent to groundwater borehole PC10a;

- Adjacent to dust location PCDD07; and,
- Adjacent to dust location PCDD05.

564. The dust monitoring was undertaken at PCDD04 and PCDD05 (shown on plan auus23115.pdf), this is up and downwind of the landfill operations on the prevailing SW wind direction. The Particulates and Asbestos MAP sets out monitoring locations and ability of monitoring equipment in Section 4.

565. Surface soil samples use the following method to obtain representative samples (detailed in the MAP). A soil sample will be taken from each of the locations specified in Table 1.1 of the MAP using a Soil Sampler Pro, Cross Sectional Soil Sampler and avoiding previous sample locations.

- Samples will be taken to a maximum depth of 10 cm.
- The soil sampler will be marked at a depth of 10 cm, and the monitoring technician will then hammer the tube into the ground or use the footrest for extra force as required.
- The sampling tube will be twisted at least twice to break the base of the soil core and extract the sample.
- Once extracted the discharge rod will be used to push the sample out into a clean sample pot.
- The sample pot will be labelled with the date and location of sampling and returned to the laboratory as soon as practicably possible.

566. The monitoring will be reviewed on an annual basis as part of the annual reporting with a review of the nuclides of interest, and additional monitoring locations or analysis included as necessary.

7.5.3 Reassurance

567. The monitoring results will be made available for public scrutiny and published through the company website (https://www.augean.co.uk/site/port-clarence/). This will include a commentary to provide a context for the monitoring results and help with their interpretation.

568. It is expected that independent analysis of samples from the site will be undertaken periodically by the Environment Agency to provide a check on the validity of the monitoring work undertaken by Augean.

569. Additional monitoring will also be undertaken prior to work starting on new waste cells to ensure the development has no impact on system performance. This will be repeated once work on each cell is completed.

7.5.4 Groundwater monitoring programme

570. Groundwater monitoring will be undertaken at the following locations (shown on plan auus23115.pdf that accompanies this submission and discussed in Section 4.0 of the Groundwater MAP LLW):

- Upgradient boreholes: PC09, PC10a/b, PC15, PC14; and,

- Downgradient boreholes: PC08, PC22, PC18, PC19, PC01a/b, PC03a/b, PC04a/b, PC12a/b, PC11a/b.

571. The monitoring programme for groundwater has considered the predicted groundwater concentrations, the detection limits and the expected doses from the predicted concentrations.

572. The projected peak groundwater concentrations at the boundary of the site are shown in Table 45 for the radionuclides listed above. The peak concentration during the period of authorisation (PoA) and that observed over the whole period modelled are presented. Typical detection limits are also listed. This shows that even if the radiological capacity is disposed of at the site, no radionuclides would be detected in groundwater during the PoA.

Table 45 Peak groundwater concentrations at the site boundary, analytical detection limits and water concentrations producing a dose of 20 µSv

Radionuclide	Typical detection limit	Peak projected groundwater concentration after disposal of the Maximum Inventory Max to 100,000 y (Bq l^{-1})	Projected groundwater concentration after disposal of the Maximum Inventory – Max to 60 y (Bq l^{-1})	Drinking water concentration giving a dose of 20 µSv (Bq l^{-1})
H-3	4 Bq l^{-1}	$4.45\ 10^{-3}$	$5.93\ 10^{-6}$	2000
Cl-36[1]	0.29 Bq l^{-1}	$2.32\ 10^{0}$	$3.82\ 10^{-8}$	20.8
Sr-90[1]	0.11 Bq l^{-1}	$3.03\ 10^{-10}$	$2.44\ 10^{-17}$	0.8
I-129[1]	0.02 Bq l^{-1}	$1.37\ 10^{-2}$	$3.02\ 10^{-12}$	0.2
Pb-210	0.002 Bq g^{-1}	$2.02\ 10^{-10}$	$1.56\ 10^{-26}$	0.012

1 Detection limit reported for Sellafield groundwater assessments.

573. The last column of the table provides an estimate of activity concentrations in water that result in a dose of 20 µSv y^{-1}, based on HPA assessments (Ewers & Mobbs, 2010). Their value is greater than the projected groundwater concentration for all radionuclides, indicating that doses from groundwater will be lower than 20 µSv y^{-1} even if these radionuclides are disposed of at the maximum inventory.

574. This review shows that, based on the radiological capacity that can be disposed of at the site and the radionuclide mix of the wastes, these radionuclides are very unlikely to be detected in groundwater using current techniques. Routine analysis of radionuclides that are expected to be at levels below the detection limits, and are found to be below the detection limits, does not provide any useful information.

575. There is uncertainty associated with the groundwater model predictions and for this reason the list of radionuclides routinely analysed in groundwater should be reviewed as the inventory accumulates. Thus, additional radionuclides would be analysed as the inventory of the radionuclides increases and passes the trigger levels (inventory) specified above for in-scope leachate (see Table 11).

576. Routine groundwater monitoring will include analysis for H-3 and Pb-210. If the levels are found to be above those expected, then following confirmation of the unexpected results, the analytical approach will be changed to look for all of the radionuclides identified above.

8 Summary of the Environmental Safety Case

577. This document is a new ESC for the disposal of LLW at the Port Clarence site. A permit is sought to allow receipt and disposal of radioactive waste to the hazardous and non-hazardous landfills. A submission to the European Commission under Article 37 of the Euratom treaty is based on this ESC.

578. The overall safety strategy for the disposal of LLW at Port Clarence involves both active (operational) management and the construction of passive barriers ensuring that disposed wastes will give rise to low impacts, within the dose and risk guidance levels laid down in the regulatory guidance, the NS-GRA (UK Environment Agencies, 2009). The ESC has considered all of the requirements in the NS-GRA and put forward calculations and arguments to demonstrate compliance. The sections of this document follow the structure of the NS-GRA (section titles indicate how document sections relate to the NS-GRA requirements). This final section draws together the main arguments that demonstrate the environmental safety of the Port Clarence landfills now and in the future.

579. The Port Clarence landfills have been operating since 2000 and by Augean North Limited since 2004. The site has two landfills, one accepting hazardous waste and one accepting non-hazardous waste. Very low activity NORM waste has been disposed at the site since 2016. Typically this NORM waste has concentrations between 1 and 2 Bq g^{-1} and is disposed at Port Clarence without an Environmental Permit through compliance with Paragraphs 18 and 19 in Section 6 of Part 6 to Schedule 23 of the Environmental Permitting Regulations.

580. The strategic need for disposal of LLW at a site in the northeast is discussed in Section 1.1 in terms of national policy and location. The withdrawal of Clifton Marsh Landfill (operated by Suez UK) from the LLW disposal market has reduced the availability of landfill disposal sites and therefore increased the strategic importance of Port Clarence.

581. Transboundary impacts are considered in Appendix H.

8.1 Protection against radiological hazards

582. The inventory requiring disposal at Port Clarence is uncertain at this stage. Our approach is therefore to define the inventory that can be safely accepted and to put in place controls to ensure that this inventory is not exceeded. The ESC considers scenarios involving exposure to waste during normal operations, scenarios involving the expected site evolution and a full range of scenarios involving unexpected exposure resulting from the disposal of LLW. This range of scenarios ensures that for all reasonably foreseeable circumstances doses or risks remain below the relevant dose and risk guidance levels. The ESC also defines activity concentration limits for the wastes, again based on a range of scenarios, to ensure that for all reasonably foreseeable circumstances doses or risks remain below the relevant dose and risk guidance levels. The level of complexity that we have used in our assessments is proportionate and consistent with the level of detail in other safety cases and proportionate for the proposed activity concentration limits in the wastes.

583. The ESC takes a similar approach to the application document prepared for the ENRMF (Eden NE, 2023) using many of the same models that supported the radiological assessments underpinning the proposed disposal limits for LLW. The

parameters used in the models have been updated as necessary to reflect the Port Clarence environment and any intervening changes in recommendations. The ESC also takes account of comments and discussions with the Environment Agency since February 2020.

584. The assessment methodology that we have used draws heavily on methodologies developed under the sponsorship of the Environment Agency. We have used approaches developed by the Health Protection Agency (now UKHSA), the environment agencies (SNIFFER) and a screening methodology developed by the Environment Agency for operational releases. Where relevant we have also adopted approaches used in the LLWR ESC that have already been subject to detailed review by the Environment Agency.

585. The SNIFFER methodology and data have been used for several scenarios (SNIFFER, 2006). Model parameters have been adjusted to account for site specific inputs and have been adapted to take into account National Dose Assessment Working Group (NDAWG) recommendations concerning critical groups (NDAWG, 2013). The scenarios that use the SNIFFER approaches are shown in Table 46. The latest version of PC CREAM (version 1.7.3.127) has been used to assess impacts associated with atmospheric dispersion and marine dispersion (HPA, 2015).

586. The assessment of worker exposures has been carried out using the occupancy times used for the ENRMF assessment. The assessment of dropped loads adopts the UKAEA methodology as used for the ENRMF assessment. Assessment of the impact of radioactive particles and discrete items was based on the models used by LLWR.

587. The assessment of the impact on non-human biota has been undertaken using the assessment tool developed as part of the ERICA project (Environmental Risk from Ionising Contaminants: Assessment and Management) (ERICA, 2024) and has used version 2.0 released in November 2021. The ERICA toolkit allows for consideration of three ecosystems: terrestrial, freshwater and marine. Each of these has been considered for the Port Clarence site. Within these ecosystems, the ERICA Tool considers a range of wildlife groups. The assessment undertaken for non-human biota shows that the controls on the waste inventory, which are aimed at protecting the public, do not represent a risk to local biota. The assessment also includes the impact on burrowing mammals that dig into the waste post closure and show that they are protected if LLW waste is buried below the burrowing depth, or restrictions are placed on wastes within the burrowing depth.

588. The groundwater pathways have been assessed using a model implemented specifically for the Port Clarence site and environs. The model was developed using the GoldSim software, which was used because it provides a flexible modelling framework and the effects of decay and ingrowth can easily be accounted for. Where appropriate, input data have been used that are consistent with the HRA (MJCA, 2019b). Data have been used from other sources where appropriate.

Table 46 Summary of modelling approaches

Scenario	Exposed group	Modelling approach
Period of Authorisation – likely to occur		
Direct exposure	Worker	HPA/IAEA SR44
Loose tipping	Worker	IAEA SR44
	Member of public	IAEA SR44
Leachate processing off- site at treatment works	Treatment worker	Initial radiological assessment methodology (Environment Agency)
	Farming family	
	Angler	
Leachate processing using Reed Bed	Treatment worker	Initial radiological assessment methodology
	Angler	
Release to atmosphere	Member of public	SNIFFER/PC Cream
Period of Authorisation – unlikely to occur		
Leachate spillage	Farming family	SNIFFER
Dropped load	Worker	UKAEA methodology
Wound exposure	Worker	NCRP biokinetic model and IAEA injection dose
Landfill fire	Member of public	SNIFFER
After the Period of Authorisation – likely to occur		
Recreational user	Member of public	SNIFFER
Site erosion	Member of public	PC Cream/LLWR ESC
Groundwater to estuary	Member of public	Goldsim/PC CREAM
Wildlife exposure	Critical species	ERICA assessment tool
After the Period of Authorisation – unlikely to occur		
Water abstraction	Farming family	GoldSim
Bathtubbing	Farming family	
Gas release and external	Site resident	SNIFFER
Informal scavenger	Member of public	
Borehole drilling	Worker	
Material Recovery	Worker	
Trial pit excavation	Worker	
Excavation for housing	Worker/Resident	SNIFFER
Excavation for smallholder	Farming family	
Heterogeneous wastes		
Exposure to discrete items	Worker	LLWR ESC
	Member of public	
Exposure to heterogeneously contaminated large objects during or following excavation	Worker	LLWR ESC
	Member of public	
Exposure to particles	Worker	LLWR ESC
	Member of public	

589. The radiological assessments described in the ESC have been used to derive a radiological capacity for each radionuclide that will ensure the dose constraints and risk guidance levels are not exceeded in any of the assessed scenarios. The use of a sum of fractions approach based on these limits ensures that the disposed inventory will not result in impacts in excess of regulatory requirements. The following criteria have been used based on the NS-GRA (Environment Agency, 2012).

590. During the Period of Authorisation:

- Dose constraint for the public from a single source 0.3 mSv y^{-1}; and,
- Site dose criterion for workers – 1 mSv y^{-1}

After the end of management:

- 0.02 mSv y^{-1} for events that are certain to occur; and,
- 3 mSv y^{-1} for human intrusion.

591. The radiological assessments of dose to the public from disposals of LLW to Port Clarence landfills look at the behaviour of radionuclides in the landfill, consider ways that material can enter the local environment and have looked at the timescale over which this may occur. Particular attention has been given to groundwater and leachate. Assessments also consider the future of the site once it has been closed, examining different site uses and potential intrusion scenarios. The assessment approaches are cautious in nature and overestimate the doses that may occur, this leads to a set of radiological capacities that are also cautious. The scenario radiological capacities that are proposed for use with the sum of fractions are given in Table 37 and shown as the proposed relevant values for Schedule 3 of a revised permit (Table 41 and Table 42).

592. The sum of fractions is calculated for each landfill and each scenario separately using the relevant values in Table 41 or Table 42. The results from the two landfills are then combined to produce a total sum of fractions for each scenario. This combined value must be less than or equal to one for each of the scenarios listed in Table 41 and Table 42 for waste disposal to occur.

593. Port Clarence also accepts Type 2 NORM under the provisions of the exemption from the requirement for a permit described in EPR. The radiological assessment that supported the Type 2 NORM exemption submission assumed that the Port Clarence site accepts about 85,000 t of Type 2 NORM per year. We propose to control the disposal of the Type 2 NORM according to this tonnage capacity, as is currently the case.

594. We also propose to control the disposal of LLW against the LLW radiological capacity, using the sum of fractions approach described above. In addition, we will check the dose to a member of the public and record the combined dose from the LLW and the NORM disposed at the site, noting that LLW and NORM disposals have different dose criteria. A record will be maintained for relevant scenarios during the period of authorisation and after the period of authorisation.

595. We propose to use a sum of fractions approach to control the activity concentration in waste that is accepted at Port Clarence. Radionuclide specific activity concentration limits for a consignment and for a package within a consignment have been determined from a set of exposure scenarios. We propose 8 bands of activity concentration for packaged waste and an overall limit of 2000 Bq g^{-1} for a consignment fingerprint. We also propose lower activity concentration limits for loose tipped waste.

596. Discrete items are defined as “a distinct item of waste that, by its characteristics, is recognisable as unusual or not of natural origin and could be a focus of interest, out of curiosity or potential for recovery and recycling/re-use of materials should the waste item be exposed after repository closure.” We have derived Discrete item Limits for the discrete items that can be accepted at Port Clarence. These limits are more restrictive than those applied at LLWR.

597. We have assessed the impact of particles in waste disposed at Port Clarence. It is not possible to determine generic waste acceptance criteria for waste containing particles as the characteristics of the particles (e.g., nuclides, size, solubility) will be specific to

the consignment. Therefore, for waste acceptance purposes, waste containing particles will be considered on a case-by-case basis.

598. The LLW that is expected to come to Port Clarence is similar to the LLW that has been accepted at ENRMF. Therefore the inventory that has been disposed of at ENRMF (December 2023) has been used to illustrate the expected doses and use of the radiological capacity. Port Clarence does not have an LLW tonnage limit but Augean wish to keep the quantity of LLW at or below 5% of the mass of the waste accepted at the site.

599. The impact of uncertainty in estimated doses and risks has been considered and demonstrates that the ESC is robust in meeting all relevant dose and risk guidance levels.

600. Environmental monitoring during the period of authorisation will check the integrity of barriers and safety plans. Site monitoring will check the levels of radioactivity in groundwater, surface water, landfill gas, dust, surface soils and leachate. Samples will be taken on a regular basis, and an interpretative report will be prepared for the Environment Agency, which will also undertake an independent sampling programme. All these samples will provide additional assurance that the site is performing as expected and can be used as the basis for dose assessments to confirm that impacts are low. Site perimeter dose rate measurements will also be undertaken.

601. Monitoring will continue to the end of the period of authorisation (the period of management control). If any undue adverse impacts were to arise, appropriate action will be agreed with the Environment Agency.

602. The Augean management culture and safety procedures ensure that wastes are transported and handled safely reducing the potential for dose impact to the workforce and the risk of accidents leading to unplanned impacts on the environment. The site management controls will ensure that the inventory is not exceeded. There are working procedures in place controlling LLW activities at Port Clarence (Section 5.2.5). The procedures cover prior agreement between the consignor and Augean for disposal, detail appropriate receipt procedures and keeping records of disposals, procedures for waste emplacement, monitoring worker exposure, environmental monitoring and emergency plans to deal with events such as dropped loads. These are all part of Augean's Integrated Management System.

8.2 Optimisation

603. The requirement for optimisation in relation to radiological risk may be considered at three levels.

- The design of the Port Clarence landfills is consistent with best practice and regulatory requirements for the disposal of hazardous wastes and non-hazardous wastes and may therefore be considered to be optimised;
- We have considered a number of specific ways in which the management and the design of the site may be enhanced to achieve an optimised solution for the disposal of radioactive wastes; and,
- Waste consignors are required to manage wastes in a manner consistent with BAT and must demonstrate that disposal to Port Clarence is an optimal solution and, hence, consistent with BAT. We note that this aspect is a matter for consignors.

604. The design features and arrangements provide an appropriate strategy to limit the environmental impacts arising from non-radioactive contaminants. The design satisfies the requirements set out in the Landfill Directive. In the context of the assumed timescales and approach to landfill risk assessment, these measures will also be effective in limiting the environmental impacts arising from radioactive contaminants. In this sense, the design of the facility may already be considered to have been optimised. As the design of the facility is already recognised as consistent with good practice for landfills and the hazards associated with the proposed disposals of radioactive waste are low, a detailed and systematic analysis of alternative design and management strategies for the facility has not been undertaken.

605. A number of specific considerations have led to enhancements to the operational or emplacement approach to ensure that performance for radioactive waste is optimised. These include:

- The use of waste packages, which reduce the probability of doses during operations, will also reduce leaching post-closure and increase the prospect of the waste being recognised as hazardous during future intrusion. Lower limits to the activity concentrations of any loose tipped waste and site procedures to cover these operations which will minimise dispersion of the waste material during tipping.
- The implementation of a limit on putrescible materials accepted at the hazardous waste landfill ensures that microbial activity is minimised and gaseous release from microbial action or the potential for fire is minimised.
- Augean places a constraint on the level of dust on the surface of LLW packages to ensure this does not represent a hazard. LLW placed in the landfill are also covered daily to prevent dust suspension and, hence, the risk of impacts via the inhalation pathway are minimised during the operational period.
- A check is also undertaken on dose measurements at 1 m above the surface of the covered LLW, to ensure exposure of less than 2 μSv h^{-1}. The depth of cover is optimised (0.4 m) and will be increased if necessary to ensure that this limit is not exceeded. These precautions will provide additional confidence that no specific protective measures are needed for workers at the site who are closest to the LLW and will provide additional confidence that anyone off-site is also suitably protected.
- RPA and RWA advice ensures operational doses are optimised and disposal is optimised, an RPS also supervises receipt, handling and disposal operations.
- Use of the landfills is limited to 5% to constrain capacity and further reduce doses whilst still providing a useful service
- Operational constraints have been put in place to restrict the placement of LLW in a landfill cell, placing non-radioactive waste to a specified depth at the base (2 m), distance from sides (2 m) and top (1 m) of a cell. This creates a barrier between the LLW and the side liner of a waste cell which will need to be located when the cell is capped. An additional limitation is proposed for wastes with significant radium contamination. Such wastes will be disposed of at least 5 m below the restored surface of the site. This places radium below a reasonable intrusion depth and reduces the potential dose due to radon gas release from the landfill.

- The inventory of LLW disposed of at the site is controlled so that the dose constraint to members of the public during the period of authorisation is not exceeded, a record of potential doses from relevant scenarios will be maintained for LLW and Type 2 NORM disposals at the site.

606. The profiling of the restored surface will encourage surface runoff, preventing the development of puddles and reducing infiltration.

607. Disposability assessments will be undertaken when novel waste streams are proposed for disposal.

8.3 Protection against non-radiological hazards

608. The Port Clarence landfills are designed to take either hazardous wastes or non-hazardous wastes and the HRA (MJCA, 2019b) for the site demonstrates that no unacceptable environmental impacts will arise. The existing landfills at Port Clarence are permitted under the Environmental Permitting Regulations and satisfy the requirements of the Landfill Directive in terms of the management, engineering and monitoring of the site.

609. Those defined as hazardous under the European Waste Catalogue are subject to the hazardous waste acceptance criteria under the Landfill Directive (European Commission, 1999). The hazardous wastes accepted at the site are largely hazardous due to harmful, toxic, carcinogenic, irritant or eco-toxic properties. No explosive, flammable, corrosive, oxidising or infectious wastes are accepted at the site. The IMS includes established procedures for safe handling and disposal of the hazardous wastes accepted at the site. These processes are similar to those for the handling of LLW and do not conflict with them.

610. The arrangements for construction design, waste acceptance, groundwater protection, landfill gas management, leachate management, landfill stability, pollution prevention, nuisance prevention and quality assurance, construction quality assurance, maintenance, landfill capping, site restoration, operations, waste handling/placement, security, use of raw materials, secondary wastes, accident arrangements, monitoring, closure, aftercare and surrender are described in existing documentation for the landfill site.

8.4 Reliance on human action

611. The disposal facility is designed to minimise any reliance on human action to maintain the safety case during the period of operation. During the post-closure period of authorisation (i.e. the period after which no further disposals are received and the disposal cells are capped, but during which the site Permit issued under EPR2016 remains in force), leachate management will continue alongside monitoring to demonstrate that the overall system is continuing to limit entry of radionuclides to the accessible environment, consistent with the arguments in this ESC.

612. The site permits will be surrendered when the Environment Agency is satisfied that safety will be maintained without further human action. Following surrender of the site permit (i.e., at the end of the period of authorisation), there is no continuing reliance on monitoring or any other active management or intervention measure to ensure the continuing safety of the overall system.

8.5 Openness and inclusivity

613. Augean's approach to the local community is based on openness and inclusivity and draws on its extensive experience from preparations for disposals of LLW at the ENRMF. The company recognises the importance of ongoing engagement with the local community to provide reassurance and to promote greater understanding about the site and its operations throughout the lifetime of the site. The effect of providing information and opportunities to visit the ENRMF in an iterative manner over many years has created an acceptance by the local community of the disposal of LLW at the site. A similar approach has been taken at Port Clarence. Although the formal consultation to support the planning applications is complete, a programme of events to coincide with the Environment Agency's consultation on the ESC is planned.

614. On submission of this Environmental Safety Case Augean will inform the local elected representatives of the submission. Augean will also prepare a non-technical summary of the application proposals for circulation to elected representatives and the local community.

615. In addition to the ongoing existing engagement activities that include an open day and the circulation of a twice yearly community newsletter, the programme of events will include further briefings for local Members of Parliament, District Councillors and the Tees Valley Combined Authority should they wish. Augean will also host community information days at local community centres, offer a further open day with site tours and, dependent on levels of interest, workshops and drop in sessions.

616. Augean has established a register of stakeholders. This is used to contact those interested in the proposal via an electronic newsletter. This provides a good and responsive medium for offering further opportunities to visit the site, and explaining in a detailed way aspects of the scheme by giving further information about specific topics that may be of particular interest or concern raised during the programme of events.

617. The Kings Cliffe Liaison Group attached to the ENRMF has been beneficial to the local community as a point of ongoing dialogue and accountability. The establishment of a similar group at Port Clarence would be welcomed by Augean subject to agreement with local community representatives.

8.6 Conclusion

618. The ESC (Eden NE, 2019) submitted to the Environment in 2019 has been substantially revised. Augean also commissioned Bangor University (Bangor University, 2023) to provide an independent review of potential erosion rates with the Tees Estuary and the result of that work is provided and incorporated within this document (see Section 2.8). This revised ESC takes account of comments from the Environment Agency and others and includes new scenarios and exposure pathways.

619. Overall, we consider that the measures set out in this ESC provide assurance that the proposed disposal of LLW will be managed appropriately and will give rise to radiological impacts well within relevant regulatory criteria.

620. The ESC will be subject to periodic review. It is suggested that this is undertaken every 10 years. However, should any new information arise that affects the assumptions supporting the ESC (see Section 5.2), or monitoring results indicate that the assessments could be challenged, a review would be initiated.

621. Disposal of LLW at Port Clarence would secure a cost-effective, regional LLW disposal solution for nuclear sites located in the north east of the United Kingdom, which exceeds the required environmental standards. In accordance with national objectives for LLW management, it would help to ensure that disposal capacity at the LLWR is only used for wastes requiring a more highly engineered disposal solution.

9 References

Environment Agency, 2016. *Northumbria River Basin District Flood Risk Management Plan 2015-2021. PART B – Sub Areas in the Northumbria River Basin District,* Horizon House, Bristol: Environment Agency.

Allen, D. J. et al., 1997. *The Physical Properties of Major Aquifers in England and Wales,* Keyworth, Nottingham: BGS Technical Report, WD/97/34; Environment Agency R & D Publication 8.

Augean, 2006. *Hydrogeological risk assessment for Port Clarence Landfill Site near Middlesbrough,* Atherstone, Warwickshire: MJCA Report reference AU/PC/PDH/2603/01/HRA.

Augean, 2009a. *Application for Disposal of LLW including HV-VLLW under the Radioactive Substances Act 1993, for the East Northants Resource Management Facility,* Walton, Nr Wetherby: Augean plc.

Augean, 2010. *Information to satisfy the requirements Article 37 of the Euraton Treaty,* Walton, Nr Wetherby: Augean plc.

Augean, 2014. *Planning Application to Remove Condition 2 of Planning Permission Reference TDC/94/065 to Extend the Operational Life of the Non-Hazardous and Hazardous Waste Landfill Site at Port Clarence, Stockton-On-Tees. Part 2 Environmental Statement,* Atherstone, Warwickshire: MJCA, AU/PC/ABW/1636/01/ES November 2014.

Augean, 2019. *Conditions for Acceptance of Solid Low Level Radioactive,* Walton, Nr Wetherby: Augean South Ltd.

Bailey, B. R., Eckerman, K. F. & Townsend, L. W., 2003. An analysis of a puncture wounds case with medical intervention". *Radiarion Protection Dosimetry,* 105(1-4), pp. 509 - 512.

Baker, M. V., Tapper, B., Johns, C. & Herring, P., 2007. *England's Historic Seascapes: Scarborough to Hartlepool and Adjacent Marine Zone, Historic Seascape Characterisation,* Truro: Cornwall County Council, Report No. 2007R021.

Bangor University, 2023. *Quantifying future bank erosion rates at the Port Clarence Landfill Site, Tees Estuary, UK,* Bangor: Bangor University.

BEIS and NDA, 2017. *Radioactive Wastes in the UK: UK Radioactive Waste Inventory Report,* Herdus House, Mor Row, Cumbria: Nuclear Decommissioning Authority.

BGS, 2012. *UK Geohazard Note: Coastal Erosion,* Keyworth: British Geological Society.

Bishop, G. P., 1989. *Review of biosphere information: biotic transport of radionuclides as a result of mass movement of soil by burrowing animals,* Oxford: Nires Safety Studies.

Blott, S. et al., 2013. Great Britain. In: E. Pranzini & A. Williams, eds. *Coastal erosion and protection in Europe.* Abingdon, Oxon: Routledge, pp. pp. 173-208.

Boas, M. L., 2006. Chapter 8 Section 3: Linear first-order equations. In: *Mathematical methods in the physical sciences.* Third edition ed. Hoboken(New Jersey): John Wiley & Sons Inc, pp. 401-404.

Boyer, P., Wells, C. & Howard, B., 2018. Extended Kd Distributions for Freshwater Environment. *Journal of Environmental Radioactivity,* Volume 192, pp. 128-142.

Brown, J. E. et al., 2004. Radiation doses to aquatic organisms from natural radionuclides. *Journal of Radiological Protection,* Volume 24, pp. A63-A77.

Clarke, R. H., 1979. *The first report of a Working Group on Atmospheric Dispersion: a model for short and medium range dispersion of radionuclides released to atmosphere,* Harwell, Didcot: National Radiological Protection Board.

Copplestone, D., Brown, J. E. & Beresford, N. A., 2010. Considerations for the integration of human and wildlife radiological assessments. *Journal of Radiological Protection,* Volume 30, pp. 283-297.

Copplestone, D., Hingston, J. & Real, A., 2008. The development and purpose of the FREDERICA radiation effects database. *Journal of Environmental Radioactivity,* Volume 99, pp. 1456-1463.

DECC, 2012. *Strategy for the management of solid low level radioactive waste from the non-nuclear industry in the United Kingdom: Part 1 – Anthropogenic radionuclides,* London: Department of Energy & Climate Change.
DECC, 2014. *Strategy for the management of Naturally Occurring Radioactive Material (NORM) waste in the United Kingdom,* London: Department of Energy & Climate Change.
DECC, 2016. *UK Strategy for the Management of Solid Low Level Waste from the Nuclear Industry,* London: Department of Energy & Climate Change.
Defra, DTI and the Devolved Administrations, 2007. *Policy for the Long Term Management of Solid Low Level Radioactive Waste in the United Kingdom,* London: Department for Environment and Rural Affairs, PB12522.
Defra, 2009. *Protecting our Water, Soil and Air. A Code of Good Agricultural Practice for farmers, growers and land managers..* Norwich: The Stationery Office.
Defra, 2011. *Guidance on Applying the Waste Hierarchy,* London: Crown Copyright.
Delacroix, D., Guerre, J. P., Leblanc, P. & Hickman, C., 2002. *Radionuclide and Radiation Protection Data Handbook.* 2 ed. Ashford: Nuclear Technology Publishing.
Department for Communities and Local Government, 2008. *Woodland Establishment on Landfill Sites: Ten Years of Research,* London: HMSO.
DESNZ and Devolved Administrations, 2024. *UK policy framework for managing radioactive substances and nuclear decommissioning,* London: UK Government and devolved administrations.
DESNZ, 2024. *Scope of and exemptions from the radioactive substances legislation in England, Wales and Northern Ireland. Guidance document,* London: Department for Energy Security & Net Zero, Department for Environment, Food & Rural Affairs, Welsh Government and Department of Agriculture, Environment and Rural Affairs (Northern Ireland).
Devlin, A., Jay, D., Talke, S. & Zaron, E., 2017. Coupling of sea level and tidal range changes, with implications for future water levels. *Scientific Reports,* 7(1), pp. pp.1-12.
Dewar, A., Jenkinson, S. & Smedley, C., 2011. *Parameter values used in coastal dispersion modelling for radiological assessments,* Bristol: Environment Agency.
Eden NE, 2015a. *Environmental Safety Case: Disposal of Low Activity Low Level Radioactive Waste at East Northants Resource Management Facility,* Penrith, Cumbria: Eden Nuclear and Environment Ltd.
Eden NE, 2015b. *Addendum to Environmental Safety Case: Disposal of Low Activity Low Level Radioactive Waste at East Northants Resource Management Facility,* Penrith, Cumbria: Eden NE, ENE-154/002.
Eden NE, 2015c. *Information to satisfy the requirements Article 37 of the Euraton Treaty: Annex V General data applicable to modifications of a plan on which an opinion has already been given.,* Penrith: Eden Nuclear and Environment Ltd.
Eden NE, 2018. *Description of the Particle Assessment Tool v2,* Penrith, Cumbria: Eden Nuclear and Environment Limited.
Eden NE, 2019. *Environmental Safety Case: Disposal of Low Activity Low-level Radioactive Waste at the Port Clarence Landfill Sites,* Penrith, Cumbria: Eden Nuclear and Environment Ltd..
Eden NE, 2023. *Environmental Safety Case 2023: Disposal of Low Level Radioactive Waste at East Northants Resource Management Facility,* Penrith, Cumbria: Eden Nuclear and Environment Ltd.
Eden, L., 2010. *Environmental Safety Case for the disposal of very low and low level radioactive waste at the Clifton Marsh Landfill Site,* Risley, Warrington: Nuvia, Issue 2.
Environment Agencies, 2009. *Near-surface Disposal Facilities on Land for Solid Radioactive Wastes Guidance on Requirements (Environment Agency, Northern Ireland Environment Agency, and Scottish Environment Protection Agency).* Bristol: Environment Agency, Northern Ireland Environment Agency, and Scottish Environment Protection Agency.
Environment Agencies, 2018. *Management of radioactive waste from decommissioning of nuclear sites: Guidance on Requirements for Release from Radioactive Substances Regulation,* Bristol: Environment Agency.

Environment Agencies, 2021. *Guidance on the classification and assessment of waste (1st Edition v1.2.GB) Technical Guidance WM3,* Bristol: Environment Agency.
Environment Agency, 1999. *State of the Tees Estuary environment, and strategy into the millenium,* Newcastle Upon Tyne: Environment Agency.
Environment Agency, 2003. *The Development of LandSim 2.5.* Bristol: Environment Age.
Environment Agency, 2009. *Habitats Assessments for Radioactive Substances,* Bristol: Science report: SC060083/SR1.
Environment Agency, 2010. *RSR: Principles of Optimisation in the Management and Disposal of Radioactive Waste (version 2),* Bristol: Environment Agency.
Environment Agency, 2011. *Greatham Managed Realignment: Environmental Statement,* Bristol: Environment Agency.
Environment Agency, 2012. *Guidance Note for Developers and Operators of Radioactive Waste Disposal Facilities in England and Wales. Near-Surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation. Supplementary.* Bristol: Environment Agency.
Environment Agency, 2015. *Review of LLW Repository Ltd's 2011 environmental safety case: Assessments,* Bristol: Environment Agency.
Environment Agency, 2018. *Flood map for planning.* [Online]
Available at: https://flood-map-for-planning.service.gov.uk
[Accessed 20 11 2018].
Environment Agency, 2022a. *Initial Radiological Assessment Tool 2; Part 1 User Guide,* Bristol: Environment Agency.
Environment Agency, 2022b. *Initial Radiological Assessment Tool 2; Part 2 methods and input data,* Bristol: Environment Agency.
Environment Agency, 2022. *Form Guidance EP-RSR: How to apply for an environmental permit – Form RSR-B5 Version 3,* Bristol: Environment Agency.
Environment Agency, 2024. *Get flood risk information for planning in England.* [Online]
Available at: https://flood-map-for-planning.service.gov.uk/
[Accessed 17 01 2025].
Environmental Permitting (England and Wales) Regulations, 2016. *UK Statutory Instrument 2016 No 1154,* London: HMSO.
ERICA, 2024. *ERICA Assessment Tool. Version 2.0.225,* Oslo: Consortium led by the Norwegian Radiation and Nuclear Safety Authority .
ESL, 2014a. *A Planning Application to Amend Condition 2 of Planning Permission Reference TDC/94/065 for the Continuation of Waste Disposal Activities at Port Clarence Landfill Site, Stockton on Tees: Updated Baseline Ecology Survey and Assessment of Impacts,* Lincoln: ESL (Ecological Services) Ltd.
ESL, 2014b. *Ornithological Studies of Port Clarence Landfill Site, Stockton on Tees,* Lincoln: ESL (Ecological Services) Ltd.
European Commission, 1993. *Principles and Methods for Establishing Concentrations and Quantities (Exemption Values) below which Reporting is not Required in the European Directive,* Luxembourg: Commission of the European Communities, Radiological Protection - RP65.
European Commission, 1995. *Propositions de niveaux d'activité pour l'enfouissement de déchets en décharges contrôlées en France et en Belgique. J.-M. Asselineau, P. Guétat, P. Renaud, L. Baekelandt and B. Ska.* Luxembourg: Commission of the European Communities, Rapport EUR 15483 FR.
European Commission, 1999. *Council Directive of 26 April 1999 on the landfill of waste.* Official Journal of the European Communities, L182/1: Luxembourg.
European Commission, 2011. *Commission Opinion: relating to the plan for the disposal of radioactive waste arising from the East Northants Low-level Radioactive Waste Disposal Facility, located in Northamptonshire, United Kingdom, in accordance with Article 37 of the Euratom Treaty,* Brussels: Official Journal of the European Union.

European Commission, 2014. *Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation.,* Luxembourg: European Commission.
European Communities, 2003. *Council Decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC,* Brussels: Official Journal of European Communities 2003/33/EC.
Eurostat, 2024. *Population Change.* [Online]
Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Population_change_2024_table01_v2.png
[Accessed 10 03 2025].
Ewers, L. W. & Mobbs, S. M., 2010. *Derivation of liquid exclusion or exemption levels to support the RSA93 Exemption Order,* Didcot, OXON: Health Protection Agency.
Finch, H. J., Samuel, A. M. & Lane, G. P., 2002. *Lockhart and Wiseman's Crop husbandary including grassland.* Oxford: Pergammon Press.
Fouracre, L., 2005. *A Cultural Heritage Desk-Based Assessment of Northern Gateway, Teesside,* Midlothian: AOC Archaeology Group.
Galson Science Ltd, 2011. *Assessment Calculations for Human Intrusion for the LLWR 2011 ESC.* Oakham, Rutland: Galson Science Ltd.
Gane, R., 2014. *Pers. Comm to Andy Baker, Eden NE Ltd, Landfill cap details - 5 February.* Walton, Nr Wetherby: Augean plc.
GoldSim Technology Group, 2021a. *Goldsim User's Guide (Version 14).* Seattle: GoldSim Technology Group.
GoldSim Technology Group, 2021b. *User's Guide: GoldSim Contaminant Transport Module.* Seattle: GoldSim Technology Group.
Good Stuff Ltd, 2024. *River Tees at Tees Dock.* [Online]
Available at: https://riverlevels.uk/north-yorkshire-tees-dock-tidal#.XKd-baR7mCg
[Accessed 14 November 2024].
Green, B., Miles, J., Bradley, E. & Rees, D., 2002. *Radon Atlas of England and Wales,* Didcot, Oxon: National Radiological Protection Board, NRPB W26.
Griffiths, K. J., Shand, P., Marchant, P. & Peach, D., 2006. *Baseline Report Series: 23. The Lincolnshire Limestone.* Keyworth, Nottingham: British Geological Survey Commissioned Report No. CR/06/060N.
Grinsted, A., Jevrejeva, S., Riva, R. E. M. & Dahl-Jensen, D., 2015. Sea level rise projections for northern Europe under RCP8.5. *CLIMATE RESEARCH,* Volume 64, p. 15–23.
Guthrie, G. & Lane, N., 2007. *Shoreline Management Plan 2: River Tyne to Flamborough Head,* Peterborough: HASKONING UK LTD for North East Coastal Authorities Group Reference 9P0184/R/nl/PBor.
Hicks, T. W. & Baldwin, T. D., 2011. *Assessment Calculations for Human Intrusion for the LLWR 2011 ESC.* Oakham, Rutland: Gaslon Sciences Ltd 977-3: Issue 2.
HPA, 2005. *Health Implications of Dounreay Fuel Fragments: Estimates of Doses and Risks.* Didcot, Oxon: Health Protection Agency.
HPA, 2007. *Radiological Assessment of Disposals of Large Quantities of Very Low Level Waste in Landfill Sites.* Didcot, Oxon: Health Protection Agency.
HPA, 2008. *Guidance on the Application of Dose Coefficients for the Embryo, Fetus and Breastfed Infant in Dose Assessments for Members of the Public.* Didcot, Oxon: Health Protection Agency.
HPA, 2009. *Radiological Protection Objectives for the Land-based Disposal of Solid Radioactive Wastes: Advice from the Health Protection Agency, Radiation, Chemical and Environmental Hazards.* Didcot, Oxon: Health Protection Agency.
HPA, 2011. *Health risks from radioactive objects on beaches in the vicinity of the Sellafield site.,* Didcot, Oxon: HPA-CRCE-018.

HPA, 2015. *The Methodology for Assessing the Radiological Consequences of Routine Releases of Radionuclides to the Environment Used in PC-CREAM 08,* Didcot: Health Protection Agency, HPA-RPD-058.
HSE, 2001. *Reducing Risks, Protecting People. HSE's decision-making process.* Norwich: Health and Safety Executive.
Hung, C. Y., 2000. *User's Guide for PRESTO-EPA-CPG/POP Operation System – Version 4.2.* Washington, DC 20460: U.S. Environmental Protection Agency, Office of Radiation and Indoor Air.
IAEA, 1992. *Effects of ionising radiation on plants and animals at levels implied by current radiation protection standards, Technical Report Series 332..* Vienna: International Atomic Energy Agency.
IAEA, 2002. *External human induced events in site evaluation for nuclear power plants.* Vienna: International Atomic Energy Agency.
IAEA, 2003. *Derivation of activity limits for the disposal of radioactive waste in near surface disposal facilities.* Vienna: International Atomic Energy Agency, IAEA TecDoc 1380.
IAEA, 2004. *Improvement of Safety Assessment Methodologies for Near-Surface Disposal Facilities (2 volumes).* Vienna: International Atomic Energy Agency.
IAEA, 2004. *Safety Reports Series No. 37 Methods for assessing occupational radiation doses due to intakes of radionuclides,* Vienna: IAEA.
IAEA, 2005. *Derivation of activity concentration values for exclusion, exemptiom and clearance,* Vienna: International Atomic Energy Agency, IAEA SR44.
IAEA, 2010. *Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments.* Vienna: International Atomic Energy Agency TRS 472.
IAEA, 2018. *Regulations for the Safe Transport of Radioactive Material. 2018 Edition. Specific Safety Requirements No. 6. IAEA Safety Standards Series No. SSR-6 (Rev. 1),* Vienna: International Atomic Energy Agency. STI/PUB/1798..
ICRP, 1994. *Human Respiratory Tract Model for Radiological Protection,* Oxford: ICRP Publication 66, Annals of the ICRP, 24(1-3).
ICRP, 1996. *ICRP Publication 72: Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 5: Compilation of Ingestion and Inhalation Dose Coefficients,* Oxford: International Commission on Radiological Protection.
ICRP, 2007. ICRP Publication 103. The 2007 recommendations of the International Commission on Radiological Protection. *Annals ICRP,* Volume 37 (2-4).
ICRP, 2008. *Environmental Protection: the Concept and Use of Reference Animals and Plants.* Elsevier, Amsterdam: ICRP Publication 108.
ICRP, 2012. *ICRP Publication 119, Compendium of Dose Coefficients based on ICRP 60.* Elsevier, Amsterdam: ICRP Volume 41 Supplement 1.
Ilyn, L. A., 2001. *Skin wounds and burns contamianted by radioactive substances (metabloism, decontamination, tactics and techniques of medical care),* Boca Raton, Florida: CRC Press.
Inst. of Geological Sciences, 1981. *Tyne-Tees Sheet 54N-02W 1:250,000 Series.* Keyworth, Nottingham: Institute of Geological Sciences.
IPCC, 2023. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the IPCC [Core Writing Team, H. Lee and J. Romero (eds.)],* Geneva, Switzerland: Intergovernmental Panel on Climate Change.
Jackson, D., Smith, K. & Wood, M., 2014. Demonstrating Compliance with Protection Objectives for Non-Human Biota within Post-closure Safety Cases for Radioactive Waste Repositories. *J Environ Radioact,* Volume 133, pp. 60-68.
Jakes, S., 2017. *East Northants Resource Management Facility. Ionising Radiations Regulations 1999. Radiation Risk Assessment for LLW with a Specific Activity up to 200Bq/g,* Didcot, Oxon: Public Health England.

Jones, K. A., Anderson, T. & Harvey, M. P., 2014. *Assessment of the radioalogical capacity of the Port Clarence landfill site for the disposal of NORM waste,* Didcot, Oxfordshire: Public Health England, Contract Report CRCE-EA-7-2014.
Lambeck, K. et al., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *PNAS October 28,* 111(43), pp. 15296-15303.
Le Guillou, M., 1978. *A History of the River Tees.* Middlesborough: Cleveland County Libraries.
Leuven, J., Kleinhans, M., Weisscher, S. & van der Vegt, M., 2016. Tidal sand bar dimensions and shapes in estuaries. *Earth-Science Reviews,* Volume 161, pp. 204-223.
Lindborg, T., 2018. *BIOMASS 2020: Interim report. BIOPROTA report, produced in association with IAEA MODARIA II working group 6,* Solna: Svensk Kärnbränslehantering AB, SKB R-18-02.
LLWR Ltd, 2011a. *The 2011 Environmental Safety Case,* Pelham House, Seascale, Cumbria: LLWR/ESC/R(11)10016.
LLWR Ltd, 2011b. *Radiological Handbook.* Pelham House, Seascale, Cumbria: Low Level Waste Repository Ltd.
LLWR Ltd, 2011c. *The 2011 Environmental Safety Case: Assessment of Long Term Radiological Impacts, LLWR/ESC/R(11)10028.* Pelham House, Seascale, Cumbria: LLW Repository Ltd.
LLWR Ltd, 2013a. *Assessment of Discrete Items and Basis for WAC,* Pelham House, Seascale, Cumbria: LLW Repository Ltd.
LLWR Ltd, 2013b. *The LLWR Environmental Safety Case: Assessment of Carbon-14 Bearing Gas,* Pelham House, Seascale, Cumbria: LLWR/ESC/R(13)10059.
LLWR Ltd, 2019. *Discrete Item Decision Summaries.* [Online]
Available at: https://tools.llwrsite.com/introduction-to-discrete-items/discrete-item-decision-summaries/
[Accessed 14 June 2019].
Lowe, J. A. & et al., 2009. *UK Climate Projections science report: Marine and coastal projections,* Exeter, UK: Met Office Hadley Centre.
Met Office Hadley Centre, 2018. *UKCP18 exploratory extended time-mean sea level projections around the UK for 2007-2300,* Exeter: Centre for Environmental Data Analysis.
MJCA, 2007. *Waste Recovery Park Planning Application. Appendix C: Copies of the Historical Maps for the Site and Surrounding Area,* Atherstone, Warwickshire: Augean plc.
MJCA, 2012. *Hydrogeological risk assessment for the use of a 1m clay liner with a flexible membrane liner for the future hazardous waste landfill areas at Port Clarence landfill site near Middlesbrough,* Atherstone: MJCA.
MJCA, 2018. *Personal communication Heasman, L,* Atherstone: MJCA.
MJCA, 2019a. *An Application to Vary Environmental Permit Numbers EPR/BV1399IT And EPR/BV1402IC for the Port Clarence Hazardous and Non Hazardous Waste Landfill Sites Operated by Augean North Limited. Environmental Setting and Installation Design (ESID) Report.,* Atherstone: Report reference: AU/PC/AW/5606/01/ESID.
MJCA, 2019b. *Review of the Hydrogeological Risk Assessment for Port Clarence Non-hazardous Waste and Hazardous Waste Landfill Sites,* Atherstone, Warwickshire: AU/PC/JRC/2977/01.
MJCA, 2019c. *Port Clarence Permit Variation Application, Appendix I: Stability Risk Assessment (SRA) Report,* Report reference: AU/PC/DFR/44559/01: Augean North Limited.
MJCA, 2024. *The results of the topographical survey carried out by MJCA on 27 and 28 June 2024,* Atherstone: MJCA.
Mobbs, S. & Sumerling, T., 2012. *Assessment of impact of heterogeneity at the particulate scale,* Pelham House, Seascale, Cumbria: LLWR/ESC/Mem(12)146.
Natural England, 2014. *National Character Area profile: 23. Tees Lowlands,* Worcester: Crown Copyright.

NCRP, 2007. *Development of a biokinetic Model for Radionuclide contaminated Wounds and Procedures for their Assessment, Dosimetry and Treatment,* Bethesda, Maryland: National Council on Radiation Protection and Measurements.
NDA, 2010. *UK Strategy for the Management of Solid Low Level Radioactive Waste from the Nuclear Industry,* Moor Row, Cumbria: Nuclear Decommissioning Authority.
NDA, 2010. *UK Strategy for the Management of Solid Low Level Radioactive Waste from the Nuclear Industry,* Moor Row, Cumbria: Nuclear Decommissioning Authority.
NDA, 2013. *UK Radioactive Waste Inventory: Radioactivity Content of Wastes.* Moor Row, Cumbria: Nuclear Decommissioning Authority.
NDA, 2016. *Radioactive Wastes in the UK: UK Radioactive Waste Inventory Report,* Moor Row, Cumbria: Nuclear Decommissioning Authority.
NDA, 2016. *Strategy Effective from April 2016,* Moor Row, Cumbria: Nuclear Decommissioning Authority.
NDA, 2019. *Integrated Waste Management - Radioactive Waste Strategy,* Moor Row, Cumbria: Nuclear Decommissioning Authority.
NDA, 2021. *Strategy - Effective from April 2021,* Moor Row, Cumbria: Nuclear Decommissioning Authority.
NDA, 2023. *2022 UK Radioactive Waste Inventory,* Moor Row, Cumbria: Nuclear Decommissioning Authority and Department for Business, Energy & Industrial Strategy.
NDA, 2023. *NDA strategic position on radioactive waste treatment: August 2023,* Moor Row, Cumbria: Nuclear Decommissioning Authority.
NDAWG, 2013. *NDAWG Guidance Note 7. Use of habits data in prospective dose assessments..* Didcot, Oxon: National Dose Assessment Working Group.
NEA, 1987. *Shallow land burial of radioactive waste: reference levelsfor the acceptanceof long-lived radionuclides,* Paris: Nuclear Energy Agency.
NEA, 2017. *Decision and Recommendation Concerning the Application of the Paris Convention on Third Party Liability in the Field of Nuclear Energy to Nuclear Installations for the Disposal of Certain Types of Low-level Radioactive Waste.* Paris: OECD, NUCLEAR ENERGY AGENCY STEERING COMMITTEE FOR NUCLEAR ENERGY.
Nelson, T. J., 2003. *Identifying sediment sources in the tees catchment,* Durham: Durham theses, Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/3684/.
Nix, J., 2010. *Farm management pocketbook.* Melton Mowbray: The Andersons Centre.
NRPB, 2003b. *Generalised Habit Data for Radiological Assessments.* Didcot, Oxon: National Radiological Protection Board.
Nuclear Industry Guide, 2017. *Clearance and Radiological Sentencing: Principles, Process and Practices - Good Practice Guide,* s.l.: Nuclear Industry Safety Directors Forum.
NWS, 2022. *Nuclear Waste Services: Waste Metrics Dashboard.* [Online] Available at: https://www.gov.uk/government/collections/waste-metric-dashboards [Accessed 3 1 2023].
Oatway, W. B. & Mobbs, S. F., 2003. *Methodology for Estimating the Doses to Members of the Public from the Future Use of Land Previously Contaminated with Radioactivity.* Didcot, Oxon: National Radiological Protection Board.
Oatway, W. et al., 2011. *HPA CRCE 018 supplement "Supporting information for the assessment of health risks from radioactive objects on beaches in the vicinity of the Sellafield Site",* Chilton, Didcot: Health Protection Agency.
ONR, 2018. *Analysis of Coastal Flood Hazards for Nuclear Sites: NS-TAST-GD-013 Annex 3 Reference Paper,* Bootle: Office for Nuclear Regulation.
Palmer, K., Watson, C. & Fischer, A., 2019. Non-linear interactions between sea-level rise, tides, and geomorphic change in the Tamar Estuary, Australia. *Palmer, K., Watson, C. and Fischer, A., 2019. Non-linear interactions between sea-level rEstuarine, Coastal and Shelf Science,* Volume 225, pp. p106-247.
Palmer, M. et al., 2018. *UKCP18 Marine report,* Exeter: Met Office Hadley Centre Climate Programme.

Passive House Institute, 2012. *Criteria for residential passive house buildings.* Darmstadt: Passivhaus Institut GmbH.
Penfold, J. & Paulley, A., 2011. *Assessment of Environmental Safety during the Period of Authorisation for the LLWR 2011 ESC,* Pelham House, Seascale, Cumbria: LLWR: Quintessa Report QRS-1433ZB-1 Version 1.4.
Quintessa Ltd, 2011. *Assessment Calculations for Radon for the LLWR 2011 ESC.* Henley, Oxfordshire: Quintessa Ltd.
Rabbitmatters, 2024. *Wild rabbits.* [Online]
Available at: http://www.rabbitmatters.com/wildrabbits.html
[Accessed 23 July 2024].
Real, A., Sundell-Bergman, S., Knowles, J. F. & Woodhead, D. S., 2004. Effects of ionising radiation exposure on plants, fish and mammals: relevant data for environmental radiation protection. *Journal of Radiological Protection,* Volume 24, pp. A123-A137.
RIFE, 2024. *Radioactivity in Food and the Environment No. 29, 2023.* [Online]
Available at: https://www.gov.uk/government/publications/radioactivity-in-food-and-the-environment-rife-reports
[Accessed 1 2 2025].
Robinson, C., Smith, K., Jackson, D. & Towler, P., 2010. *Application of Radiation Screening Levels for Biota in Geological Disposal Facility Assessments: Issues to Consider,* London: SKM Enviros report to NDA JL30168.
Robins, P. & Davies, A., 2010. Morphological controls in sandy estuaries: the influence of tidal flats and bathymetry on sediment transport. *Ocean Dynamics,* 60(3), pp. 503-517.
Robins, P. & Lewis, M., 2020. *Response to the review by the Environment Agency of the Environmental Safety Case (ENE-0154/F2/001): Disposal of Low Activity Low-level Radioactive Waste at the Port Clarence Landfill Sites,* Bangor: Bangor University.
Schadilov, A. E., Belosokhov, M. V. & Levina, E. S., 2010. A Case of wound intake of Pu isotopes and 241Am in a human: application and improvement of the NCRP wound model. *Health Physics,* 99(4), pp. 560-567.
Shaw, G., Wadey, P. & Bell, J. N. B., 2004. Radionuclide transport above a near surface water table: IV. Soil migration and crop uptake of Chlorine-36 and Technetium-99, 1990 to 1993. *Journal of Environmental Quality,* Volume 33, pp. 2272-2280.
Smith, G. M. et al., 1988. *Assessment of the Radiological Impact of Disposal of Solid Radioactive Waste at Drigg.* Didcot, Oxon: NRPB M148.
Smith, J. G. & Simmonds, J. R., 2015. *The Methodology for Assessing the Radiological Consequences of Routine Releases of Radionuclides to the Environment Used in PC-CREAM 08, version1.1,* Didcot, Oxon: Health Protection Agency.
Smith, K. R. & Jones, A. L., 2003. *Generalised Habit Data for Radiological Assessments.* Didcot, Oxon: National Radiological Protection Board, NRPB W41.
Smith, K. et al., 2010. *Non-human Biota Dose Assessment: Sensitivity Analysis and Knowledge Quality Assessment.* Eurajoki, Finland: Posiva.
SNIFFER, 2006. *Development of a Framework for Assessing the Suitability of Controlled Landfills to Accept Disposals of Solid Low-Level Radioactive Waste: Technical Reference Manual.* Edinburgh: Scotland & Northern Ireland Forum for Environmental Research.
SNIFFER, 2006. *Development of a Framework for Assessing the Suitability of Controlled Landfills to Accept Disposals of Solid Low-Level Radioactive Waste: Technical Reference Manual (as update 2010).* Edinburgh: Scotland & Northern Ireland Forum for Environmental Research.
Spencer, T. et al., 2015. Southern North Sea storm surge event of 5 December 2013: Water levels,waves and coastal impacts. *Earth-Science Reviews,* Volume 146, pp. 120-145.
Stewart, T. H., Fulker, M. J. & Jones, S. R., 1990. A survey of habits of people living close to the Sellafield nuclear processing plant. *Journal of Radiological Protection,* 10(2), pp. 115-122.

Stocker, T. F. et al., 2013. *Climate change 2013: the physical science basis. Working Group I Contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change,* Cambridge: Cambridge University Press.
Stockton on Tees Borough Council, 2013. *Lead Local Flood Authority: Flood Investigation Report - Tees Tidal Flooding,* Stockton on Tees: Stockton on Tees Borough Council.
Stroud, K. A. & Booth, D. J., 2007. Programme 24: First-order differential equations. In: *Engineering Mathematics.* Sixth edition ed. Basingstoke(Hampshire): Palgrave Macmillan, pp. 1051-1090.
Sumerling, T. J., 2013. *Assessment of individual radioactive particles and WAC for active particles,* Pelham House, Seascale, Cumbria: LLW Repository Ltd.
Tees Valley Climate Change Resilience Group, 2012. *An assessment of the impact of climate change on the natural environment of the Tees Valley,* Tees Valley: Tees Valley Nature Partnership.
The East Northamptonshire Resource Management Facility Order, 2023. *UK Statutory Instrument. SI No. 110.* London: Crown Copyright.
The Planning Inspectorate, 2013. *Examining Authority's Report of Findings, Conclusions and Recommendations to the Secretary of State.,* London: The Planning Inspectorate.
Thorne, M., 2010. *External Memorandum: Comparison of Sphere and Slab Dose Factors,* Durham: Mike Thorne and Associates Limited.
Thorne, M. C., 2006. *Distinctions in Annual Effective Dose between Different Age Groups, Report to United Kingdom Nirex Limited.* Durham: Mike Thorne and Associates Limited.
Toohey, R. E. et al., 2014. *Dose Coefficients for intakes of Radionuclides via Conmtaminated Wounds,* Oak Ridge: Oak Ridge Institute for Science and Education.
Towler, G. et al., 2010. *Development and Testing of a Capability for Radiological Assessment of Coastal Erosion,* Henley, Oxon: QRS-1443U-R1 Version 1.1.
Tyler, A. N. et al., 2013. The radium legacy: Contaminated land and the committed effective dose from the ingestion of radium contaminated materials. *Environment International,* Volume 59, p. 449–455.
UK Environment Agencies, 2009. *Near-surface Disposal Facilities on Land for Solid Radioactive Wastes Guidance on Requirements (Environment Agency, Northern Ireland Environment Agency, and Scottish Environment Protection Agency),* Bristol: Environment Agency.
UK Goverment, 2016. *Guidance Flood risk assessments: climate change allowances.* [Online]
Available at: https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances#H-plus-plus
[Accessed 25 01 2025].
UK Government SI, 2016. *The Environmental Permitting (England and Wales) Regulations 2016, SI2016/675,* London: The Stationery Office.
UK Government SI, 2018. *The Environmental Permitting (England and Wales) (Amendment) (No. 2) Regulations 2018, SI2018/428,* London: The Stationary Office.
UNSCEAR, 1996. *Sources and effects of ionising radiation, Report of the general assembly with scientific annex A/AC.82/R.54.* New York: United Nations.
UNSCEAR, 2011. *Sources and Effects of Ionizing Radiation. Report to the General Assembly with Scientific Annexe (2008).* New York: United Nations.
US EPA, 1993. *External Exposure to Radioniuclides in air, water and soil (KF Eckerman & JC Ryman). Federal Guidance Report 12,* Washington DC, USA: US Environmental Protection Agency, EPA-402-R-93-081.
US EPA, 2014. *Memorandum dated 6/2/2014; US EPA OSWER Directive 9200.1-120.* Washington, DC: United States Environmental Protection Agency.
US EPA, 2017. *Soil and dust ingestion: Update for Chapter 5 of the Exposure Factors Handbook,* Washington: National Center for Environmental Assessment.

US EPA, 2018. *External Exposure to Radionculides in Air, Water and Soil. External Dose Rate Coefficients for General Application,* Washington: FEDERAL GUIDANCE REPORT NO. 15, EPA 402-R-18-001.

US NRC, 2014. *NRC Regulations Title 10, Code of Federal Regulations (61.55 Waste classification),* Washington, DC: U.S. Nuclear Regulatory Commission.

Villars, M. T. & Delvigne, G., 2001. *Estuarine Processes,* The Netherlands: WL Delft hydraulics.

Wheater, H. S. et al., 2007. *Biosphere implications of deep disposal of nuclear waste.* 1 ed. London: Imperial College Press.

Wilson, G., 2013. *Pers. Comm to Andy Baker, Eden NE Ltd, Landfill cap details - 18 December.* Walton, Nr Wetherby: Augean plc.

Appendix A. Glossary

In the context of this Glossary, the term 'waste' refers, in general, to radioactive waste unless otherwise specified.

Absorbed dose. See *dose, absorbed.*

Activation. The process of inducing *radioactivity.* Most commonly used to refer to the induction of *radioactivity* in moderators, coolants, and structural and shielding materials, caused by irradiation with neutrons.

Activation product. A *radionuclide* produced by *activation*. Often used in distinction from *fission products*. For example, in decommissioning waste comprising structural materials from a *nuclear facility*, activation products might typically be found primarily within the matrix of the material, whereas *fission products* are more likely to be present in the form of *contamination* on surfaces.

Activity. The quantity *A* for an amount of *radionuclide* in a given energy state at a given time. The SI unit of activity is the reciprocal second (s^{-1}), termed the Becquerel (Bq). Formerly expressed in curie (Ci), which is still sometimes used.

Activity concentration. Of a material, the *activity* per unit mass or volume of the material in which the *radionuclides* are essentially uniformly distributed.

Activity, specific. Of a *Waste Consignment* means the *Activity in the consignment* divided by the weight of the consignment. In the context of conditioned wastes, the weight of the consignment is the weight of the waste and immobilising material or grout. In accounting for *Activity* against these limits, the *Activity* of *Decay Products* shall be accounted for as listed in Column 1 of 0.

ALARP & ALARA. As low as reasonably practicable. As low as reasonably achievable. ALARP & ALARA describe approaches to optimisation. The optimisation principle states "in relation to any particular source within a practice, the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures where these are not certain to be received should all be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account…" ALARA is incorporated in UK law via RSA 1993 (BSS) Direction 2000. ALARA & ALARP focus on impacts to people.

Aquifer. A water bearing formation below the surface of the earth that can furnish an appreciable supply of water for a well or spring.

Area, controlled. A defined area in which specific protection measures and safety provisions are or could be required for controlling *normal exposures* or preventing the spread of *contamination* during normal working conditions, and preventing or limiting the extent of *potential exposures*.

Assessment. The process, and the result, of analysing systematically the hazards associated with *sources* and *practices*, and associated protection and safety measures, aimed at quantifying performance measures for comparison with criteria.

Assessment, environmental (impact). An evaluation of radiological and non-radiological impacts of a proposed activity, where the performance measure is overall environmental impact, including radiological and other global measures of impact on safety and environment.

Assessment, performance. An *assessment* of the performance of a system or subsystem and its implications for protection and safety at a planned or an authorised *facility*. This differs from *safety assessment* in that it can be applied to parts of a *facility*, and does not necessarily require assessment of radiological impacts.

Assessment, risk. An *assessment* of the radiological *risks* associated with normal *operation* and potential accidents involving a *source* or *practice*. This will normally include *consequence assessment* and associated probabilities.

Assessment, safety. An analysis to evaluate the performance of an overall system and its impact, where the performance measure is radiological impact or some other global measure of impact on safety. See also *assessment, performance.*

Audit. A documented activity performed to determine by investigation, examination and evaluation of objective evidence the adequacy of, and adherence to, established procedures, instructions, specifications, codes, standards, administrative or operational programmes and other applicable documents, and the effectiveness of implementation.

Authorisation. The granting by a *regulatory body* or other governmental body of written permission for an *operator* to perform specified activities*.* Authorisation could include, for example, a permit, licensing*,* certification and registration. See also *licence*.

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

Barrier. A physical obstruction that prevents or delays the movement of *radionuclide*s or other material between components in a system, for example a waste *repository*. In general, a barrier can be an engineered barrier which is constructed or a natural (or geological) barrier*.*

Barrier, intrusion. The components of a *repository* designed to prevent inadvertent access to the *waste* by humans, animals and plants.

Barriers, multiple. Two or more natural or engineered *barriers* used to isolate *radioactive waste* in, and prevent *radionuclide* migration from, a *repository*. See also *barrier.*

Borehole. A cylindrical excavation, made by a drilling device. Boreholes are drilled during *site* investigation and testing and are also used for *waste* emplacement in repositories and *monitoring*.

Bq/g A Becquerel (abbreviated as Bq) is the International System (SI) unit for the activity of radioactive material. One Bq of radioactive material is that amount of material in which one atom is transformed or undergoes one disintegration every second. A Gram (abbreviated as g) is a unit of mass. A Becquerel per Gram (abbreviated Bq/g) is therefore a measure of the concentration of radioactivity in a material.

Characterisation, site. Detailed surface and subsurface investigations and activities at candidate *disposal* sites to obtain information to determine the suitability of the *site* for a *repository* and to evaluate the long term performance of a *repository* at the *site.*

Characterisation, waste. Determination of the physical, chemical and radiological properties of the *waste* to establish the need for further adjustment, *treatment*, *conditioning*, or its suitability for further handling, *processing*, *storage* or *disposal.*

Clay. *Mineral*s that are essentially hydrated aluminium silicates or occasionally hydrated magnesium silicates, with sodium, calcium, potassium and magnesium cations. Also denotes a natural material with plastic properties which is essentially a composition of fine to very fine clay particles. Clays differ greatly mineralogically and chemically and consequently in their physical properties. Because of their large surface areas, most of them have good *sorption* characteristics.

Clearance. Removal of *radioactive materials* or radioactive objects within authorised *practice*s from any further *regulatory control* by the *regulatory body.*

Closure. Administrative and technical actions directed at a *repository* at the end of its operating lifetime — for example covering the disposed *waste* (for a *near surface repository*) or backfilling and/or sealing (for a *geological repository* and the passages leading to it) — and termination and completion of activities in any associated structures.

Conductivity, hydraulic, *K*. Ratio of groundwater flow rate n to driving force d*h*/d*l* (the change of hydraulic head with distance) for viscous flow of a fluid in a porous medium. This is the so-called constant of proportionality *K* in Darcy's Law and depends on both the porous medium and the fluid properties. See also *permeability.*

Consignment, a set of one or more waste packages not exceeding 10 tonnes.

Container, waste. The vessel into which the *waste form* is placed for handling, transport, *storage* and/or eventual *disposal*; also the outer *barrier* protecting the *waste* from external intrusions. The waste container is a component of the *waste package*. See also *barrier*; *waste package*.

Containment. Methods or physical structures designed to prevent the release of *radioactive substances*.

Contamination. (1) *Radioactive substances* on surfaces, or within solids, liquids or gases (including the human body), where their presence is unintended or undesirable, (2) the presence of such substances in such places or (3) the process giving rise to their presence in such places.

Control, institutional. Control of a *waste site* by an authority or institution designated under the laws of a country. This control may be active (*monitoring*, *surveillance* and remedial work) or passive (land use control) and may be a factor in the *design* of a *nuclear facility* (e.g. a *near surface repository*).

Control, regulatory. Any form of control applied to facilities or activities by a *regulatory body* for reasons related to protection or safety.

Criteria. Conditions on which a decision or judgement can be based. They may be qualitative or quantitative and should result from established principles and standards. See also *requirement*; *specifications*.

Critical group. See ***representative person***.

Decommissioning. Administrative and technical actions taken to allow the removal of some or all of the *regulatory control*s from a *facility.* This does not apply to a *repository* or to certain *nuclear facilities* used for mining and *milling* of *radioactive materials,* for which *closure* is used.

Decontamination. The complete or partial removal of *contamination* by a deliberate physical, chemical or biological process.

Diffusion. The movement of atoms or molecules from a region of higher concentration of the diffusing species to regions of lower concentration, due to a concentration gradient.

Discharge. A planned and controlled release of (usually gaseous or liquid) *radioactive material* to the environment.

Disintegration per second. See also Bq/g. A disintegration is any nuclear transformation

disposal. Emplacement of *waste* in an appropriate *facility* without the intention of retrieval. Some countries use the term *disposal* to include *discharge*s of effluents to the environment.

Distribution coefficient, K_d. The ratio of the amount of substance sorbed on a unit mass of dry solid to the concentration of the substance in a solution in contact with the solid, assuming equilibrium conditions. The SI units are: m^3 kg^{-1}.

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

Dose, absorbed, *D*. The fundamental dosimetric quantity *D.* The unit is J kg^{-1}, termed the gray (Gy).

Dose constraint. A prospective and source related restriction on the individual dose from a source, which provides a basic level of protection for the most highly exposed individuals from a source and serves as an upper bound on the dose in optimisation of protection for that source. The UK government has set a maximum dose constraint value of 0.3 mSv y^{-1} when determining applications for discharge authorisation from a single new source.

Dose, effective, *E*. A summation of the tissue *equivalent dose*s, each multiplied by the appropriate tissue weighting factor: The unit of effective dose is J kg^{-1}, with the special name Sievert (Sv). The committed effective dose is the effective dose that will be received by the person over their lifetime as a result of radionuclides taken into the body e.g. by ingestion or inhalation.

Dose, equivalent, H_T. The radiation-weighted dose in a tissue or organ. This takes account of the different amounts of damage caused by different types of radiation e.g. alpha particles, gamma radiation. The unit of equivalent dose is J/kg, termed Sievert (Sv).

Dose limit. See *limit, dose.* The value of the effective dose or the equivalent dose to individuals from planned exposure situations that shall not be exceeded. For the purposes of discharge authorisations, the UK has (since 1986) applied a dose limit of 1 mSv y^{-1} to members of the public from all man-made sources of radioactivity (other than from medical applications).

Effluent. Gaseous or liquid *radioactive materials* which are discharged to the environment. See also *discharge, authorised*.

Emanation. Generation of radioactive gas by the decay of a radioactive solid.

Environmental impact statement. A set of documents recording the results of an evaluation of the physical, ecological, cultural and socioeconomic effects of a planned *facility* (e.g. a *repository*) or of a new technology.

Exemption. The determination by a *regulatory body* that a *source* or *practice* need not be subject to some or all aspects of *regulatory control* on the basis that the *exposure* (including *potential exposure*) due to the *source* or *practice* is too small to warrant the application of those aspects. See also *level, clearance*.

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

Exposure, normal. *Exposure* which is expected to occur under the normal operating conditions of a *facility* or activity, including possible minor mishaps that can be kept under control, i.e. during normal operation and anticipated operational occurrences.

Exposure, potential. *Exposure* that is not expected to occur with certainty but that may result from an accident at a *source* or owing to an event or sequence of events of a probabilistic nature, including equipment failures and operating errors.

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

Fissile material. Uranium-233, uranium-235, plutonium-239, plutonium-241, or any combination of these *radionuclide*s. Excepted from this definition is: (a) *natural uranium* or *depleted uranium* which is unirradiated, (b) *natural uranium* or *depleted uranium* which has been irradiated in thermal reactors only.

Fission product. A *radionuclide* produced by nuclear fission.

Flow, unsaturated. The flow of water in unsaturated soil by capillary action and gravity.

Fracture. A general term for any breaks in *rock* whether or not it causes displacement.

Gradient, hydraulic. The change in total hydraulic head per unit distance of flow in a given direction.

Groundwater. Water that is held in *rock*s and soil beneath the surface of the earth.

Half-life, *T*1/2. The time taken for the quantity of a specified material (e.g. a *radionuclide*) in a specified place to decrease by half as a result of any specified process or processes that follow similar exponential patterns to radioactive decay.

Half-life, effective, *Teff*. The time taken for the *activity* of a *radionuclide* in a specified place to halve as a result of all relevant processes.

Half-life, radioactive. For a *radionuclide*, the time required for the *activity* to decrease, by a radioactive decay process, by half.

Harwell. The UKAEA Harwell site in Oxfordshire is an ex-RAF WWII airbase that has been used since 1946 for nuclear research, mainly in support of civilian power generation. The site is now well advanced with decommissioning. The aim is to return the site to a delicensed status by 2025 CE.

HV-VLLW. High volume very low level waste. A sub-category of LLW as defined in “Policy for the Long Term Management of Solid Low Level Radioactive Waste in the United Kingdom” (DEFRA, 2007).

HPA. The Health Protection Agency (HPA) was an independent body, now UK Health Security Agency (UKHSA) that protects the health and well-being of the population. The HPA includes the ex-National Radiological Protection Board (NRPB).

HSE. Britain’s Health and Safety Commission (HSC) and the Health and Safety Executive (HSE) are responsible for the regulation of almost all the risks to health and safety arising from work activity in Britain.

Inadvertent human intrusion. Accidental intrusion into a disposal facility without prior knowledge of the presence of the facility or accidental intrusion, without prior knowledge, into an area adjacent to the facility in such a way that it degrades the environmental safety performance of the facility.

Immobilisation. Conversion of *waste* into a *waste form* by *solidification*, *embedding* or *encapsulation*. The aim is to reduce the potential for *migration* or *dispersion* of *radionuclide*s during handling, transport, *storage* and/or *disposal*. See also *conditioning.*

Inert waste. Material which does not undergo any significant physical, chemical or biological transformations; does not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect other matter with which it comes into contact in a way likely to give rise to environmental pollution or harm to human health; and whose total leachability and pollutant content and the ecotoxicity of its leachate are insignificant and in particular do not endanger the quality of any surface water or groundwater. This is defined by UK waste legislation for non-radioactive wastes.

Infiltration. The downward entry of water through the ground surface into soil or *rock*.

Intervention. Any action intended to reduce or avert *exposure* or the likelihood of *exposure* to *source*s which are not part of a controlled *practice* or which are out of control as a consequence of an accident.

Leach rate. The rate of dissolution or erosion of material or the release by *diffusion* from a solid, this is hence a measure of how rapidly radionuclides may be released from that material. The term usually refers to the durability of a solid *waste form* but also describes the removal of sorbed material from the surface of a solid or porous bed.

Leach test. A test conducted to determine the *leach rate* of a *waste form*. The test results may be used for judging and comparing different types of *waste form*s, or may serve as input data for a *long term safety assessment* of a *repository*. Many different test parameters have to be taken into account, for example water composition and temperature.

Leachate. A solution that has been in contact with *waste form* and, as a result, may contain *radionuclide*s.

Level, clearance. A value, established by a *regulatory body* and expressed in terms of activity concentration and/or total *activity*, at or below which a *source* of radiation may be released from *regulatory control*. See also *clearance.*

Level, exemption. A value, established by a *regulatory body* and expressed in terms of activity concentration and/or total *activity*, at or below which a *source* of radiation may be granted *exemption* from *regulatory control* without further consideration.

Licence. A legal document issued by the *regulatory body* granting *authorisation* to perform specified activities related to a *facility* or activity. The holder of a current licence is termed a licensee**.** A licence is a product of the *authorisation* process, although the term licensing process is sometimes used.

Limit, dose. The value of the *effective dose* or the *equivalent dose* to individuals from controlled *practice*s that shall not be exceeded.

Liner. (1) A layer of material placed between a *waste form* and a container to resist *corrosion* or any other degradation of a *waste package*. (2) A layer of *clay*, plastic, asphalt or other low permeability material placed around or beneath a landfill site, *repository* or *tailings impoundment* to minimise leakage and/or erosion. (3) A structural component (made, for example, of concrete or steel) on the surface of a tunnel or *shaft* in a *repository*.

LLW. See *waste, low and intermediate level.* Low Level Radioactive Waste. With certain specific exceptions, LLW is defined as waste which has an activity concentration greater than the *out of scope levels* and up to 4,000 Bq g^{-1} for alpha emitters and 12,000 Bq g^{-1} for beta-gamma emitters. Where Bq g^{-1} is Becquerel per gram, a measure of activity within the SI system equivalent to 1 disintegration per second. Where an alpha emitter is a form of radioactive decay involving emission of alpha particles (a helium nucleus). Where beta decay is a type of radioactive decay involving the emission of electrons or positrons.

Low Level Waste Repository (LLWR). The LLWR is located 6 km southeast of Sellafield near the village of Drigg, and has operated safely for over 40 years disposing of Low Level Radioactive Wastes (LLW) from the nuclear and general industries, universities and hospitals.

Long term. In *radioactive waste disposal*, refers to periods of time that exceed the time during which active *institutional control* can be expected to last.

Long term stewardship. Conducting, supervising, or managing something entrusted to one's care. In the context of nuclear waste sites the phrase encompasses the activities undertaken after closure of the site to maintain and monitor the wastes in the long term.

LSG. Local Stakeholder Group. A group of stakeholders that meet regularly in relation to a nuclear licensed site.

Isotope. Different forms of atoms of the same element that have different numbers of neutrons in their nuclei. An element may have a number of isotopes. For example, the three isotopes of hydrogen are protium, deuterium, and tritium. All three have one proton in their nuclei, but deuterium also has one neutron, and tritium has two neutrons. Different isotopes can have different radioactive properties and present different risks.

Migration. The movement of contaminants in the environment as a result of natural processes.

Minimisation, waste. The process of reducing the amount and *activity* of *radioactive waste* to a level as low as reasonably achievable, at all stages from the *design* of a *facility* or activity to *decommissioning*, by reducing *waste* generation and by means such as recycling and reuse, and *treatment*, with due consideration for secondary as well as primary *waste.* See also *pretreatment*; *treatment*; *volume reduction*.

Model. A representation of a system and the ways in which phenomena occur within that system, used to simulate or assess the behaviour of the system for a defined purpose.

Model, computational. A calculation tool that implements a *mathematical model*.

Model, conceptual. A set of qualitative assumptions used to describe a system.

Model, mathematical. A set of mathematical equations designed to represent a *conceptual model*.

Model, pathways. A mathematical representation used to simulate the transport of *radionuclide*s from a *source* to a receptor.

Model, transport. A mathematical representation of mechanisms controlling the movement of finely dispersed or dissolved substances in fluids.

Monitoring. Continuous or periodic measurement of radiological and other parameters or determination of the status of a system.

Naturally occurring radioactive material (NORM). Material containing no significant amounts of *radionuclide*s other than *naturally occurring radionuclide*s. The exact definition of 'significant amounts' would be a regulatory decision. Materials in which the *activity* concentrations of the *naturally occurring radionuclides* have been changed by human made processes are included. These are sometimes referred to as technically enhanced NORM or TENORM.

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

NDA. Nuclear Decommissioning Authority. A public body that oversees nuclear decommissioning in the UK on designated sites such as Harwell.

NRPB. The National Radiological Protection Board (NRPB) was an independent body, now UK Health Security Agency (UKHSA), that protects the health and well-being of the population.

Nuclear facility. A facility and its associated land, buildings and equipment in which radioactive materials are produced, processed, used, handled, stored or disposed of on such a scale that consideration of safety is required.

Nuclear material. Plutonium except that with isotopic concentration exceeding 80% in plutonium- 238; uranium-233; *uranium* enriched in the isotope 235 or 233; uranium containing the mixture of isotopes occurring in nature other than in the form of ore or ore residue; any material containing one or more of the foregoing.

Nuclear site licence. A licence issued under the Nuclear Installations Act.

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

ONR. Office for Nuclear Regulation. Under UK law (the Health and Safety at Work etc. Act 1974) employers are responsible for ensuring the safety of their workers and the public, and this is just as true for a nuclear site as for any other. This responsibility is reinforced for nuclear installations by the Nuclear Installations Act 1965 (NIA), as amended. Under the relevant statutory provisions of the NIA, a site cannot have nuclear plant on it unless the user has been granted a site licence by the Health and Safety Executive (HSE). This licensing function is administered by HSE's Office for Nuclear Regulation (ONR).

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

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

Operational period. The period during which a *nuclear facility* (e.g. a *repository*) is being used for its intended purpose until it is decommissioned or is submitted for permanent *closure*.

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

Out of scope level (OoSL). The activity concentration of a radionuclide that is out of the scope of the radioactive substances regulations. Material and waste containing levels of radioactivity below the OoSL are not considered to be *radioactive material* or radioactive waste. Applies to solid waste only. Often the same as *clearance levels*.

Overpack. A secondary (or additional) outer container for one or more *waste package*s, used for handling, transport, *storage* or *disposal*.

Package, waste. The product of *conditioning* that includes the *waste form* and any container(s) and internal *barrier*s (e.g. absorbing materials and *liner*s), prepared in accordance with the *requirement*s for handling, transport, *storage* and/or *disposal*.

Permeability, *k*. The ability of a porous medium to transmit fluid.

Permit. A document issued by the Environment Agency to allow the accumulation, disposal or discharge of waste.

Plume. The spatial distribution of a release of airborne or waterborne material as it disperses in the environment.

PHE. Public Health England (PHE) was an independent body, now UK Health Security Agency (UKHSA), that protects the health and well-being of the population. The HPA includes the ex-National Radiological Protection Board (NRPB).

porosity. The ratio of the aggregate volume of interstices in *rock*, soil or other porous media to its total volume.

Post-closure period. The period of time following the *closure* of a *repository* and *decommissioning* of related surface facilities. Some type of *surveillance* or control will probably be maintained in this period, particularly for *near surface repositories*. See also *closure*; *preclosure period*.

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

Preclosure period. The period of time spanning the construction and *operation* of a *repository* up to and including the *closure* and *decommissioning* of related surface *facilities*. See also *closure*; *post-closure period*.

Predisposal. Any *radioactive waste management* steps carried out prior to *disposal*, such as *pretreatment*, *treatment*, *conditioning*, *storage* and transport activities. *Decommissioning* is considered to be a part of predisposal management of *radioactive waste*.

Pretreatment. Any or all of the operations prior to *waste treatment*, such as collection, *segregation*, chemical adjustment and *decontamination*.

Quality assurance (QA). Planned and systematic actions necessary to provide adequate confidence that an item, process or service will satisfy given *requirement*s for quality, for example those specified in the *licence*.

Quality control (QC). The part of *quality assurance* intended to verify that systems and components correspond to predetermined *requirement*s.

Radioactive material. Material designated in national law or by a *regulatory body* as being subject to *regulatory control* because of its *radioactivity*.

Radioactivity. The phenomenon whereby atoms undergo spontaneous random disintegration, usually accompanied by the emission of radiation.

Radionuclide. A nucleus (of an atom) that possesses properties of spontaneous disintegration (*radioactivity*). Nuclei are distinguished by their mass and atomic number.

Records. A set of documents, such as instrument charts, certificates, log books, computer printouts and magnetic tapes for each *nuclear facility,* organised in such a way that it provides past and present representations of facility *operation*s and activities including all phases from *design* through *closure* and *decommissioning* (if the facility has been decommissioned). Records are an essential part of *quality assurance*.

Regulatory body. An authority or a system of authorities designated by the government of a State as having legal authority for conducting the regulatory process, including issuing *authorisation*s*,* and thereby for regulating the *siting, design,* construction, *commissioning*, *operation*, *closure*, *decommissioning* and, if required, subsequent *institutional control* of the *nuclear facilities* (e.g. *near surface repositories*) or specific aspects thereof.

Remedial action. Action taken when a specified action level is exceeded, to reduce a radiation *dose* that might otherwise be received, in an intervention situation involving chronic *exposure*. Examples are: (a) actions which include *decontamination*, *waste* removal and environmental restoration of a *site* during *decommissioning* and/or *closure* efforts; (b) actions taken beyond stabilisation of *tailings impoundment*s to allow for other uses of the area or to restore the area to near pristine conditions.

Repository. A *nuclear facility* where *waste* is emplaced for *disposal*.

Repository, near surface. A *facility* for *disposal* of *radioactive waste* located at or within a few tens of metres from the earth's surface.

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

Retardation. A reduction in the rate of *radionuclide* movement through the soil due to the interaction (e.g. by *sorption*) with an immobile *matrix*.

Retardation coefficient, *R*d. A measure of capability of porous media to impede the movement of a particular *radionuclide* being carried by fluid.

Retrievability. The ability to remove *waste* from where it has been emplaced.

Risk. A multiattribute quantity expressing hazard, danger or chance of harmful or injurious consequences associated with actual or *potential exposures.* It relates to quantities such as the probability that specific deleterious consequences may arise and the magnitude and character of such consequences. (2) The combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event. The concept of risk always has two elements: the frequency or probability with which a hazardous event occurs and the consequences of the hazardous event. Risk = Probability x Consequence.

Safety case. An integrated collection of arguments and evidence to demonstrate the safety of a *facility.* This will normally include a *safety assessment*, but could also typically include information (including supporting evidence and reasoning) on the robustness and reliability of the *safety assessment* and the assumptions made therein.

Safety culture. The assembly of characteristics and attitudes in organisations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance.

Safety report. A document required from the *operating organisation* by the *regulatory body* containing information concerning a *nuclear facility* (e.g. a *repository*), the site characteristics, *design*, operational procedures, etc., together with a *safety analysis* and details of any provisions needed to restrict *risk* to personnel and the public.

Scenario. A postulated or assumed set of conditions and/or events. They are most commonly used in *analysis* or *assessment* to represent possible future conditions and/or events to be modelled, such as possible accidents at a *nuclear facility*, or the possible future evolution of a *repository* and its surroundings.

Screening. A type of *analysis* aimed at eliminating from further consideration factors that are less significant for the purpose of the *analysis*, in order to concentrate on the more significant factors. Screening is usually conducted at an early stage in order to narrow the range of factors needing detailed consideration in an *analysis* or *assessment*.

Segregation. An activity where *waste* or materials (radioactive and exempt) are separated or are kept separate according to radiological, chemical and/or physical properties which will facilitate *waste* handling and/or *processing*. For example, it may be possible to segregate radioactive waste from exempt waste and thus reduce the *waste* volume.

Semi infinite plane. A semi-infinite plane is bounded in one direction, i.e. it is a surface, and unbounded in another (stretches infinitely in all directions).

Shielding. A material interposed between a *source* of radiation and persons, or equipment or other objects, in order to absorb radiation and thereby reduce radiation exposure.

Site. The area containing, or under investigation for its suitability for, a *nuclear facility* (e.g. a *repository*). It is defined by a boundary and is under effective control of the *operating organisation*.

Solidification. *Immobilisation* of gaseous, liquid or liquid-like materials by conversion into a solid *waste form*, usually with the intent of producing a physically stable material that is easier to handle and less dispersible. *Calcination*, drying, *cementation*, *bituminisation* and *vitrification* are some of the typical ways of solidifying liquid *waste*. See also *conditioning*; *immobilisation*.

Solubility. The amount of a substance that will dissolve in a given amount of another substance.

Sorption. The interaction of an atom, molecule or particle with the surface of a solid. A general term including absorption (sorption taking place largely within the pores of a solid) and adsorption (surface sorption with a non-porous solid). The processes involved may also be divided into chemisorption (chemical bonding with the substrate) and physisorption (physical attraction, for example by weak electrostatic forces).

Source. (1) Anything that may cause radiation *exposure,* such as by emitting ionizing radiation or by releasing *radioactive substances* or materials. (2) More specifically, *radioactive material* used as a source of radiation.

Source, natural. A naturally occurring *source* of radiation, such as the sun and stars (*source*s of cosmic radiation) and *rock*s and soil (terrestrial *source*s of radiation).

Source term. A mathematical expression used to denote information about the actual or potential release of radiation or *radioactive material* from a given *source*, which may include further *specification*s, for example the composition, the initial amount, the rate and the mode of release of the material.

Storage. (1). The holding of *spent fuel* or of *radioactive waste* in a *facility* that provides for its *containment*, with the intention of retrieval. (2). Storage is by definition an interim measure, and the term interim storage would therefore be appropriate only to refer to short term temporary storage when contrasting this with the longer term fate of the *waste*. Storage as defined above should not be described as interim storage.

Surface water. Water which fails to penetrate into the soil and flows along the surface of the ground, eventually entering a lake, a river or the sea.

Survey, radiological. An evaluation of the radiological conditions and potential hazards associated with the production, use, transfer, release, *disposal*, or presence of *radioactive material* or other *source*s of radiation.

Transport, radionuclide. The movement (*migration*) of *radionuclide*s in the environment, for example radionuclide transport by *groundwater*. This could include processes such as *advection*, *diffusion*, *sorption* and *uptake*. This usage does not include intentional transport of radioactive materials by humans (transport of radioactive *waste*s in *cask*s, etc). See also *migration*.

Treatment. Operations intended to benefit safety and/or economy by changing the characteristics of the *waste*. Three basic treatment objectives are: *volume reduction,* removal of *radionuclide*s from the *waste* and change of composition. Treatment may result in an appropriate *waste form*.

UKAEA The United Kingdom Atomic Energy Authority (UKAEA) was incorporated as a statutory corporation in 1954 CE and pioneered the development of nuclear energy in the UK. Today UKAEA are responsible for managing the decommissioning of the nuclear reactors and other radioactive facilities used for the UK's nuclear research and development programme in a safe and environmentally sensitive manner. UKAEA is a non-departmental public body, funded mainly by its lead department the Department of Trade and Industry under contract to the NDA.

uptake. A general term for the processes by which *radionuclide*s enter one part of a biological system from another. Used in a range of situations, particularly in describing the overall effect when there are a number of contributing processes, for example *root uptake*, the transfer of *radionuclide*s from soil to plants through the plant roots.

Very low level waste (VLLW). See *waste, very low level*.

Volume reduction. A *treatment* method that decreases the physical volume of a *waste*. Volume reduction is employed because it is economical and facilitates subsequent handling, *storage*, transport and *disposal* of the *waste*. Typical volume reduction methods are mechanical *compaction*, *incineration* and *evaporation*. Volume reduction of a given *waste* results in a corresponding increase in *radionuclide* concentration. The total volume of *waste* may also be reduced through *decontamination* (with subsequent *exemption*) or through the avoidance of *waste* generation. See also *minimisation, waste*.

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

Waste, alpha bearing. *Radioactive waste* containing one or more alpha emitting *radionuclide*s. Alpha bearing waste can be short lived or long lived.

Waste, exempt. *Waste* released from *regulatory control* in accordance with *exemption* principles. See also *clearance level*s; *exemption*.

Waste, mixed. *Radioactive waste* that also contains non-radioactive toxic or hazardous substances.

Waste, radioactive. For legal and regulatory purposes, *waste* that contains or is contaminated with *radionuclide*s at concentrations or *activities* greater than *clearance levels* or *out of scope levels* as established by the *regulatory body*. It should be recognised that this definition is purely for regulatory purposes and that material with *activity* concentrations equal to or less than *clearance level*s is radioactive from a physical viewpoint — although the associated radiological hazards are considered negligible.

Waste, secondary. A form and quality of *waste* that results as a by-product from *processing* of *waste*.

Waste, very low level (VLLW). *Radioactive waste* considered suitable by the *regulatory body* for authorised *disposal*, subject to specified conditions, with ordinary *waste* in facilities not specifically designed for radioactive waste disposal.

Waste acceptance criteria. Quantitative or qualitative criteria for *radioactive waste* to be accepted by the *operator* of a *repository* for *disposal*, or by the *operator* of a storage facility for *storage*. Waste acceptance criteria might include, for example, restrictions on the *activity* concentration or the total *activity* of particular *radionuclide*s (or types of *radionuclide*) in the *waste* or *requirement*s concerning the *waste form* or *waste package*.

Waste form. *Waste* in its physical and chemical form after *treatment* and/or *conditioning* (resulting in a solid product) prior to packaging. The waste form is a component of the *waste package*.

Waste generator. The *operating organisation* of a *facility* or activity that generates *waste*. See also *operator*.

Waste inventory. Quantity, *radionuclide*s, *activity* and *waste form* characteristics of *waste*s for which an operator is responsible.

Waste management, radioactive. All activities, administrative and operational, that are involved in the handling, *pretreatment*, *treatment*, *conditioning*, transport, *storage* and *disposal* of *radioactive waste*.

Water table. The upper surface of a zone of *groundwater* saturation.

Zone, saturated. A subsurface zone in which all the interstices are filled with water. This zone is separated from the *unsaturated zone*, i.e. the zone of aeration, by the *water table*. See also *zone, unsaturated*.

Zone, unsaturated. A subsurface zone in which at least some interstices contain air or water vapour, rather than liquid water. Also referred to as the 'zone of aeration'. See also *zone, saturated*.

Appendix B. Baseline Monitoring

B.1. WATER SAMPLES 211
B.2. DUST SAMPLING 216

622. Samples of water, dust and surface soil were taken to establish the background level of radioactivity at the site prior to receipt of any radioactive waste in accordance with a radioactive substances permit. The dose rate at the site perimeter was also monitored.

B.1. Water samples

623. Groundwater samples were collected from the existing boreholes at/around the site. The samples were collected after an appropriate volume of water had been purged using the waterra tubing installed in the boreholes or a clean sampling bailer. A sample was then collected and placed straight into a 1 litre sampling bottle. This was then placed in a coolbox until it was transferred into packaging to be sent off to UK Health Protection Agency (UKHSA; formally PHE and HPA) within sample stability times.

624. Surface water samples were collected using a jug connected to an extendable rod. To avoid stagnant water being collected, a purge was conducted in the area of water that a sample will be collected (two litres of surface water). A sample was then collected and placed straight into a 1 litre sampling bottle. This was then placed in a coolbox until it was transferred into packaging to be sent off to UKHSA within sample stability times.

625. All leachate samples were collected using a clean 1 m sampling bailer. Once the 1 litre sampling bottle had been filled, it was transferred to a coolbox where it was kept until the sample was packaged for collection to be delivered to UKHSA within the specified stability times.

626. In the following tables, "<" indicates a result is less than or equal to a test methods Limit of Detection (LOD) for that parameter at the time of analysis.

Table 47 Analysis of radioactivity in groundwater samples from various locations on 03/06/2019

Component	Units	Location Id							
		PCGW01	PCGW03	PCGW09	PCGW10B	PCGW11	PCGW12	PCGW17	PCGW18
Total alpha	Bq/g	<0.00085	<0.00085	<0.00082	<0.00084	<0.00084	<0.00083	<0.00084	<0.00083
Total beta	Bq/g	<0.00535	0.00581	0.00595	0.01153	<0.00529	0.00711	<0.00525	0.00543
Total Gamma	Bq/L	3.43	7.39	10.1	8.74	15.46	9.1	3.72	0.662
Tritium Liquids	Bq/L	<6.69	<6.69	<6.53	<6.68	<6.6	<6.69	<6.67	<6.66
Total Actinium-228	Bq/g	<0.00125	0.00173	<0.00121	0.000556	0.00117	<0.00124	<0.00083	0.000662
Total Americium-241	Bq/g	<0.00131	<0.00104	<0.00135	<0.00021	<0.00124	<0.00136	<0.0002	<0.00021
Total Cobalt-60	Bq/g	<0.00029	<0.0003	<0.0003	<0.00025	<0.00032	<0.00031	<0.00024	<0.00025
Total Caesium-137	Bq/g	<0.0003	<0.00028	<0.0003	<0.00021	<0.00032	<0.0003	<0.00022	<0.00022
Total Potassium-40	Bq/g	0.00237	0.00521	<0.00483	0.00799	<0.00397	0.00782	0.00339	<0.00298
Total Lead-210	Bq/g	<0.0273	<0.0254	<0.0279	<0.00207	<0.0287	0.0281	<0.00196	<0.00195
Total Lead-212	Bq/g	<0.00062	0.000445	<0.00061	0.000194	<0.0006	0.00063	0.000326	<0.00029
Total Lead-214	Bq/g	0.00106	<0.00073	<0.00074	<0.00044	0.00843	0.00128	<0.00042	<0.00046
Total Radium-224	Bq/g	<0.00652	<0.00601	<0.00645	<0.00316	0.00586	<0.00671	<0.00322	<0.00306
Total Radium-226	Bq/g	<0.00674	<0.00691	<0.00692	<0.00298	<0.00686	<0.00692	<0.00305	<0.0031
Total Thorium-234	Bq/g	<0.0116	<0.0099	0.0101	<0.00199	<0.0116	<0.0118	<0.00193	<0.00198
Total Uranium-235	Bq/g	<0.00042	<0.00043	<0.00043	<0.00018	<0.00043	<0.00043	<0.00019	<0.00019

Table 48 Analysis of radioactivity in surface water samples from various locations on 03/06/2019

Component	Units	Location Id			
		PCSWGate	PCSWTees	PCSWBlag	PCSWWheelwash
Total alpha	Bq/g	<0.00085	<0.00085	<0.00085	<0.00085
Total beta	Bq/g	<0.00534	0.01204	<0.00533	0.00618
Total Gamma	Bq/L	2.71	10.3	<0.28	<0.31
Tritium Liquids	Bq/L	<6.66	<6.68	<6.65	<6.68
Total Actinium-228	Bq/g	<0.0012	<0.00079	<0.00108	<0.00118
Total Americium-241	Bq/g	<0.00131	<0.00017	<0.00104	<0.00131
Total Cobalt-60	Bq/g	<0.0003	<0.00024	<0.0003	<0.00451
Total Caesium-137	Bq/g	<0.00031	<0.0002	<0.00028	<0.00031
Total Potassium-40	Bq/g	0.00271	0.0103	<0.00361	<0.00451
Total Lead-210	Bq/g	<0.0276	<0.00195	<0.025	<0.0273
Total Lead-212	Bq/g	<0.00061	<0.00028	<0.00052	<0.00059
Total Lead-214	Bq/g	<0.00071	<0.00043	<0.00068	<0.0007
Total Radium-224	Bq/g	<0.00645	<0.00298	<0.00568	<0.00629
Total Radium-226	Bq/g	<0.00673	<0.00308	<0.00613	<0.00682
Total Thorium-234	Bq/g	<0.0113	<0.00202	<0.00961	<0.0115
Total Uranium-235	Bq/g	<0.00042	<0.00019	<0.00038	<0.00042

Table 49 Analysis of radioactivity in leachate samples from various locations on 05/06/2019

Component	Units	Location Id								
		PCLW1A1	PCLW1BC1	PCLW1BM1	PCLWDC1	PCLW2A1	PCLW2B1	PCLW3A1	PCLW4A1	PCLW5A1
Total Actinium-228	Bq/g	<0.00112	<0.00112	<0.00112	<0.00128	<0.00113	0.00101	<0.00118	<0.00103	<0.00127
Total alpha	Bq/g	<0.00085	<0.00085	<0.00084	<0.00084	<0.00084	<0.00083	<0.00085	<0.00085	<0.00085
Total Americium-241	Bq/g	<0.00066	<0.00067	<0.00106	<0.00135	<0.00066	<0.00023	<0.00068	<0.00026	<0.00118
Total beta	Bq/g	0.0233	0.0392	0.0333	0.0421	0.0467	0.0317	0.0994	0.136	0.154
Total Cobalt-60	Bq/g	<0.00028	<0.00028	<0.00031	<0.00034	<0.00029	<0.00025	<0.00032	<0.00031	<0.00037
Total Caesium-137	Bq/g	<0.00028	<0.00028	<0.0003	<0.00021	<0.00029	<0.00021	<0.0003	<0.00025	<0.00032
Total gamma in liquid	Bq/L	25	34.8	35.3	38.7	51.2	33.1	104	132	163
Tritium Liquids	Bq/L	45.2	45.7	23.9	28.1	29	59	<6.67	55.9	33.7
Total Potassium-40	Bq/g	0.025	0.0348	0.0353	0.0387	0.0478	0.0321	0.0996	0.132	0.163
Total Lead-210	Bq/g	<0.00674	<0.000674	<0.0258	<0.0283	0.00337	<0.00209	0.00446	<0.00253	<0.0268
Total Lead-212	Bq/g	<0.00058	<0.00059	<0.00052	<0.00061	<0.00059	<0.00027	<0.00093	<0.00031	<0.00057
Total Lead-214	Bq/g	<0.00067	<0.00069	<0.0007	<0.00073	<0.00069	<0.00044	<0.0007	<0.00046	<0.00073
Total Radium-224	Bq/g	<0.00626	<0.00509	<0.00572	<0.00648	<0.00646	<0.00197	<0.00631	<0.00337	<0.00619
Total Radium-226	Bq/g	<0.00774	<0.00777	<0.00612	<0.0068	<0.00769	<0.00315	<0.00788	<0.00328	<0.00656
Total Thorium-234	Bq/g	<0.00647	<0.00653	<0.00975	<0.012	<0.00648	<0.0021	<0.00658	<0.00249	<0.0106
Total Uranium-235	Bq/g	<0.00048	<0.00048	<0.00038	<0.00042	<0.00048	<0.0002	<0.00049	<0.0002	<0.00041

Table 50 Analysis of radioactivity in leachate collection tanks on 05/06/2019

Component	Units	Location ID	
		PCLWTankNon-Haz	PCLWTankHaz
Total Actinium-228	Bq/g	<0.00133	<0.001
Total alpha	Bq/g	<0.00083	<0.00085
Total Americium-241	Bq/g	<0.00133	<0.00027
Total beta	Bq/g	0.0412	0.129
Total Cobalt-60	Bq/g	<0.00033	<0.00031
Total Caesium-137	Bq/g	<0.00033	<0.00025
Total gamma in liquid	Bq/L	46.5	132
Tritium Liquids	Bq/L	46.2	41.8
Total Potassium-40	Bq/g	0.0465	0.132
Total Lead-210	Bq/g	<0.0282	<0.00254
Total Lead-212	Bq/g	<0.00061	<0.00031
Total Lead-214	Bq/g	<0.00074	<0.00046
Total Radium-224	Bq/g	<0.00645	<0.0033
Total Radium-226	Bq/g	<0.00687	<0.00338
Total Thorium-234	Bq/g	<0.0117	<0.00243
Total Uranium-235	Bq/g	<0.00042	<0.00021

B.2. Dust sampling

627. All dust samples were collected during the monthly routine monitoring. De-ionised water was used to rinse the deposited dust from the top of the dust gauge (collection Frisbee) through 227mm pipework into a 5 litre HDPE collection bottle. The entire sample is filtered at the on-site laboratory and the dried filter sent off for analysis at UKHSA.

Table 51 Analysis of radioactivity in dust samples (Bq/filter) from two locations on 30/04/2019

Component in dust	Location PCDD04	Location PCDD05
Total Actinium-228 in dust	<0.135	0.142
Total alpha in dust	0.09	0.02
Total Americium-241 in dust	<0.073	<0.114
Total beta in dust	0.39	0.19
Total Cobalt-60 in dust	<0.044	<0.04
Total Caesium-137 in dust	<0.034	<0.034
Total gamma in deposited dust	0.331	1.33
Total Potassium-40 in dust	0.331	1.19
Total Lead-210 in dust	<1.36	<2.68
Total Lead-212 in dust	<0.049	<0.06
Total Lead-214 in dust	<0.071	<0.077
Total Radium-224 in dust	<0.54	<0.656
Total Radium-226 in dust	<0.554	<0.142
Total Thorium-234 in dust	<0.699	<0.041
Total Uranium-235 in dust	<0.035	<0.114

Appendix C. Policy Statement and Integrated Management System

APPENDIX C. POLICY STATEMENT AND INTEGRATED MANAGEMENT SYSTEM 217
C.1. SURFACE SOIL SAMPLES 220
C.2. SITE PERIMETER DOSE RATE 220

Augean		Health, Safety, Environment and Quality Policy		FUTURE INDUSTRIAL SERVICES LTD PART OF THE AUGEAN GROUP	
Document Number: AG_HSEQ_Pol.01		Version No.	4	Page 1 of 1	
Creation Date:	25/05/2023	Last review date:	12/09/2024	Next review date:	12/09/2025

This policy outlines our commitment to be a responsible and sustainable business and our commitment to satisfying all requirements that are applicable to our business. These core values are the foundation for our Environmental, Social and Corporate Governance commitment. Our sustainable development goals and actions are detailed in our annual Corporate Social Responsibility Report.

This policy describes how we manage our impact on the environment; ensure the health, safety and welfare of our colleagues, stakeholders, contractors, visitors, and the public; and provide customer satisfaction through service excellence.

It applies to Augean Limited business units including Future Industrial Services Ltd. It applies to our people. It also applies to those working on our behalf where we control or influence the outcome of the work performed.

We are committed to meeting the applicable legal and other compliance obligations; and preventing foreseeable accidents and responding effectively to emergencies where this is not possible, to reduce their consequences.

Our directors are committed to protecting and improving the environment, and the health and safety of their colleagues, by promoting continual improvement and periodically reviewing our management policies and objectives. This policy provides a framework for setting clear objectives for the Occupational Health and Safety, Environmental and Quality management systems by which we regularly measure our progress.

Our directors and managers are committed to the consultation and participation of all colleagues in the process of continual improvement.

We achieve our commitments by continually improving the management system and following these principles:

Health and Safety

- Recognising that our people are our greatest asset and that their health and safety is a top priority for the organisation.
- The Board of Directors are committed to providing safe and healthy working conditions for the prevention of work-related injury and ill health by eliminating (where possible) hazards and reducing risks.
- Consulting with colleagues about their health, safety and working conditions. We use proactive communications on day-to-day matters.
- Managing occupational health matters. This includes offering assistance with mental health and wellbeing.
- The Board of Directors and I are accountable for all health and safety matters.
- Line managers and supervisors have non-negotiable responsibility for the health and safety of their team members.
- Employees have a duty to take care of their own safety and that of colleagues and visitors, and to cooperate with their supervisor to achieve this.

Quality

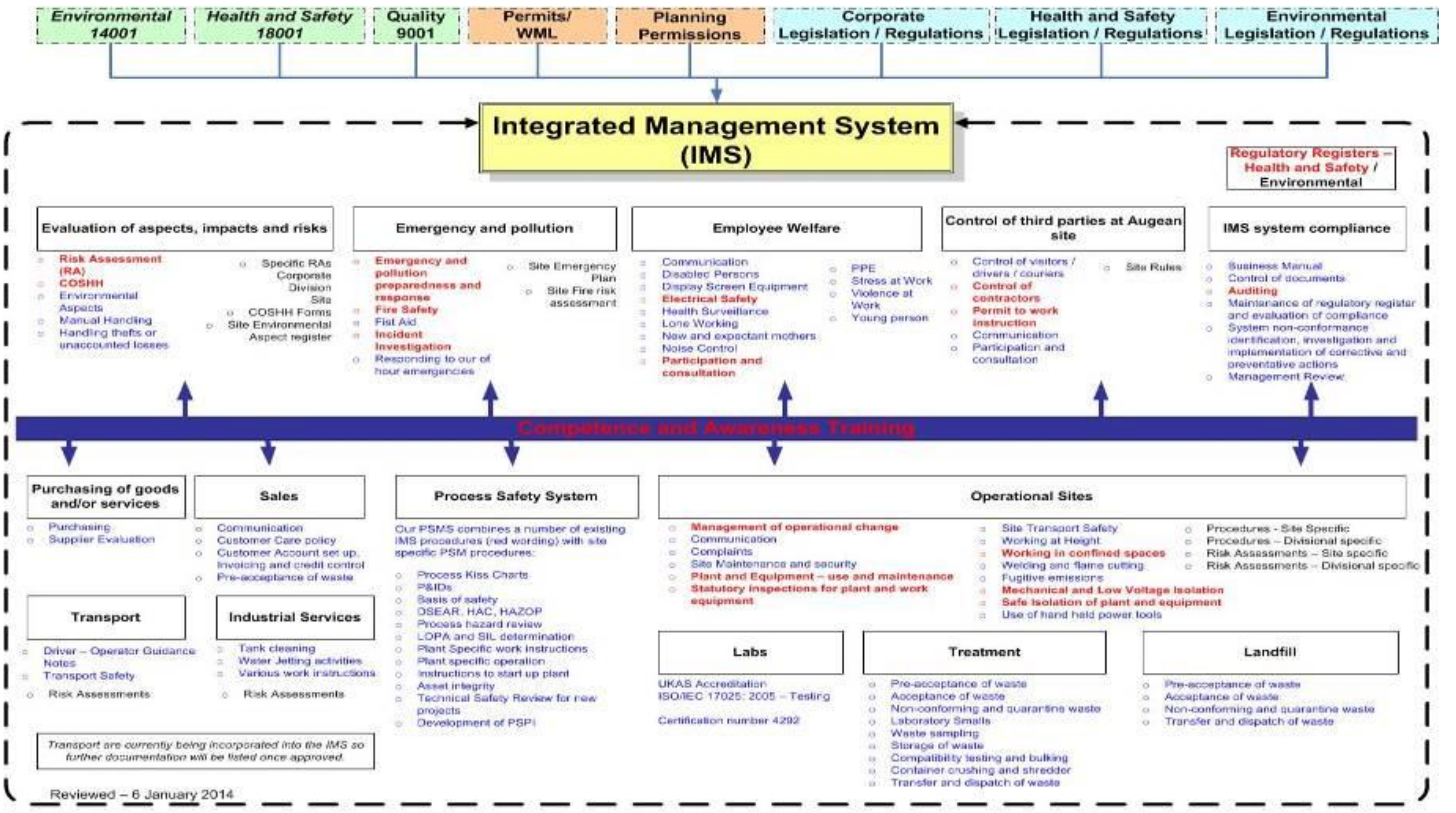
- Monitoring performance periodically at management meetings and reviews.
- Embracing our customers' goals and delivering to their expectations.
- Setting operational improvement and corporate objectives annually and monitoring performance with audits and inspections.
- Continually improving all aspects of our business to achieve a high level of regulatory compliance and customer satisfaction.
- Encouraging our people to own their work and communicating the importance of customer satisfaction.
- Ensuring our people are trained, competent and are aware that the delivery of our product/service to the required specification is the result of their effort.
- Identifying and solving problems to avoid compromising our service quality.
- Providing growth and development opportunities for our people.

Environmental

- Ensuring we understand and meet our environmental compliance obligations to prevent unacceptable air pollution, limit greenhouse gas emissions, minimise use of hazardous substances, make efficient use of energy and water and manage waste in accordance with the waste hierarchy to deliver best environmental outcomes.
- Ensuring procedures are in place to manage potential environmental risks arising from our activities. This underlines our commitment to protect the environment, prevent pollution and pursue sustainable development.
- Promoting sustainable transport alternatives to, from and between our sites including the use of electric vehicles (or other low or zero emission vehicles) or public transport where feasible or cycling where safe to do so.
- Ensuring our activities and building developments are sensitive to visual amenity and the local community.
- Ensuring site developments deliver improved biodiversity, where required.
- Providing environmental training for appropriate colleagues to raise environmental awareness of all colleagues.
- Providing efficient environmental solutions which draw on proven or innovative technology and best practice.

Colleagues with concerns about compliance with this policy are encouraged to report this directly, and if necessary, anonymously, to the Director of Corporate Stewardship who will investigate confidentially under our whistleblowing policy. Delivery of this policy is a business priority.

Richard Brooke
Interim Chief Executive Officer
September 2024


Environmental 14001
Health and Safety 18001
Quality 9001
Permits/ WML
Planning Permissions
Corporate Legislation / Regulations
Health and Safety Legislation / Regulations
Environmental Legislation / Regulations
Integrated Management System (IMS)
Regulatory Registers – Health and Safety / Environmental
Evaluation of aspects, impacts and risks
Risk Assessment (RA)
COSHH
Environmental Aspects
Manual Handling
Handling thefts or unaccounted losses
Specific RAs Corporate Division Site
COSHH Forms
Site Environmental Aspect register
Emergency and pollution
Emergency and pollution preparedness and response
Fire Safety
First Aid
Incident Investigation
Responding to our of hour emergencies
Site Emergency Plan
Site Fire risk assessment
Employee Welfare
Communication
Disabled Persons
Display Screen Equipment
Electrical Safety
Health Surveillance
Lone Working
New and expectant mothers
Noise Control
Participation and consultation
PPE
Stress at Work
Violence at Work
Young person
Control of third parties at Augean site
Control of visitors / drivers / couriers
Control of contractors
Permit to work instruction
Communication
Participation and consultation
Site Rules
IMS system compliance
Business Manual
Control of documents
Auditing
Maintenance of regulatory register and evaluation of compliance
System non-conformance identification, investigation and implementation of corrective and preventative actions
Management Review
Competence and Awareness Training
Purchasing of goods and/or services
Purchasing
Supplier Evaluation
Sales
Communication
Customer Care policy
Customer Account set up, Invoicing and credit control
Pre-acceptance of waste
Transport
Driver – Operator Guidance Notes
Transport Safety
Risk Assessments
Industrial Services
Tank cleaning
Water Jetting activities
Various work instructions
Risk Assessments
Transport are currently being incorporated into the IMS so further documentation will be listed once approved.
Process Safety System
Our PSMS combines a number of existing IMS procedures (red wording) with site specific PSM procedures:
Process Kiss Charts
P&IDs
Basis of safety
DSEAR, HAC, HAZOP
Process hazard review
LOPA and SIL determination
Plant Specific work instructions
Plant specific operation
Instructions to start up plant
Asset integrity
Technical Safety Review for new projects
Development of PSPI
Operational Sites
Management of operational change
Communication
Complaints
Site Maintenance and security
Plant and Equipment – use and maintenance
Statutory inspections for plant and work equipment
Site Transport Safety
Working at Height
Working in confined spaces
Welding and flame cutting
Fugitive emissions
Mechanical and Low Voltage Isolation
Safe Isolation of plant and equipment
Use of hand held power tools
Procedures - Site Specific
Procedures – Divisional specific
Risk Assessments – Site specific
Risk Assessments – Divisional specific
Labs
UKAS Accreditation
ISO/IEC 17025: 2005 – Testing
Certification number 4292
Treatment
Pre-acceptance of waste
Acceptance of waste
Non-conforming and quarantine waste
Laboratory Smalls
Waste sampling
Storage of waste
Compatibility testing and bulking
Container crushing and shredder
Transfer and dispatch of waste
Landfill
Pre-acceptance of waste
Acceptance of waste
Non-conforming and quarantine waste
Transfer and dispatch of waste
Reviewed – 6 January 2014

C.1. Surface soil samples

628. All soil samples were collected using a Soil Sampler Pro (a cross-sectional soil sampler) to a maximum depth of 10 centimetres at four locations. The samples were stored in labelled plastic tubs which were then securely sealed and boxed to be collected and delivered to UKHSA within the specified stability times.

Table 52 Analysis of radioactivity in soil samples from four locations on 04/06/2019

Component in soil	Units	Location PCSoil01	Location PCSoil02	Location PCSoil03	Location PCSoil04
Total alpha	Bq/g	0.1416	0.1215	0.0672	0.123
Total beta	Bq/g	0.2813	0.1741	0.0967	0.3008
Total Gamma	Bq/kg	399	371	228	776
Total Actinium-228	Bq/g	0.037	0.0364	0.0275	0.0586
Total Americium-241	Bq/g	<0.0005	<0.00071	<0.00059	<0.00084
Total Cobalt-60	Bq/g	<0.00065	<0.00056	<0.00052	<0.00091
Total Caesium-137	Bq/g	0.00191	0.00178	0.00267	0.0246
Total Potassium-40	Bq/g	0.178	0.165	0.0799	0.414
Total Lead-210	Bq/g	0.0469	0.0289	0.0243	0.0661
Total Lead-212	Bq/g	0.0344	0.0363	0.0275	0.0555
Total Lead-214	Bq/g	0.035	0.0192	0.0186	0.0387
Total Radium-224	Bq/g	<0.021	0.0106	0.0289	0.0233
Total Radium-226	Bq/g	0.0298	0.0463	<0.0105	0.0431
Total Thorium-234	Bq/g	0.033	0.0235	0.00245	0.0487
Total Uranium-235	Bq/g	0.00331	0.00287	0.00245	0.00267

C.2. Site perimeter dose rate

629. The site perimeter dose rate check is carried out by Augean's Environmental Monitoring Technician. In accordance with the Monitoring Action Plan for perimeter dose rate monitoring, the perimeter dose rate analysis was carried out using a fully calibrated AT1121 X Ray and Gamma Radiation Dosimeter. An average reading over a 10 minute period at a height of 1 m is recorded at each location. Weather conditions including barometric pressure, temperature, wind speed and direction and ground conditions are also recorded.

Table 53 Site perimeter total gamma dose rate (µSv h^{-1}) measurements at the site boundary location (02/07/2019)

Location ID	Gamma dose rate (µSv h^{-1})
Office	0.139
Office Car Park	0.152
PC22	0.129
PCDD07	0.194
PCDD05	0.120
PC16AB	0.140
PC10AB	0.128

Appendix D. Impact of Waste Disposal Using Illustrative Waste Streams

D.1. INTRODUCTION ... 222
D.2. ILLUSTRATIVE RADIOLOGICAL IMPACT DURING THE PERIOD OF AUTHORISATION ... 225
D.3. ILLUSTRATIVE RADIOLOGICAL IMPACT AFTER THE PERIOD OF AUTHORISATION ... 225
D.4. ILLUSTRATIVE RADIOLOGICAL IMPACT FOR INTRUSION SCENARIOS ... 226
D.5. DETAILED ILLUSTRATION OF THE SUM OF FRACTIONS APPROACH ... 226
D.5.1. ACTIVITY CONCENTRATION SUM OF FRACTIONS ... 227
D.5.2. SITE CAPACITY SUM OF FRACTIONS ... 228
D.6. ILLUSTRATION OF CHECKS ON THE IMPACT OF DISPOSALS ... 229

D.1. Introduction

630. Illustrative inventories have been used to demonstrate the impact of disposal of LLW at Port Clarence. These are disposal of an inventory based on current disposals to the ENRMF, disposal of waste using the specific activity of ENRMF waste and disposal of wastes based on the proportions of radionuclides in the national LLW inventory and in example LLW waste streams.

631. These calculations do not show the total impact of the whole facility, this will be dependent on the waste that is actually received for disposal. However, the calculations illustrate the dose that would arise from waste streams typical of those that might be disposed to Port Clarence. None of these inventories are assumed to contain particles, discrete items or large heterogeneously contaminated items.

632. The inventory that has already been disposed of at the ENRMF (up to December 2023), the proportion of each radionuclide in the waste disposed at the ENRMF and in the national low level waste inventory are presented in Table 54. Columns 3 and 4 of this Table provide an indication of the likely waste composition that will be disposed at Port Clarence. We note that there are some significant differences between the composition of waste disposed at the ENRMF and the national low level waste inventory. The composition of the national LLW inventory assigns 24.4% to any other radionuclides, omitted from this analysis.

Table 54 Activity disposed at the ENRMF and the composition of the national inventory of low level waste

Radionuclide	Activity disposed at ENRMF to December 2023 (MBq)	Composition of ENRMF disposals (percentage)	Composition of national LLW inventory (percentage)
H-3	$9.44\ 10^{4}$	14.79%	17.01%
C-14	$2.57\ 10^{4}$	4.03%	0.95%
Cl-36	$1.75\ 10^{3}$	0.27%	0.089%
Ca-41	0	0.0%	0.00016%
Mn-54	0	0.0%	0.052%
Fe-55	$1.88\ 10^{4}$	2.94%	2.22%
Co-60	$2.55\ 10^{4}$	3.99%	2.75%
Ni-59	0	0.0%	0.018%
Ni-63	$3.17\ 10^{4}$	4.96%	8.17%

Radionuclide	Activity disposed at ENRMF to December 2023 (MBq)	Composition of ENRMF disposals (percentage)	Composition of national LLW inventory (percentage)
Zn-65	0	0.0%	0.0017%
Se-79	0	0.0%	0.000000063%
Sr-90	$3.83\ 10^{4}$	5.99%	4.90%
Mo-93	0	0.0%	0.0013%
Zr-93	0	0.0%	0.0052%
Nb-93m	0	0.0%	0.0084%
Nb-94	$6.45\ 10^{1}$	0.010%	0.0023%
Tc-99	$2.98\ 10^{4}$	4.67%	0.022%
Ru-106	$3.09\ 10^{2}$	0.048%	0.0016%
Ag-108m	$1.01\ 10^{2}$	0.016%	0.075%
Ag-110m	0	0.0%	0.00069%
Cd-109	0	0.0%	0.000081%
Sb-125	$3.60\ 10^{3}$	0.56%	0.020%
Sn-119m	0	0.0%	0.0%
Sn-123	0	0.0%	0.0%
Sn-126	$2.19\ 10^{-2}$	0.0000034%	0.00000016%
Te-127m	0	0.0%	0.0%
I-129	$3.52\ 10^{2}$	0.055%	0.010%
Ba-133	$2.30\ 10^{2}$	0.036%	0.0049%
Cs-134	$1.57\ 10^{2}$	0.025%	0.018%
Cs-135	0	0.0%	0.00000025%
Cs-137	$9.08\ 10^{4}$	14.23%	18.16%
Ce-144	0	0.0%	0.0015%
Pm-147	$5.54\ 10^{2}$	0.087%	0.027%
Sm-147	0	0.0%	$2.4\ 10^{-16}$%
Sm-151	0	0.0%	0.052%
Eu-152	$4.54\ 10^{3}$	0.71%	0.015%
Eu-154	$1.72\ 10^{3}$	0.27%	0.028%
Eu-155	$1.75\ 10^{2}$	0.027%	0.0092%
Gd-153	0	0.0%	0.0%
Pb-210	$1.80\ 10^{4}$	2.83%	0.018%
Po-210	0	0.00%	0.029%
Ra-226	$6.24\ 10^{4}$	9.78%	0.22%
Ra-228	$2.16\ 10^{3}$	0.34%	0.00050%
Ac-227	$1.80\ 10^{1}$	0.0028%	0.000019%
Th-228	0	0.0%	0.0010%
Th-229	$2.96\ 10^{1}$	0.0046%	0.0000000066%
Th-230	$3.94\ 10^{2}$	0.062%	0.00039%
Th-232	$2.68\ 10^{4}$	4.20%	0.0010%
Pa-231	$1.85\ 10^{1}$	0.0029%	0.000089%
U-232	$1.39\ 10^{2}$	0.022%	0.00063%
U-233	$7.96\ 10^{1}$	0.012%	0.0041%
U-234	$3.10\ 10^{4}$	4.86%	2.65%
U-235	$2.09\ 10^{3}$	0.33%	0.092%
U-236	$6.26\ 10^{2}$	0.10%	0.040%
U-238	$4.28\ 10^{4}$	6.70%	0.87%
Np-237	$6.32\ 10^{2}$	0.10%	0.021%
Pu-238	$3.22\ 10^{3}$	0.50%	3.17%
Pu-239	$8.39\ 10^{3}$	1.31%	1.10%
Pu-240	$8.57\ 10^{3}$	1.34%	0.61%
Pu-241	$3.32\ 10^{4}$	5.20%	9.51%
Pu-242	$2.13\ 10^{1}$	0.0033%	0.00%
Pu-244	0	0.0%	0.0%

Radionuclide	Activity disposed at ENRMF to December 2023 (MBq)	Composition of ENRMF disposals (percentage)	Composition of national LLW inventory (percentage)
Am-241	2.78 10^4	4.35%	2.57%
Am-242m	0	0.0%	0.0014%
Am-243	0	0.0%	0.000020%
Cm-242	0	0.0%	0.0012%
Cm-243	6.83 10^2	0.11%	0.0037%
Cm-244	7.36 10^2	0.12%	0.022%
Cm-245	0	0.0%	0.0021%
Cm-246	0	0.0%	0.0000043%
Cm-248	0	0.0%	0.000092%

633. The first test is whether the activity concentration in these streams meets the activity concentration sum of fractions test. The activity concentration of each radionuclide in this example is obtained from the average activity concentration and the composition. The results of the test are shown in Table 55 .

Table 55 Activity concentration sum of fractions for illustrative inventories

Illustrative inventory	Specific activity (Bq/g)	Sum of fractions for activity concentration	Pass or fail?
Average of current ENRMF disposals	4.12 10^1	0.23	Pass
Average of national LLW inventory	8.82 10^2	3.14	Fail

634. Table 55 shows the activity concentration and composition of the ENRMF disposals would also be suitable for disposal at Port Clarence whereas the average composition of the national LLW inventory would not. In addition, it can be deduced from the sum of fractions results that wastes with the same composition as at ENRMF disposals would be acceptable at consignment activity concentrations of 179 Bq/g. Similarly, wastes with the same composition as the average LLW national inventory would be acceptable at consignment specific activity concentrations up to 281 Bq/g. This indicates that some LLW streams would be acceptable, whereas others would not. In both cases the overall limit of 2000 Bq g^{-1} for a consignment fingerprint is met so this is not the deciding factor.

635. The second test is to identify whether the site has sufficient radiological capacity for the acceptable waste stream, in this case the example uses the waste stream with the same specific activity as the ENRMF disposals. The ENRMF disposals specific activity concentration and compositions are used to calculate the activity (MBq) of each radionuclide for each 10 t consignment of waste and then these are compared with the radiological capacities for the individual radionuclides (MBq) to obtain the sum of fractions. The sum of fractions for 10 t can then be used to determine the quantity (t) of the illustrative waste stream that can be disposed of at the site and meet the dose criteria. The results indicate that disposal of the inventory in Table 56 would meet the dose criteria.

Table 56 Quantity of illustrative waste stream that could be disposed of at Port Clarence

Illustrative inventory	Specific activity (Bq/g)	Mass (t)	Inventory (MBq)	Sum of fraction
Extrapolated from specific activity of current ENRMF disposals	$4.12\ 10^{1}$	$4.91\ 10^{5}$	$4.56\ 10^{6}$	1.00

D.2. Illustrative radiological impact during the period of authorisation

636. In Table 57 the results of assessment calculations for the period of authorisation are applied to the illustrative inventories to indicate the potential radiological impact of waste disposal. The doses to members of the public and workers from both likely and unlikely events are considered. The doses from the NORM waste stream that has been disposed of at the site are shown in Table 66.

Table 57 Total doses arising during the period of authorisation based on illustrative inventories

Illustrative inventory	Inventory (MBq)	Dose (µSv y^{-1})				
		Off-site gas (Operations)	Leachate spillage – Farming family	Leachate treatment – on-site Facility worker	Recreational	Fire
ENRMF inventory	$6.40\ 10^{5}$	$1.86\ 10^{-1}$	$8.09\ 10^{-3}$	$6.72\ 10^{-3}$	$4.99\ 10^{-3}$	$2.92\ 10^{0}$
Extrapolated from specific activity of current ENRMF disposals	$4.56\ 10^{6}$	$1.33\ 10^{0}$	$5.77\ 10^{-2}$	$4.79\ 10^{-2}$	$3.56\ 10^{-2}$	$2.08\ 10^{1}$

D.3. Illustrative radiological impact after the period of authorisation

637. The results for the scenarios after the period of authorisation are given below.

Table 58 Total doses arising after the period of authorisation based on illustrative inventories

Illustrative inventory	Inventory (MBq)	Dose (µSv y^{-1})			Risk quotient
		Bathtubbing	Coastal erosion – beach user	Coastal erosion – fishing family	Erica - Burrowing animals
ENRMF inventory	6.40 10^{5}	1.34 10^{0}	9.13 10^{-1}	9.66 10^{-1}	2.17 10^{-2}
Extrapolated from specific activity of current ENRMF disposals	4.56 10^{6}	9.57 10^{0}	6.50 10^{0}	6.88 10^{0}	1.54 10^{-1}

D.4. Illustrative Radiological Impact for Intrusion Scenarios

508. The results for three intrusions scenarios are given below.

Table 59 Total doses arising from intrusion scenarios based on illustrative inventories

Illustrative inventory	Inventory (MBq)	Dose (mSv y^{-1})		
		Material recovery worker	Borehole operator	Smallholder
ENRMF inventory	6.40 10^{5}	1.67 10^{-3}	1.55 10^{-3}	8.10 10^{-3}
Extrapolated from specific activity of current ENRMF disposals	4.56 10^{6}	1.19 10^{-2}	1.10 10^{-2}	5.77 10^{-2}

D.5. Detailed Illustration of the sum of fractions approach

638. This section illustrates the sum of fractions approach in more detail using two nominal waste streams.

639. Waste stream A consists of 2457 m^{3} non-hazardous waste with a density of 1.4 t m^{-3}. The radiological composition is illustrated in Table 60.

Table 60 Radiological composition of waste stream A.

Radionuclide	Activity concentration (TBq m^{-3})	Specific activity (Bq g^{-1})	Total activity (MBq)
Ni-63	1.36 10^{-7}	9.71 10^{-2}	3.34 10^{2}
Sr-90	5.99 10^{-7}	4.28 10^{-1}	1.47 10^{3}
Cs-137	1.28 10^{-6}	9.14 10^{-1}	3.14 10^{3}
Pu-239	1.21 10^{-8}	8.64 10^{-3}	2.97 10^{1}
Pu-240	1.65 10^{-8}	1.18 10^{-2}	4.05 10^{1}

640. Waste stream B consists of 949 m^3 hazardous waste with a density of 4.6 t m^{-3}. The radiological composition is illustrated in Table 61.

Table 61 Radiological composition of waste stream B.

Radionuclide	Activity concentration (TBq m^{-3})	Specific activity (Bq g^{-1})	Total activity (MBq)
H-3	3.65 10^{-6}	7.93 10^{-1}	3.46 10^{3}
C-14	3.33 10^{-6}	7.24 10^{-1}	3.16 10^{3}
Cl-36	1.43 10^{-6}	3.11 10^{-1}	1.36 10^{3}
U-234	3.32 10^{-9}	7.22 10^{-4}	3.15 10^{0}
U-238	3.32 10^{-9}	7.22 10^{-4}	3.15 10^{0}

D.5.1. Activity concentration sum of fractions

641. First, we demonstrate that the waste streams comply with the limits set for specific activities. We assess both normal operations and loose tipping in the examples.

642. Table 62 illustrates the sum of fractions approach applied to specific activities in waste stream A. This table demonstrates that waste stream A would be suitable for normal operations and for loose tipping.

Table 62 Illustration of sum of fractions approach to assess the specific activity of waste stream A for normal operations and loose tipping.

Radionuclide	Specific activity (Bq g^{-1})	Normal operations		Loose tipping	
		Specific activity limit (Bq g^{-1})	Fraction	Specific activity limit (Bq g^{-1})	Fraction
Ni-63	9.71 10^{-2}	5000	1.94 10^{-5}	100	9.71 10^{-4}
Sr-90	4.28 10^{-1}	200	2.14 10^{-3}	100	4.28 10^{-3}
Cs-137	9.14 10^{-1}	200	4.57 10^{-3}	100	9.14 10^{-3}
Pu-239	8.64 10^{-3}	100	8.64 10^{-5}	5	1.73 10^{-3}
Pu-240	1.18 10^{-2}	200	5.89 10^{-5}	5	2.36 10^{-3}
Sum of fractions		6.88 10^{-3}		1.85 10^{-2}	

643. Table 63 illustrates the sum of fractions approach applied to specific activities in waste stream B. This table demonstrates that waste stream B would also be suitable for normal operations and for loose tipping.

Table 63 Illustration of sum of fractions approach to assess the specific activity of waste stream B for normal operations and loose tipping.

Radionuclide	Specific activity (Bq g^{-1})	Normal operations		Loose tipping	
		Specific activity limit (Bq g^{-1})	Fraction	Specific activity limit (Bq g^{-1})	Fraction
H-3	7.93 10^{-1}	5000	1.59 10^{-4}	100	7.93 10^{-3}
C-14	7.24 10^{-1}	5000	1.45 10^{-4}	100	7.24 10^{-3}
Cl-36	3.11 10^{-1}	5000	6.22 10^{-5}	100	3.11 10^{-3}
U-234	7.22 10^{-4}	200	3.61 10^{-6}	50	1.44 10^{-5}
U-238	7.22 10^{-4}	200	3.61 10^{-6}	100	7.22 10^{-6}
Sum of fractions		3.73 10^{-4}		1.83 10^{-2}	

D.5.2. Site capacity sum of fractions

644. Next, we look at the site capacity for the different assessment scenarios, as proposed for the Permit and listed below:

- Recreational (0y);
- Erosion - Dog walker (Combining 60 y and 20,000 y);
- Erosion to coast (60 y);
- WRP treatment worker;
- Seepage;
- Flooding;
- Leachate spillage;
- ERICA (Mammals - small-burrowing); and,
- Landfill fire (non-hazardous only).

645. In this example, we consider each scenario capacity for waste stream A. The test would be made for each of the scenarios listed in the Permit table. We assume that the non-hazardous landfill already contains the current ENRMF disposals and investigate whether waste stream A can now be accepted for disposal at the non-hazardous waste site.

646. Table 64 illustrates the sum of fractions approach applied to total activities in waste stream A (non-hazardous waste). For each scenario the additional fractions added to the sum of fractions from previous disposals is <1 so the radiological capacity for these scenarios is not exceeded. The contribution of waste stream A to the sum of fractions varies by several orders of magnitude for the different scenarios (from 2 10^{-8} to 2 10^{-5}), disposal to the hazardous waste landfill would have a lower impact because the landfill fire scenario is not used.

D.6. Illustration of checks on the impact of disposals

647. This section illustrates the check on the overall impact of the LLW and NORM disposed of at the site against the dose constraints and risk quotient. Table 65 illustrates the dose constraint calculations for waste stream A and LLW disposals. The peak dose during operations would occur from a landfill fire during operations (2.92 µSv y^{-1}), and after closure 0.11 µSv y^{-1} following seepage from the site once engineered barriers start to fail. All doses are substantially below the relevant dose constraint. The risk quotient for burrowing animals also remains low (2.27 10^{-2}).

648. The disposal inventory of exempt NORM waste is also considered (Table 66) and the dose implications of these disposals are shown for the different scenarios. The average activity of disposals was 1.01 Bq g^{-1} Th-232 and 0.47 Bq g^{-1} U-238 with a cumulative disposal of 733,508 t to end of September 2024.

649. The greatest dose from these scenarios from disposed NORM waste (Table 66) is 2.26 10^{1} µSv y^{-1}, which is well below the dose constraint of 300 µSv y^{-1}, during both the period of authorisation (leachate spillage and WRP leachate processing scenarios) and afterwards (erosion scenarios, recreational use of site, bathtubbing and inundation/flooding scenarios).

Table 64 Illustration of sum of fractions approach to assess the total activity of waste stream A (non-hazardous waste landfill)

Radionuclide	Activity in waste for disposal (MBq)	Recreational		WRP Leachate treatment		Fire in non-hazardous cell	
		Scenario radiological capacity (MBq)	Fraction	Scenario radiological capacity (MBq)	Fraction	Scenario radiological capacity (MBq)	Fraction
Ni-63	$3.34\ 10^{2}$	$3.86\ 10^{9}$	$8.65\ 10^{-8}$	$2.08\ 10^{14}$	$1.60\ 10^{-12}$	$8.11\ 10^{12}$	$4.12\ 10^{-11}$
Sr-90	$1.47\ 10^{3}$	$1.84\ 10^{25}$	$7.99\ 10^{-23}$	$6.58\ 10^{10}$	$2.24\ 10^{-8}$	$6.53\ 10^{10}$	$2.26\ 10^{-8}$
Cs-137	$3.14\ 10^{3}$	$2.63\ 10^{20}$	$1.20\ 10^{-17}$	$2.25\ 10^{11}$	$1.40\ 10^{-8}$	$2.70\ 10^{9}$	$1.17\ 10^{-6}$
Pu-239	$2.97\ 10^{1}$	$5.59\ 10^{31}$	$5.32\ 10^{-31}$	$6.22\ 10^{11}$	$4.78\ 10^{-11}$	$8.78\ 10^{7}$	$3.39\ 10^{-7}$
Pu-240	$4.05\ 10^{1}$	$4.02\ 10^{54}$	$1.01\ 10^{-53}$	$6.23\ 10^{11}$	$6.51\ 10^{-11}$	$8.78\ 10^{7}$	$4.62\ 10^{-7}$
Sum of fractions (SoF)		$8.65\ 10^{-8}$		$3.65\ 10^{-8}$		$1.99\ 10^{-6}$	
SoF current disposals*		$2.50\ 10^{-4}$		$6.83\ 10^{-6}$		$9.74\ 10^{-3}$	
SoF if waste stream A accepted		$2.50\ 10^{-4}$		$6.86\ 10^{-6}$		$9.75\ 10^{-3}$	
Pass or fail		Pass		Pass		Pass	
Radionuclide	Activity in waste for disposal (MBq)	Leachate spillage		Erosion - Dog walker		Erosion to coast (60y)	
		Scenario radiological capacity (MBq)	Fraction	Scenario radiological capacity (MBq)	Fraction	Scenario radiological capacity (MBq)	Fraction
Ni-63	$3.34\ 10^{2}$	$2.20\ 10^{13}$	$1.52\ 10^{-11}$	$4.32\ 10^{10}$	$7.73\ 10^{-9}$	$5.66\ 10^{11}$	$5.91\ 10^{-10}$
Sr-90	$1.47\ 10^{3}$	$1.85\ 10^{10}$	$7.94\ 10^{-8}$	$1.09\ 10^{9}$	$1.35\ 10^{-6}$	$9.40\ 10^{11}$	$1.57\ 10^{-9}$
Cs-137	$3.14\ 10^{3}$	$9.17\ 10^{10}$	$3.43\ 10^{-8}$	$7.70\ 10^{9}$	$4.08\ 10^{-7}$	$2.77\ 10^{10}$	$1.14\ 10^{-7}$
Pu-239	$2.97\ 10^{1}$	$1.55\ 10^{11}$	$1.92\ 10^{-10}$	$4.44\ 10^{7}$	$6.70\ 10^{-7}$	$2.21\ 10^{8}$	$1.34\ 10^{-7}$
Pu-240	$4.05\ 10^{1}$	$1.55\ 10^{11}$	$2.62\ 10^{-10}$	$4.46\ 10^{7}$	$9.10\ 10^{-7}$	$2.22\ 10^{8}$	$1.82\ 10^{-7}$
Sum of fractions (SoF)		$1.14\ 10^{-7}$		$3.34\ 10^{-6}$		$4.32\ 10^{-7}$	
SoF current disposals*		$2.71\ 10^{-5}$		$4.57\ 10^{-2}$		$4.83\ 10^{-2}$	
SoF if waste stream A accepted		$2.72\ 10^{-5}$		$4.57\ 10^{-2}$		$4.83\ 10^{-2}$	
Pass or fail		Pass		Pass		Pass	

Radionuclide		Seepage		Flooding (60y - 100ky)		ERICA results for Mammals	
	Activity in waste for disposal (MBq)	Scenario radiological capacity (MBq)	Fraction	Scenario radiological capacity (MBq)	Fraction	Scenario radiological capacity (MBq)	Fraction
Ni-63	$3.34\ 10^{2}$	$5.63\ 10^{13}$	$5.94\ 10^{-12}$	$4.39\ 10^{14}$	$7.61\ 10^{-13}$	$6.61\ 10^{11}$	$5.05\ 10^{-10}$
Sr-90	$1.47\ 10^{3}$	$7.77\ 10^{10}$	$1.89\ 10^{-8}$	$1.30\ 10^{11}$	$1.14\ 10^{-8}$	$9.61\ 10^{8}$	$1.53\ 10^{-6}$
Cs-137	$3.14\ 10^{3}$	$3.46\ 10^{13}$	$9.09\ 10^{-11}$	$5.88\ 10^{13}$	$5.35\ 10^{-11}$	$1.08\ 10^{9}$	$2.91\ 10^{-6}$
Pu-239	$2.97\ 10^{1}$	$3.89\ 10^{6}$	$7.63\ 10^{-6}$	$9.13\ 10^{9}$	$3.25\ 10^{-9}$	$5.11\ 10^{8}$	$5.82\ 10^{-8}$
Pu-240	$4.05\ 10^{1}$	$5.98\ 10^{6}$	$6.77\ 10^{-6}$	$9.18\ 10^{9}$	$4.42\ 10^{-9}$	$5.12\ 10^{8}$	$7.91\ 10^{-8}$
Sum of fractions (SoF)		$1.44\ 10^{-5}$		$1.91\ 10^{-8}$		$4.58\ 10^{-6}$	
SoF current disposals*		$8.83\ 10^{-2}$		$5.91\ 10^{-3}$		$5.42\ 10^{-3}$	
SoF if waste stream A accepted		$8.83\ 10^{-2}$		$5.91\ 10^{-3}$		$5.43\ 10^{-3}$	
Pass or fail		Pass		Pass		Pass	
* Assumed to be same as current inventory in ENRMF for the purposes of this example							

Table 65 Dose calculation for waste stream A and total LLW disposal (non-hazardous waste landfill)

Radionuclide	Activity in waste for disposal (MBq)	Recreational		WRP Leachate treatment		Fire in non-hazardous cell	
		Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)	Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)	Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)
Ni-63	$3.34\ 10^{2}$	$5.18\ 10^{-9}$	$1.73\ 10^{-6}$	$4.80\ 10^{-12}$	$1.60\ 10^{-9}$	$3.70\ 10^{-11}$	$1.24\ 10^{-8}$
Sr-90	$1.47\ 10^{3}$	$1.09\ 10^{-24}$	$1.60\ 10^{-21}$	$1.52\ 10^{-8}$	$2.24\ 10^{-5}$	$4.60\ 10^{-9}$	$6.77\ 10^{-6}$
Cs-137	$3.14\ 10^{3}$	$7.60\ 10^{-20}$	$2.39\ 10^{-16}$	$4.44\ 10^{-9}$	$1.40\ 10^{-5}$	$1.11\ 10^{-7}$	$3.50\ 10^{-4}$
Pu-239	$2.97\ 10^{1}$	$3.58\ 10^{-31}$	$1.06\ 10^{-29}$	$1.61\ 10^{-9}$	$4.78\ 10^{-8}$	$3.42\ 10^{-6}$	$1.02\ 10^{-4}$
Pu-240	$4.05\ 10^{1}$	$4.97\ 10^{-54}$	$2.02\ 10^{-52}$	$1.61\ 10^{-9}$	$6.51\ 10^{-8}$	$3.42\ 10^{-6}$	$1.38\ 10^{-4}$
Consignment dose ($\mu Sv\ y^{-1}$)		$1.73\ 10^{-6}$		$3.65\ 10^{-5}$		$5.97\ 10^{-4}$	
Dose from current disposals* ($\mu Sv\ y^{-}$		$4.99\ 10^{-3}$		$6.72\ 10^{-3}$		$2.92\ 10^{0}$	
Total dose ($\mu Sv\ y^{-1}$)		$4.99\ 10^{-3}$		$6.76\ 10^{-3}$		$2.92\ 10^{0}$	
Constraint ($\mu Sv\ y^{-1}$)		$2.00\ 10^{1}$		$1.00\ 10^{3}$		$3.00\ 10^{2}$	
Pass or fail		Pass		Pass		Pass	
Radionuclide	Activity in waste for disposal (MBq)	Leachate spillage		Erosion – Dog walker		Erosion to coast (60y)	
		Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)	Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)	Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)
Ni-63	$3.34\ 10^{2}$	$1.37\ 10^{-11}$	$4.56\ 10^{-9}$	$4.63\ 10^{-10}$	$1.55\ 10^{-7}$	$3.53\ 10^{-11}$	$1.18\ 10^{-8}$
Sr-90	$1.47\ 10^{3}$	$1.62\ 10^{-8}$	$2.38\ 10^{-5}$	$1.83\ 10^{-8}$	$2.70\ 10^{-5}$	$2.13\ 10^{-11}$	$3.13\ 10^{-8}$
Cs-137	$3.14\ 10^{3}$	$3.27\ 10^{-9}$	$1.03\ 10^{-5}$	$2.60\ 10^{-9}$	$8.17\ 10^{-6}$	$7.23\ 10^{-10}$	$2.27\ 10^{-6}$
Pu-239	$2.97\ 10^{1}$	$1.94\ 10^{-9}$	$5.77\ 10^{-8}$	$4.51\ 10^{-7}$	$1.34\ 10^{-5}$	$9.04\ 10^{-8}$	$2.69\ 10^{-6}$
Pu-240	$4.05\ 10^{1}$	$1.94\ 10^{-9}$	$7.87\ 10^{-8}$	$4.49\ 10^{-7}$	$1.82\ 10^{-5}$	$8.99\ 10^{-8}$	$3.64\ 10^{-6}$
Consignment dose ($\mu Sv\ y^{-1}$)		$3.43\ 10^{-5}$		$6.69\ 10^{-5}$		$8.65\ 10^{-6}$	
Dose from current disposals* ($\mu Sv\ y^{-}$		$8.09\ 10^{-3}$		$9.13\ 10^{-1}$		$9.66\ 10^{-1}$	
Total dose ($\mu Sv\ y^{-1}$)		$8.13\ 10^{-3}$		$9.13\ 10^{-1}$		$9.66\ 10^{-1}$	
Constraint ($\mu Sv\ y^{-1}$)		300		20		20	
Pass or fail		Pass		Pass		Pass	

Radionuclide		Seepage		Flooding (60y - 100ky)		ERICA results for Mammals	
	Activity in waste for disposal (MBq)	Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)	Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)	Risk quotient (@10 $\mu Gy\ h^{-1}\ MBq^{-1}$)	Risk Quotient
Ni-63	$3.34\ 10^{2}$	$3.55\ 10^{-13}$	$1.19\ 10^{-10}$	$4.55\ 10^{-14}$	$1.52\ 10^{-11}$	$6.05\ 10^{-12}$	$2.02\ 10^{-9}$
Sr-90	$1.47\ 10^{3}$	$2.57\ 10^{-10}$	$3.79\ 10^{-7}$	$1.54\ 10^{-10}$	$2.27\ 10^{-7}$	$4.16\ 10^{-9}$	$6.13\ 10^{-6}$
Cs-137	$3.14\ 10^{3}$	$5.78\ 10^{-13}$	$1.82\ 10^{-9}$	$3.40\ 10^{-13}$	$1.07\ 10^{-9}$	$3.70\ 10^{-9}$	$1.16\ 10^{-5}$
Pu-239	$2.97\ 10^{1}$	$5.13\ 10^{-6}$	$1.53\ 10^{-4}$	$2.19\ 10^{-9}$	$6.51\ 10^{-8}$	$7.83\ 10^{-9}$	$2.33\ 10^{-7}$
Pu-240	$4.05\ 10^{1}$	$3.34\ 10^{-6}$	$1.35\ 10^{-4}$	$2.18\ 10^{-9}$	$8.84\ 10^{-8}$	$7.81\ 10^{-9}$	$3.17\ 10^{-7}$
Consignment dose ($\mu Sv\ y^{-1}$)		$2.89\ 10^{-4}$		$3.82\ 10^{-7}$		$1.83\ 10^{-5}$	
Dose from current disposals* ($\mu Sv\ y^{-}$		$1.34\ 10^{0}$		$1.15\ 10^{-1}$		$2.17\ 10^{-2}$	
Total dose ($\mu Sv\ y^{-1}$)		$1.34\ 10^{0}$		$1.15\ 10^{-1}$		$2.17\ 10^{-2}$	
Constraint ($\mu Sv\ y^{-1}$ or risk)		20		20		4	
Pass or fail		Pass		Pass		Pass	
* Assumed to be same as current inventory in ENRMF for the purposes of this example							

Table 66 Dose calculation for exempt NORM disposals (non-hazardous waste landfill) to September 2024

Radionuclide	Activity in waste for disposal (MBq)	Recreational		WRP Leachate treatment		Fire in non-hazardous cell	
		Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)	Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)	Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)
Th-232	$7.43\ 10^{5}$	$4.91\ 10^{-15}$	$3.65\ 10^{-9}$	$1.41\ 10^{-8}$	$1.05\ 10^{-2}$	$4.83\ 10^{-6}$	$3.59\ 10^{0}$
U-238	$3.48\ 10^{5}$	$8.03\ 10^{-20}$	$2.80\ 10^{-14}$	$4.61\ 10^{-9}$	$1.60\ 10^{-3}$	$2.28\ 10^{-7}$	$7.94\ 10^{-2}$
U-234	$3.48\ 10^{5}$	$5.19\ 10^{-45}$	$1.81\ 10^{-39}$	$5.09\ 10^{-10}$	$1.77\ 10^{-4}$	$2.68\ 10^{-7}$	$9.32\ 10^{-2}$
Th-230	$3.48\ 10^{5}$	$4.90\ 10^{-38}$	$1.71\ 10^{-32}$	$5.23\ 10^{-10}$	$1.82\ 10^{-4}$	$2.85\ 10^{-6}$	$9.92\ 10^{-1}$
Ra-226	$3.48\ 10^{5}$	$3.48\ 10^{-16}$	$1.21\ 10^{-10}$	$1.95\ 10^{-8}$	$6.79\ 10^{-3}$	$5.56\ 10^{-7}$	$1.94\ 10^{-1}$
Dose from current disposals ($\mu Sv\ y^{-1}$)		$3.77\ 10^{-9}$		$1.92\ 10^{-2}$		$4.95\ 10^{0}$	
Constraint ($\mu Sv\ y^{-1}$)		300		1000		1000	
Pass or fail		Pass		Pass		Pass	
Radionuclide	Activity in waste for disposal (MBq)	Leachate spillage		Erosion - Dog walker		Erosion to coast (60y)	
		Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)	Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)	Dose rate ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose ($\mu Sv\ y^{-1}$)
Th-232	$7.43\ 10^{5}$	$3.46\ 10^{-8}$	$2.57\ 10^{-2}$	$6.25\ 10^{-6}$	$4.65\ 10^{0}$	$7.15\ 10^{-7}$	$5.31\ 10^{-1}$
U-238	$3.48\ 10^{5}$	$1.43\ 10^{-9}$	$5.00\ 10^{-4}$	$1.40\ 10^{-7}$	$4.89\ 10^{-2}$	$5.43\ 10^{-10}$	$1.89\ 10^{-4}$
U-234	$3.48\ 10^{5}$	$1.39\ 10^{-9}$	$4.85\ 10^{-4}$	$1.89\ 10^{-7}$	$6.57\ 10^{-2}$	$6.29\ 10^{-10}$	$2.19\ 10^{-4}$
Th-230	$3.48\ 10^{5}$	$2.70\ 10^{-9}$	$9.41\ 10^{-4}$	$9.86\ 10^{-6}$	$3.43\ 10^{0}$	$4.08\ 10^{-7}$	$1.42\ 10^{-1}$
Ra-226	$3.48\ 10^{5}$	$5.27\ 10^{-8}$	$1.83\ 10^{-2}$	$1.09\ 10^{-5}$	$3.79\ 10^{0}$	$1.44\ 10^{-5}$	$5.01\ 10^{0}$
Dose from current disposals ($\mu Sv\ y^{-1}$)		$4.60\ 10^{-2}$		$1.20\ 10^{1}$		$5.68\ 10^{0}$	
Constraint ($\mu Sv\ y^{-1}$)		1000		300		300	
Pass or fail		Pass		Pass		Pass	

Radionuclide		Seepage		Flooding (60y - 100ky)		ERICA results for Mammals	
	Activity in waste for disposal (MBq)	Dose rate (µSv y^{-1} MBq^{-1})	Dose (µSv y^{-1})	Dose rate (µSv y^{-1} MBq^{-1})	Dose (µSv y^{-1})	Risk quotient (@10 µGy h^{-1} MBq^{-1})	Risk Quotient
Th-232	$7.43\ 10^{5}$	$9.24\ 10^{-6}$	$6.87\ 10^{0}$	$1.18\ 10^{-9}$	$8.80\ 10^{-4}$	$7.90\ 10^{-8}$	$5.87\ 10^{-2}$
U-238	$3.48\ 10^{5}$	$4.80\ 10^{-6}$	$1.67\ 10^{0}$	$5.58\ 10^{-9}$	$1.95\ 10^{-3}$	$1.54\ 10^{-9}$	$5.35\ 10^{-4}$
U-234	$3.48\ 10^{5}$	$1.29\ 10^{-5}$	$4.50\ 10^{0}$	$7.44\ 10^{-9}$	$2.59\ 10^{-3}$	$1.50\ 10^{-9}$	$5.24\ 10^{-4}$
Th-230	$3.48\ 10^{5}$	$5.40\ 10^{-6}$	$1.88\ 10^{0}$	$1.05\ 10^{-9}$	$3.66\ 10^{-4}$	$7.80\ 10^{-9}$	$2.72\ 10^{-3}$
Ra-226	$3.48\ 10^{5}$	$7.73\ 10^{-8}$	$2.69\ 10^{-2}$	$3.64\ 10^{-10}$	$1.27\ 10^{-4}$	$2.90\ 10^{-7}$	$1.01\ 10^{-1}$
Dose from current disposals (µSv y^{-1})		$1.49\ 10^{1}$		$5.91\ 10^{-3}$		$1.64\ 10^{-1}$	
Constraint (µSv y^{-1} or risk)		300		300		4	
Pass or fail		Pass		Pass		Pass	

Appendix E. Environmental Safety Case – Technical Basis {R3}

E.1. FEATURES, EVENTS AND PROCESSES 240
E.1.1. PERIOD OF AUTHORISATION FOR THE PORT CLARENCE SITE 241
E.1.2. LANDFILL DIMENSIONS 242
E.1.3. BARRIER ENGINEERING 243
E.1.3.1. ENGINEERED CAP 243
E.1.3.2. BASAL LINER AND CLAY BARRIER 243
E.1.4. LANDFILL DRAINAGE 244
E.1.5. NON-RADIOLOGICAL ASPECTS OF WASTE 244
E.1.6. UNSATURATED AND SATURATED ZONES 245
E.1.7. WATER ABSTRACTION POINTS 245
E.2. IDENTIFYING SCENARIOS AND EXPOSURE GROUPS 245
E.3. RADIOLOGICAL IMPACTS DURING THE PERIOD OF AUTHORISATION {R5} 248
E.3.1. SCENARIOS NOT EXPLICITLY ASSESSED IN THE ESC 249
Exposure from groundwater abstraction 249
Exposure following slope failure 249
Exposure from perched leachate 249
Exposure from cell excavation 250
Exposure from barrier failure 250
Exposure from aircraft crash 250
E.3.2. PRESENTATION OF RESULTS OF DOSE ASSESSMENTS 250
E.3.3. DIRECT EXPOSURE FROM WASTE HANDLING AND EMPLACEMENT 251
E.3.3.1. WASTE HANDLING AND EMPLACEMENT 251
Workers at landfill site 251
E.3.4. EXPOSURE FROM LOOSE TIPPING OF WASTE 256
E.3.4.1. DOSES FROM DUST RELEASED BY LOOSE TIPPING 257
E.3.5. EXPOSURE TO GAS DURING SITE OPERATIONS 260
E.3.5.1. ESTIMATING ACTIVITY CONCENTRATIONS OF GAS RELEASE FROM DISPOSED WASTE 260
Gas generation – H-3 and C-14 261
Gas generation – Radon 263
E.3.5.2. ASSESSMENT CALCULATION FOR GAS RELEASES 264
E.3.5.3. DOSES FROM GAS RELEASES DURING OPERATIONS 265
E.3.5.4. EXPOSURE TO GASES COLLECTED FROM CAPPED CELLS 265
E.3.6. EXPOSURES FROM NON-HAZARDOUS WASTE LANDFILL FIRE 267
E.3.6.1. ASSESSMENT CALCULATION FOR RELEASES TO AIR FROM A FIRE 268
E.3.6.2. DOSES FROM A FIRE IN THE NON-HAZARDOUS WASTE LANDFILL 269
E.3.7. EXPOSURES FROM LEACHATE PROCESSING 271
E.3.7.1. ESTIMATING ACTIVITY CONCENTRATIONS IN LEACHATE 272
E.3.7.2. ASSESSMENT CALCULATIONS FOR OFF-SITE LEACHATE TREATMENT 274
Treatment Facility Worker 275
Farming family (soil treated with sludge) 278
Anglers (discharge from treatment plant) 292
Reed bed facility worker 299
E.3.7.3. DOSES FROM LEACHATE TREATMENT 300
Dose per MBq Deposited at Port Clarence – Leachate Treatment 300
Dose from maximum inventory – Leachate Treatment 305
Dose from Processing Leachate at the WRP 307
E.3.8. DOSE RESULTING FROM EXPOSURE TO WASTE FROM A DROPPED CONTAINER 309
Potentially exposed group 309
E.3.8.1. SCENARIO ASSUMPTIONS FOR ESTIMATING DOSES FOLLOWING A DROPPED LOAD 310
E.3.8.2. ASSESSMENT CALCULATION INVOLVING A DROPPED LOAD 310
E.3.8.3. DOSE FROM A DROPPED LOAD 311
E.3.8.4. DOSE FROM SPILLAGE FROM A TIPPER 317
E.3.9. WOUND EXPOSURE 319
E.3.10. EXPOSURE FROM LEACHATE SPILLAGE 322
Potentially exposed group 323

E.3.10.1. ESTIMATING ACTIVITY CONCENTRATIONS AFTER A LEACHATE SPILLAGE 323
E.3.10.2. ASSESSMENT CALCULATIONS FOR A FARMING FAMILY AFTER A LEACHATE SPILLAGE . 324
Irrigation and Drinking Water 324
Fish Contamination 325
E.3.10.3. DOSES FROM LEACHATE SPILLAGE 325
E.4. RADIOLOGICAL IMPACTS AFTER THE PERIOD OF AUTHORISATION {R6} 327
Enhanced rainfall due to climate change 330
Seismic Events 331
Transport Accidents 331
E.4.1. CRITICALITY EVENT 332
E.4.2. PRESENTATION OF RESULTS OF DOSE ASSESSMENTS 333
E.4.3. EXPOSURE OF THE PUBLIC ON THE UNDISTURBED SITE 333
Potentially exposed group 334
E.4.3.1. ASSESSMENT CALCULATIONS FOR RECREATIONAL SITE USE 334
Gas generation 334
External Irradiation 335
E.4.3.2. DOSE TO RECREATIONAL USER FROM EXPOSURE TO GAS RELEASE AND EXTERNAL RADIATION 335
E.4.4. GROUNDWATER PATHWAYS 339
E.4.4.1. EFFECT OF CLIMATE CHANGE ON GROUNDWATER LEVEL 342
E.4.4.2. WASTE CELLS 343
Activity in the waste inventories 343
Water flux 344
Leachate head and level 350
Materials 351
E.4.4.3. CLAY BARRIER 353
E.4.4.4. UNSATURATED ZONE 355
E.4.4.5. SATURATED ZONE 356
E.4.4.6. BATHTUBBING 358
E.4.4.7. AQUIFER 361
Aquifer Zone 364
Overflow Aquifer Zone 365
Aquifer Transport Zone 366
Abstraction Zone 367
E.4.4.8. ASSESSMENT CALCULATIONS FOR A HYPOTHETICAL ABSTRACTION POINT 368
Exposed group 369
Use of Groundwater as Drinking Water 370
Use of Groundwater for Irrigation of Farmland 371
Element and Radionuclide Specific Parameters 376
E.4.4.9. BATHTUBBING CAUSING CONTAMINATION OF FARMLAND 376
Element and Radionuclide Specific Parameters 377
E.4.4.10. GROUNDWATER DOSES AFTER THE PERIOD OF AUTHORISATION 378
E.4.5. RELEASE OF CONTAMINATED WATER TO THE ESTUARY 389
E.4.6. INUNDATION FROM THE SEA 394
E.4.7. EXPOSURE OF COASTAL WALKER FOLLOWING SITE EROSION 401
Potentially exposed group 402
E.4.7.1. ASSESSMENT CALCULATIONS FOR COASTAL WALKER 402
E.4.7.2. DOSE TO BEACH USER FROM EXPOSURE TO EXTERNAL RADIATION AND INGESTION/INHALATION OF SOIL 403
E.4.8. EXPOSURE FOLLOWING SITE EROSION AND RELEASE OF LEACHATE INTO SEA 405
Potentially exposed group 406
E.4.8.1. ASSESSMENT FOR COASTAL EROSION DOSE 406
E.4.8.2. DOSE TO FISHING FAMILY FOLLOWING EROSION OF THE SITE AND RELEASE OF LEACHATE TO SEA 407
E.5. HUMAN INTRUSION SCENARIOS {R7} 409
E.5.1. PRESENTATION OF RESULTS OF DOSE ASSESSMENTS 414
E.5.2. BOREHOLE DRILLING – DRILL OPERATIVE 414
E.5.2.1. ESTIMATING ACTIVITY CONCENTRATION IN WASTE FOR EXPOSURE CALCULATIONS 414
E.5.2.2. ASSESSMENT CALCULATIONS FOR DRILL OPERATIVE 416
External irradiation, inhalation and ingestion 416
Hands and face 417

E.5.2.3. DOSE TO BOREHOLE DRILL OPERATIVE ON-SITE 60 YEARS AFTER CLOSURE 419
E.5.3. TRIAL PIT EXCAVATION 421
E.5.3.1. ASSESSMENT CALCULATIONS FOR TRIAL PIT EXCAVATOR 421
E.5.3.2. DOSE TO TRIAL PIT EXCAVATOR ON-SITE 60 YEARS AFTER CLOSURE 421
E.5.4. INFORMAL SCAVENGER 423
E.5.4.1. ASSESSMENT CALCULATIONS FOR INFORMAL SCAVENGER 424
E.5.4.2. DOSE TO INFORMAL SCAVENGER ON-SITE 60 YEARS AFTER CLOSURE 425
E.5.5. MATERIAL RECOVERY 426
E.5.5.1. ASSESSMENT CALCULATIONS FOR MATERIAL RECOVERY WORKER 426
E.5.5.2. DOSE TO MATERIAL RECOVERY WORKER 60 YEARS AFTER SITE CLOSURE 429
E.5.6. EXCAVATION FOR ROAD 431
E.5.6.1. ASSESSMENT CALCULATIONS FOR ROAD EXCAVATOR 431
E.5.6.2. DOSE TO EXCAVATOR FOR ROAD ON-SITE 60 YEARS AFTER CLOSURE 432
E.5.7. SITE RESIDENT – NO CAP DAMAGE 434
E.5.7.1. ASSESSMENT CALCULATIONS FOR SITE RESIDENTS (NO CAP DAMAGE) 434
Gas generation – H-3 and C-14 435
Gas generation – Radon 436
External irradiation 437
E.5.7.2. DOSE TO SITE RESIDENT – NO CAP DAMAGE 438
E.5.8. EXCAVATION FOR HOUSING – RESIDENTIAL OCCUPANT 445
E.5.8.1. ESTIMATING ACTIVITY CONCENTRATION IN WASTE FOR EXPOSURE CALCULATIONS 445
Dilution factors 445
Activity concentration in soil 447
E.5.8.2. ASSESSMENT CALCULATIONS FOR RESIDENTIAL OCCUPANT 447
Ingestion of crops 447
External irradiation 449
Ingestion of contaminated soil 449
Inhalation of contaminated soil 450
Inhalation of gases 450
E.5.8.3. DOSE TO RESIDENTIAL OCCUPANT ON-SITE 60 YEARS AFTER CLOSURE 450
E.5.9. EXCAVATION FOR HOUSING – RADON EXPOSURE FROM A HOUSE ON SPOIL 454
E.5.9.1. ASSESSMENT CALCULATION FOR RADON EXPOSURE 454
E.5.9.2. DOSE FROM RADON WHEN BUILDING ON A WASTE/SPOIL MIX 455
E.5.10. EXCAVATION FOR A SMALLHOLDING 456
E.5.10.1. ASSESSMENT CALCULATIONS FOR THE SMALLHOLDER 456
E.5.10.2. ASSESSMENT CALCULATION FOR RADON EXPOSURE 459
E.5.10.3. DOSE TO SMALLHOLDER ON-SITE 60 YEARS AFTER SITE CLOSURE 459
E.6. HETEROGENEITY OF DISPOSED WASTE 464
E.6.1. LARGE CONTAMINATED ITEMS 465
Scenario selection 466
E.6.1.1. WASTE CHARACTERISTICS 467
E.6.1.2. ASSESSMENT CALCULATION FOR LARGE CONTAMINATED ITEMS 469
Site occupant 469
Site investigator (driller) 470
E.6.1.3. DOSE FROM LARGE CONTAMINATED WASTE ITEMS 471
Concrete demolition slabs - dose to site occupant 471
Concrete demolition slabs - dose to Site Investigator 472
Activated concrete shielding blocks - dose to Site Occupant 473
Activated concrete shielding blocks - dose to Site Investigator 474
Building rubble 1 - dose to Site Occupant 475
Building rubble 1 - dose to Site Investigator 476
Building rubble 2 - dose to Site Occupant 476
Building rubble 2 - dose to Site Investigator 477
Reinforced concrete - dose to Site Occupant 477
Reinforced concrete - dose to Site Investigator 478
Hypothetical concrete block - dose to Site Occupant 479
Hypothetical concrete block - dose to Site Investigator 479
E.6.1.4. DISCUSSION 479
E.6.2. EXCAVATION OF DISCRETE ITEMS 480
E.6.2.1. POTENTIALLY EXPOSED GROUP 481
E.6.2.2. ESTIMATING DOSES TO A LOCAL ESTUARY BANK USER 482

E.6.2.3. Assessment calculation for discrete items ... 483
E.6.2.4. Doses from discrete items ... 486
E.6.2.5. Radionuclide groups and Port Clarence Discrete Item Limits ... 491
E.6.2.6. Waste Acceptance using the Port Clarence Discrete Item Limits ... 503
E.6.3. Excavation of particles ... 504
E.6.3.1. Assessment approach ... 504
E.6.3.2. Methodology ... 505
Ingestion ... 506
External exposure (whole body) ... 507
External exposure (skin) ... 508
E.6.3.3. Results for selected radionuclides ... 508
E.6.3.4. Waste acceptance ... 509
E.6.4. Exposure to particles following site erosion ... 510
E.6.5. Radionuclide activity concentrations ... 512
E.7. Environmental radioactivity {R9} ... 519
E.7.1. Exposure to wildlife from all sources ... 519
E.7.2. The ERICA assessment tool ... 520
E.7.3. Screening levels ... 521
E.7.4. ERICA assessment for a Marine Ecosystem ... 522
E.7.5. ERICA assessment for a Freshwater Ecosystem ... 528
E.7.6. ERICA assessment for a Terrestrial Ecosystem ... 530
E.7.7. Tier 2 assessment for Burrowing Animals ... 533
E.8. Management of uncertainty ... 536
E.8.1. Parameter sensitivity ... 536
E.8.1.1. Intrusion: Smallholder ... 536
E.8.1.2. Groundwater ... 538
E.8.1.3. Erosion scenarios ... 538
Erosion: dog walker ... 538
Impact of including erosion scenarios on radiological capacity ... 540
Impact of increasing erosion rate ... 541
E.8.1.4. Leachate spillage ... 542
E.8.1.5. Leachate processing at the WRP ... 544
E.8.1.6. Recreational use (Gas and external) ... 545
E.8.1.7. Small burrowing mammals ... 545
E.8.1.8. Fire in non-hazardous waste cell ... 546
E.8.1.9. Trial pit excavator ... 546
E.9. Tables of universal model parameters ... 548
E.9.1. Radionuclide half-lives and decay constants ... 548
E.9.2. Sorption Distribution coefficients ... 550
E.9.3. Dose Coefficients ... 552
E.9.4. Crop and animal transfer parameters ... 563

> "The environmental safety case should include quantitative environmental safety assessments for both the period of authorisation and afterwards. These assessments will need to extend into the future until the radiological risks have peaked or until the uncertainties have become so great that quantitative assessments cease to be meaningful. They should show how radionuclides might be expected to move from the wastes through the immediate physical and chemical environment of the disposal facility and through the surrounding geological formations into and through the environment. After the period of authorisation and while any significant hazard remains, the environmental safety case should explore the consequences not only of the expected evolution of the disposal system, but also of less likely evolutions and events." NS-GRA (UK Environment Agencies, 2009), para 7.2.8

650. This appendix considers the radiological aspects of an Environmental Safety Case (ESC) that supports an application for an Environment Agency Permit, for receipt and disposal of low-level radioactive waste (LLW) at the Port Clarence site, Off Huntsman Drive, Port Clarence, Middlesbrough, Cleveland, TS2 1UE.

E.1. Features, events and processes

651. Analysis of relevant Features, Events and Processes (FEPs) is used in the field of radioactive waste disposal to define relevant assessment scenarios for safety assessment studies. The term scenario is applied here as defined in the glossary, i.e. a postulated or assumed set of conditions and/or events, The set of scenarios selected for the ESC is intended to cover the range of possible situations at Port Clarence – it is not meant to infer a set of possible future conditions as used elsewhere (LLWR Ltd, 2011a). For a radioactive waste disposal facility, features would include the characteristics of the system, such as the waste, groundwater and humans; events would include things that may or will occur at some time in the future, for instance intrusion into a waste cell; and processes are mechanisms which have an impact on the features described, such as erosion or groundwater flow.

652. An initial set of scenarios was based on consideration of FEPs that could lead to exposure of people from the IAEA's Improvement of Safety Assessment Methodologies for Near-Surface Disposal Facilities (ISAM) project (IAEA, 2004). This and recent Eden-NE experience with the LLWR safety case, the East Northants Resource Management Facility (ENRMF) ESC and involvement with work on Environment Agency landfill assessment methodologies has been used to supplement the initial set of scenarios.

653. Important features of the Port Clarence Site are described in the rest of this section followed by a summary of the scenarios in Section E.2. The radiological assessments are presented in three sections dealing with the period of authorisation (Section E.3), site evolution after the period of authorisation (Section E.4) and intrusion events (Section E.5). The heterogeneity of waste disposals is considered in Section E.6 presenting an assessment of large items, discrete items and particles. Biota exposure is considered in Section E.7. The scenarios that are considered in the ESC are based on identified events and the assessment models consider the appropriate processes.

654. The mathematical models used for the ESC are based mainly on approaches developed for other recent work:

- an approach for assessing special precaution burials sponsored by the Environment Agencies (SNIFFER, 2006);

- the initial radiological assessment tool (Environment Agency, 2022a); and,
- models developed for the LLWR safety case (Hicks & Baldwin, 2011).

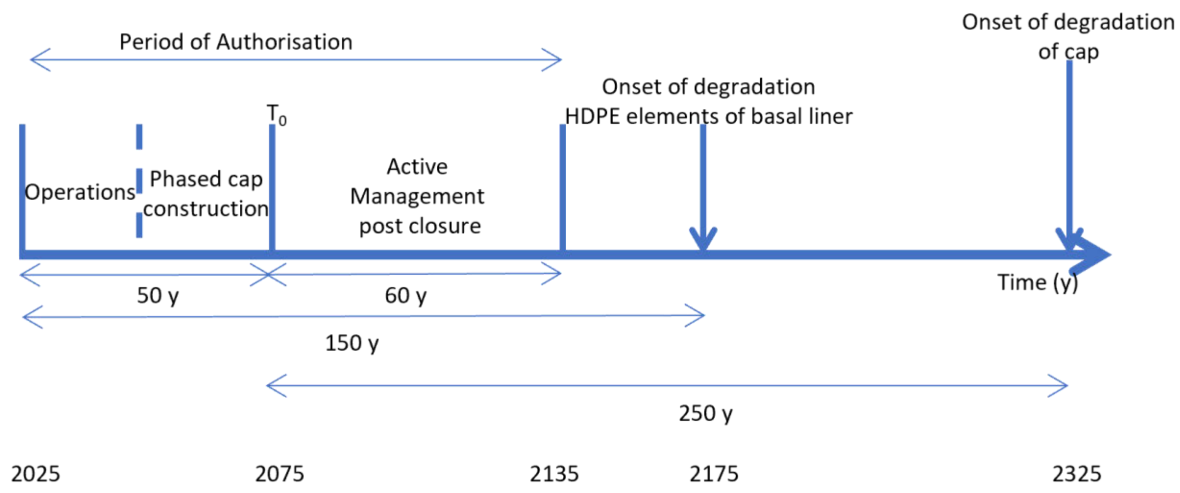
655. The impact of leaching from the landfill to groundwater is assessed using a model implemented in GoldSim (GoldSim Technology Group, 2021a). The models are described in Section E.4.4.

E.1.1. Period of authorisation for the Port Clarence site

656. Figure 16 presents the timeline for the Port Clarence site. This timeline is based on dates agreed with the Environment Agency. The figure identifies the Period of Authorisation (POA, the period during which the facility holds a permit), the period of operation, the timing of cap construction and the period of active management following cap construction.

657. The starting point of the calculations presented in this report is indicated as T_0, the time when the site has been filled and the cap constructed. This is the time of closure of the site, also known as the end of the 'operational period'. Decay prior to T_0 has been disregarded as a cautious assumption. It is assumed that for the Port Clarence landfills the future operational period would be 50 years for the purpose of the ESC – noting that planning conditions do not stipulate an end date for use of the site.

Figure 16 Timeline for the Port Clarence site



658. Figure 16 also illustrates assumptions regarding the onset of degradation of the HDPE element of the basal liner based on the HRA (MJCA, 2019b). Note that the engineered basal clay layer will not degrade and it is cautiously assumed that the cap will degrade although the current plan is for this to use a geosynthetic clay layer.

659. During the "operational period" assumed to last until 1/1/2075 (Operations and Phased cap construction), waste would be disposed to the site and both leachate and landfill gases would be managed. The landfill will then stop receiving waste, cell capping will be completed and the site restoration plan implemented. There is an ecological management and aftercare period of 10 years following restoration (Augean, 2014), but active management controls will continue until it can be confirmed that the site no longer represents a significant risk in terms of environmental pollution or harm to human health. During the active management period, which for the purpose of the radiological risk assessment is assumed to last from 2075 CE to 2135 CE, leachate

and gas would continue to be managed, monitoring would continue and access to the site would be controlled. In practice the active management period is likely to be considerably longer than 60 years. The operational period and the active management period are collectively referred to as the Period of Authorisation. Passive institutional control, e.g. through the presence of land use records, would be expected to continue for some time after the end of the active management period.

660. The assessment considers times up to 100,000 years after installation of the final cap. For most radionuclides the activity concentration in groundwater will have peaked within this timescale.

E.1.2. Landfill dimensions

661. The dimensions used in the ESC are shown in Table 67 and a plan of the proposed site layout is presented in Figure 3. The plan area of the total site is the sum of the plan areas of the currently constructed cells and planned site layout.

Table 67 Dimensions of the landfills

Waste type	Phase	Area label	Plan area (m2)	Average depth when built(m)(2)	Void when built
Non-hazardous	Constructed (1)	1 & 2	74,530	11.1	830,000
		3A-1	10,580	21.7	230,000
		3B	22,280	20.0	444,850
		4A	6,740	28.5	191,960
		6A	25,370	12.3	311,620
	Future phase		117,980	17.7	2,091,330
Hazardous	Constructed (1)	3	11,470	5.3	60,720
		4	15,560	8.1	126,500
		5	18,760	11.8	221,500
		6 North	6,970	16.0	111,630
		6 South	9,770	17.1	166,930
		7 South	16,860	12.3	206,550
		8 (including separation barrier Phase 1)	28,680	19.9	569,460
		8 Separation barrier (Phase 2) – First lift only	11,180	2.6	29,550
		9	20,180	9.6	192,760
	Future phases including separation structure		62,800	29.4	1,843,150

1) The void space for the constructed phases is calculated from the as built surveys and designed top of waste models.
2) The average waste depth has been calculated from the void space and plan area of the phase.

662. No distinctions between the disposal cells in each of the landfills are made for the radiological assessment. However, the hazardous landfill and the non-hazardous landfill are treated as separate units for the scenarios concerning landfill gas and a landfill fire.

663. The height of each cell and their exact location has not been determined at this time. Approximate dimensions are provided that are used to estimate volume and area. The gradient of the restored site has a maximum slope of 1v:7.7h pre-settlement. We note that the plan basal area will be less than the surface area of the restored landfill and calculations using the plan area will be slightly more conservative, the ratio of basal area to slope area at this gradient is 0.992.

E.1.3. Barrier engineering

664. A number of engineered barriers contribute to radiological safety:

- construction of a cap to limit infiltration;
- sorption in waste cells by soil and soil-like waste;
- installation of a HDPE liner and an engineered clay barrier below the waste cells prior to waste emplacement to limit water flow and retard radionuclide transport; and,
- dilution of the flux of released radionuclides when it enters the alluvium and glacial till which underlies the facility.

E.1.3.1. Engineered cap

665. The engineered cap has a layered construction designed to prevent water from entering the waste cells. Each phase of operation is progressively restored under a defined scheme of capping and restoration. The minimum depth of restoration material above the engineered cap will be 1 m or greater, and the depth of the engineered cap will be 0.3 m. In accordance with the HRA (MJCA, 2019b), the radiological assessment assumes that the cap gradually degrades between 250 years and 1000 years after construction. The water inflow through the intact cap (cap design infiltration) is 31.524 mm y^{-1} (MJCA, 2019b). Until the end of the regulatory control period (period of authorisation) any damage to the cap will be detected and repaired. Gradual degradation of the cap will begin 250 years after installation and the water inflow will increase to grassland infiltration levels (conservatively estimated to be 202.38 mm y^{-1}) at 1,000 years (MJCA, 2019b).

E.1.3.2. Basal liner and clay barrier

666. A flexible liner is placed at the base of the waste cells in order to limit release of leachate to the underlying engineered clay barrier and hydrogeological features. The HRA assumes that the liner starts degrading 150 years after installation, the surface area of punctures and tears being assumed to double every 100 years (MJCA, 2019b). The same assumptions are used in the radiological assessment.

667. The efficiency of the HDPE component of the basal liner is determined by the number of defects (pinholes, holes and tears) that are present. When the HDPE component of the basal liner has degraded, outflow through the base of the landfill is controlled by the engineered clay barrier.

668. The engineered clay barrier is 1 m thick under the non-hazardous landfill and has a low hydraulic conductivity of 5.95 10^{-11} (CQA data ranging from 1.40 10^{-11} to 4.40 10^{-} m s^{-1} for samples from phases 3A1, 3B, 5, 6 north and 6 south) (MJCA, 2019b), effectively limiting the water flow through the base of the waste cells. The HRA uses a value of 5.91 10^{-11} m s^{-1} and this value is also applied in the ESC. Clay also has

advantageous sorption properties, which will delay the migration of certain radionuclides through the barrier. The engineered clay barrier under the hazardous waste landfill is 1.5 m thick. Flows through the clay barrier are low and contaminants are assumed to be distributed between pore water and clay according to a linear equilibrium distribution model. The models cautiously use a depth of 1 m engineered clay for both landfills.

E.1.4. Landfill drainage

669. During the Period of Authorisation, the water level in the cells will be controlled so that it does not exceed 1 m above the base (MJCA, 2019b). Until the end of the period of authorisation, leachate is monitored and managed to ensure that leachate levels do not exceed this depth. Excess leachate is pumped off and either used in the WRP or transported off-site by tanker for treatment and disposal (MJCA, 2019b). The maintenance of the leachate level at 1 m is a landfill permit requirement which must be maintained throughout the active management period of the site.

670. After the end of the period of authorisation, the water level may increase. With an increasing head the potential for leachate flows through the HDPE liner defects to groundwater increases. For the purposes of the groundwater assessment, it has been assumed that the landfill cells are completely saturated and therefore that all of the inventory can potentially be dissolved in pore water. Waste cells are assumed to be homogeneous, saturated and in addition to LLW filled with a mix of soil, soil-like wastes and other hazardous or non-hazardous wastes as appropriate. Soil and soil-like wastes are effective sorption substrates and soil sorption distribution coefficients (Kd) are applied. LLW is not considered an effective sorption substrate and Kd values are set to zero (except for technetium). It has been assumed that all contaminants are available for dissolution and are partitioned between soil surfaces and pore water according to a linear equilibrium model.

671. The assumptions regarding the partitioning of radionuclides between waste and leachate are conservative since they disregard the sorption on wastes (except for technetium) and not all of the radioactive contamination would be on the surface of the waste and hence available for immediate dissolution.

E.1.5. Non-radiological aspects of waste

672. As noted in paragraph 180 the types of wastes to be disposed are not known and will be subject to commercial agreements and subject to permit requirements. The radioactive waste consignments received at the ENRMF fall under the following broad groupings:

- Contaminated soil and sediments (experimental and ex-works);
- Contaminated concrete, bricks and rubble from demolition works;
- NORM in drilling mud, sediments, descaling residues or filter cake;
- Contaminated plastics;
- Contaminated non-recyclable metals;
- Other wastes (clinker, incinerator filter cake, radiochemistry residues, laboratory items, luminising material); and,
- Contaminated hazardous waste (heavy metals, asbestos).

673. It is anticipated that similar wastes will be deposited at the Port Clarence site and that future wastes may also include other lightly contaminated construction and demolition material, redundant plant and equipment and soil from the decommissioning of nuclear sites as well as operational or process waste such as disposable coveralls, plastic wrapping and paper. Similar radioactive waste is also produced by hospitals, manufacturing companies, academic institutions and by the oil and gas industry.

E.1.6. Unsaturated and saturated zones

674. An unsaturated zone underlies the landfill comprising made ground that reflects the history of the site (see Section 2.4). Flow through this zone will be subvertical. A water table exists within the alluvium and glacial till at a depth of 1 m or greater below ground level. Flow occurs within the saturated and is subhorizontal. Significant dilution occurs when radionuclides enter the saturated zone and when the flow discharges to the estuary.

E.1.7. Water abstraction points

675. There are no licensed, deregulated or private water abstraction points located within 2 km of the site (MJCA, 2019a). The compliance point for predictive modelling of hazardous substances in the HRA is downgradient and directly adjacent to the edge of the discharge area (MJCA, 2019b).

E.2. Identifying scenarios and exposure groups

676. Throughout this report the term “scenario” is used to describe a postulated or assumed set of conditions and/or events that lead to exposure of people to radiation.

677. It is conventional, in assessments of facilities for the disposal of radioactive waste, to assume that management of the site does not persist indefinitely and that knowledge about the location of a disposal facility and the associated hazards is eventually lost. Regulatory guidance requires that an appropriate level of environmental performance should be provided without relying on any human intervention after the end of this management period. The assumption that controls would be lost is cautious as it is likely, for example, that knowledge of the landfill site would persist and that planning controls would continue to govern any redevelopment of the site for some time following closure. Nevertheless, it is assumed in the radiological assessment that management control over the site would cease in or around 2135 CE, 60 years after closure.

678. The radiological assessment has considered a range of potential scenarios. A review of generic guidance and previous publicly available ESCs identified a set of scenarios, from (IAEA, 2004; SNIFFER, 2006; LLWR Ltd, 2011a; Eden NE, 2023), that are discussed below. In cases where a scenario has not been assessed, because it will not or is very unlikely to occur at Port Clarence, the reasons for this are discussed. The scenarios discussed below consider exposure to both workers and members of the public in two separate periods, the period of authorisation and the period afterwards. These scenarios are further divided into two broad categories – those that are likely to occur and those where it is hard to quantify the likelihood of occurrence (unlikely to occur).

679. Doses and risks are assessed to a range of hypothetical exposure groups in order to identify those at greatest risk at a given time from the different scenarios. The present-day and planned land use can inform calculations of the radiological impact during the

period of authorisation. For longer timescales, beyond a few decades, it is considered appropriate to use potentially exposed groups (PEGs). These will draw on present-day habit data but it is recognised that different habits could occur in the future.

680. The exposure groups considered for the period of authorisation are workers at the landfill site and members of the public (see Section E.3.3). After the end of the period of authorisation, when active management controls have stopped and only passive controls such as land use records exist, the exposure groups include workers that excavate or analyse material from the site and members of the public living on the site or utilising groundwater abstracted from wells located off-site (see Section E.4). A summary of the scenarios and human exposure groups is given below (Table 68) and in the main text (Table 8, Table 16, Table 24 and Table 28). The tables list the period and expectation that the cases will occur, the scenario and the exposed group.

681. The ESC presents the dose to an individual who is representative of the most exposed group (known as the representative person, and formerly known as the critical group) and considers the dose to adults, children (aged 10) and infants (aged one) in all scenarios. However, it is recognised that the developing embryo and foetus could also be considered. The LLWR safety case (LLWR Ltd, 2011a) references an investigation into the magnitude of exposures to children, infants and the developing embryo and foetus (Thorne, 2006). In that study, it was found that committed effective doses to the embryo, foetus and breast-fed newborn were no larger than those estimated for one year-old infants and ten-year-old children. Similarly, the HPA (HPA, 2008) commented that 'for solid waste disposals it will be generally unnecessary to consider the embryo/foetus/breastfed infant as any increases in doses over those to other age groups will be small compared with the uncertainty in the assessed doses.'

682. The NRPB issued generic consumption data (Smith & Jones, 2003) that is used for the ESC. Summing doses over all foodstuffs at the 97.5th percentile consumption rates will give a conservative dose assessment that is appropriate for preliminary scoping assessments. For more realistic assessments it is not appropriate to assume that all foods are consumed at this high rate, in terms of diet and calorific intake, particularly for longer term assessments. The National Dose Assessments Working Group published guidance on the use of consumption rates data in prospective dose assessments (NDAWG, 2013). This suggested that the two foodstuffs likely to be most restrictive in terms of their radionuclide content (hence dose potential), should be assumed to be consumed at an elevated rate and all other foodstuffs, that may be reasonably assumed to be sourced locally, are assumed to be consumed at mean consumption rates expressed on a per consumer basis. The ESC has therefore followed the approach in the NDAWG guidance for scenarios involving ingestion of contaminated foods, in the case of a farmer or smallholder it is assumed sufficient food can be produced on contaminated land, whereas residential scenarios assuming contaminated food consumption consider half that ingested is sourced from retail shops.

683. Further details of the assumptions and parameters describing the exposed groups used in the radiological assessments are presented in three sections dealing with the period of authorisation (Section E.3), site evolution after the period of authorisation (Section E.4) and intrusions events (Section E.5). Exposure to heterogenous wastes is addressed in Section E.6. Biota exposure is considered in Section E.7.

Table 68 Summary of radiological assessment scenarios considered in the ESC

Scenario	Exposed group
Period of Authorisation – likely to occur	
Direct exposure	Worker
Loose tipping waste	Worker/Member of public
Leachate processing off-site at treatment works	Treatment worker
	Farming family
	Angler
Leachate processing off-site at Reed bed	Treatment worker
Leachate processing on-site	Treatment worker
Release to atmosphere	Member of public
Release to groundwater*	Member of public
Cell excavation*	Worker
Period of Authorisation – unlikely to occur	
Dropped load	Worker
Wound exposure	Worker
Leachate spillage	Farming family
Landfill fire	Member of public
Barrier failure*	Member of public
Aircraft impact*	Member of public
After the period of Authorisation – likely to occur	
Recreational user	Member of public
Wildlife exposure	Critical species
Site erosion	Member of public
Inundation from sea	Member of public
After the period of Authorisation – unlikely to occur	
Groundwater abstraction	Farming family
Bathtubbing	Farming family
Gas release and external exposure	Site resident
Drilling operative	Worker
Trial pit excavation	Worker
Informal scavenger	Worker
Laboratory analyst	Worker
Material recovery worker	Worker
Excavation for housing	Worker/Resident
Excavation for a road	Worker
Excavation for smallholder	Farming family
Site re-engineering*	Worker
Other unlikely events*	
After the period of Authorisation – exposure to different waste forms	
Exposure to discrete items	Worker/Member of public
Exposure to particles	Worker/Member of public
Exposure to large objects	Worker/Member of public

* Not assessed quantitatively.

E.3. Radiological impacts during the period of authorisation {R5}

684. The active management phase is assumed to last for 60 years after closure. In reality, the Environmental Permit for the hazardous landfill cannot be surrendered until the Environment Agency consider that the site no longer presents a potential risk to groundwater.

685. The scenarios and relevant exposure pathways considered in this ESC for the period of authorisation are summarised in Table 69. This is followed by a discussion of four other scenarios that are not considered further in the ESC; these are cell excavation, barrier failure, aircraft crash and ground water abstraction during the period of authorisation.

686. The radiological impact of each of the scenarios in Table 69 has been estimated using the approaches described in Sections E.3.3 to E.3.10.

Table 69 Summary of scenarios and exposure pathways during the period of authorisation

Event/scenario	Exposure pathway	Description
Waste receipt, storage, monitoring, transfer and placement	External irradiation	A worker is exposed to external radiation whilst accepting and disposing of waste.
Loose tipping of waste	Inhalation of contaminated dust	Contaminated dust is released in the tipping procedure.
Release to atmosphere: operational period	Gas (including radon) inhalation	Members of the public exposed to gases emanating from contaminated material in the landfill.
	Gas flaring	Members of the public exposed to gases emanating from gas burn.
	Fire in non-hazardous waste cell	Members of the public inadvertently inhales and is exposed to cloud of contaminated material released by fire.
Leachate processing off-site: treatment facility worker	External irradiation	The facility worker is exposed to external irradiation from raw sewage and sewage sludge.
	Inhalation of contaminated dust	Dust generated at the facility is inadvertently inhaled during worker activities.
	Ingestion of contaminated dust	Dust generated at the facility is inadvertently ingested during worker activities.
Leachate processing off-site: farming family	Ingestion of food grown on sewage sludge treated land	A farmer ingests contaminated foodstuffs as a result of growing crops on sludge conditioned soil.
	External irradiation	A farmer is exposed to external irradiation from surface layers of sludge conditioned soil.
	Inhalation of contaminated soil	Dust generated from sludge conditioned soil is inadvertently inhaled during farm activities.
	Ingestion of contaminated soil	Dust generated from sludge conditioned soil is inadvertently ingested during farm activities.
Leachate processing off-site: angler	Ingestion of food from the estuary that receives effluent discharges from the sewage treatment facility	An angler ingests fish and crustacea he catches or molluscs he collects in the estuary.
	External irradiation	Contaminated sediments on the bank of the estuary leads to external irradiation of the angler.

Event/scenario	Exposure pathway	Description
Dropped load: site worker and member of the public	Inhalation of contaminated dust	Contaminated dust released from a dropped container or tipper truck is inadvertently inhaled by a site worker and a member of the public.
Wound: site worker	Intake through a contaminated wound	Contaminated dust trapped in wound results in transfer of activity to blood.
Leachate spillage: farming family	Ingestion of food grown on sewage sludge treated land	A farmer ingests contaminated foodstuffs as a result of growing crops on contaminated soil or fish from a contaminated water course.
	External irradiation	A farmer is exposed to external irradiation from surface layers of contaminated soil.
	Inhalation of contaminated soil	Dust generated from contaminated soil is inadvertently inhaled during farm activities.
	Ingestion of contaminated soil	Dust generated from contaminated soil is inadvertently ingested during farm activities.
Fire	Inhalation of contaminated dust	Contaminated dust, gases and vapour released

E.3.1. Scenarios not explicitly assessed in the ESC

Exposure from groundwater abstraction

687. A groundwater abstraction scenario has not been included during the period of authorisation. There are no groundwater abstraction points within 2 km of the site and the groundwater beneath the site is subject to saline intrusion from the estuary making the water unsuitable for drinking or for irrigation. The direction of groundwater flow is assumed to be toward the estuary.

688. The ESC includes an assessment of groundwater abstraction after the period of authorisation but the results have not been used to determine the radiological capacity of the site. The expected rise in sea-level will maintain the saline content of water beneath the site and the existing levels of contamination from previous site activities strongly suggest that it is unlikely that the groundwater pathway will become a credible exposure pathway.

Exposure following slope failure

689. The potential exposure that might occur following slope failure is not addressed in the ESC. The Stability Risk Assessment (MJCA, 2019c) makes clear that this is not a credible scenario for the maximum slope (1v:7.7h) of the restored site that will cover the LLW.

Exposure from perched leachate

690. A scenario involving perched leachate has not been explicitly assessed for the following reasons. Perched leachate occurs where infiltration is unable to percolate to the base of the site due to low permeability layers within the landfill. As waste is relatively heterogeneous, any discrete low permeability layers are generally small areas within the landfill mass. Significant volumes are unlikely to perch in modern landfills as low permeability materials such as clays are avoided for use as daily cover. It is common practice if lower permeability layers are used as cover material, for the layers to be disturbed and mixed with other waste before further waste is placed above. This practice is also implemented to remove any low permeability temporary capping that may be in place. At Port Clarence, soils and filter cakes are typically used for daily cover which do not have inherently low permeability.

691. In the unlikely event that perched leachate occurs near the side of the landfill, it will drain down the drainage layer constructed inside the side liner system or through the regulating layer placed immediately below the capping material. In the unlikely event that there were issues associated with low permeability layers in the waste and perching they would be detected during the operational or active management phase of the site and addressed by interceptor drains or perforating the low permeability layers by drilling. Phases of the Port Clarence landfill have been operational for over 10 years and are in excess of 20 m in height but there has been no experience to date of leachate breakout at the sides of the site in the absence of a cap.

Exposure from cell excavation

692. A scenario involving drilling into the waste during construction of new sampling or leachate wells is not considered because this action would be executed with knowledge of the presence of radioactive material, under the appropriate regulations and with appropriate precautions to minimise doses to the workers. Assessments of landfill excavation after the end of the period of authorisation have been undertaken (see human intrusion in Section E.5).

Exposure from barrier failure

693. The barrier failure scenario was included in the SNIFFER methodology (SNIFFER, 2006) to account for the possibility of damage or defects in the basal liner and a damaged or inadequate geological barrier that could lead to leachate release to groundwater. It assumes that the engineered barriers all fail at the end of operations. The engineered composite liner system at the site includes a clay component and a HDPE component. The gradual degradation and eventual disappearance of the HDPE component of the lining system is modelled. The clay component comprises a natural mineral material and therefore will not degrade other than over geological timescales.

694. It is considered unreasonable to consider this scenario for the Port Clarence landfill sites receiving LLW where the construction, operation and monitoring during the period of authorisation will all reduce the possibility of complete barrier failure in a manner that allows early release of large amounts of leachate. Even if damage did occur, the potential for non-radiological environmental damage from leachate from such a site would ensure that remediation would occur before members of the public were exposed to radiation. The complete barrier failure scenario has not therefore been assessed.

Exposure from aircraft crash

695. An aircraft crash scenario has not been included. There are no airports or military air bases in close proximity to the site. The closest airport is the Durham Tees Valley Airport located about 16.5 km to the southwest of the landfills. The frequency of civil and military aircraft crashes in the UK is very low and it is noted by the IAEA that most aircraft crashes occur within a semicircle of 7.5 km radius from the end of the runway (IAEA, 2002). The scenario is excluded for these reasons.

E.3.2. Presentation of results of dose assessments

696. The radiological capacity (MBq) for individual radionuclides present in the LLW is obtained from the results of the assessments carried out and reported in the ESC and depends on the radiological characteristics of the radionuclide. The radiological capacity is calculated on the basis that the LLW only contains this one radionuclide

and disposal of that amount of radioactivity would produce a dose or risk equal to the limiting criteria applicable to the scenario. Each scenario therefore has an associated radiological capacity, the scenario radiological capacity.

697. The results of the assessments for the scenarios that could impact the radiological capacity are presented as effective doses per MBq disposed (mSv y^{-1} MBq^{-1} or µSv y^{-1} MBq^{-1}) in Sections E.3.3 to E.3.10 also show the scenario radiological capacity (MBq) for each radionuclide. Actual waste disposal will be controlled using a sum of fractions approach (see paragraphs 56 and 511).

698. Estimates of radiological impact based on 'illustrative inventories' for waste streams that might be typical of those contributing to the total impact from disposals at the facility have been produced. These estimates are presented in Appendix D for those scenarios that limit disposal.

E.3.3. Direct exposure from waste handling and emplacement

699. It is not intended that waste is stored on-site prior to disposal. Wastes will be placed in a landfill cell as soon as practicable on receipt. If the conditions for the acceptance of LLW at Port Clarence are not met, waste may need to be quarantined temporarily while deciding on a course of action. To allow some flexibility for waste delivery times and operational activities the ESC assumes a maximum of 24 h between receipt and disposal.

700. Wastes will be covered by at least 0.4 m thickness of suitable cover after each emplacement campaign or at the end of the working day such that there is no exposed face. Sufficient cover will be used to ensure the dose rate at 1 m above the waste is less than 2 µSv h^{-1}.

701. The exposed group considered for quarantine, waste handling and emplacement is landfill workers. Waste handling, emplacement and quarantine will not expose the public near to the site to radiation because there is no line of sight for direct radiation from the quarantine area or landfill void, and site access is controlled. The dose criterion used for this scenario is the site criterion of 1 mSv y^{-1} for workers.

E.3.3.1. Waste handling and emplacement

Workers at landfill site

702. Radiation risk to employees from normal handling operations is from external exposure as a result of their occupancy near to a waste package prior to disposal, and external irradiation from the wastes after they have been emplaced and covered. The SNIFFER model does not include this scenario.

703. ENRMF applies a dose rate criterion of 10 µSv h^{-1} at 1 m from the LLW package on arrival, and a dose rate criterion of 2 µSv h^{-1} at 1 m above the covered LLW waste, in order to ensure that the occupational dose is considerably less than the dose criterion of 1 mSv y^{-1} (Eden NE, 2023). The same approach will be used at Port Clarence.

704. The proposed authorisation condition for acceptance of LLW is that the dose at 1 m from the package face must be less than 10 µSv h^{-1}. This would be measured by the consignor prior to sending the package and would be checked upon arrival of the package at Port Clarence.

705. The proposed authorisation condition for emplacement of LLW is that wastes will be covered by at least 0.4 m thickness of suitable cover after each emplacement campaign or at the end of the working day such that there is no exposed face. Sufficient cover will be used to ensure the dose rate at 1 m above the waste is less than 2 µSv h^{-1}. Hence, additional cover may be added if needed. This authorisation condition does not apply to NORM received under the provisions of the exemption.

706. The dose rates proposed for the authorisation conditions were used to estimate the dose to workers at the landfill site. The occupancy times used for the three work activities: receipt and monitoring; transfer and emplacement; and occupancy of the covered area are reproduced in Table 70. The operations at the ENRMF are similar to those at Port Clarence and, because the limiting maximum surface dose rate is the same for both sites, if this maximum is reached the annual dose would be similar.

707. Additional ALARA precautions are that dose can be measured directly and managed actively to prevent unnecessary exposure. The dose rate drops quickly with distance from the package and hence the simple precaution of managing occupancy time and distance is practicable.

Table 70 Estimated annual dose to landfill workers based on typical dose rates

Work activity	Typical dose rate (µSv h^{-1})	Occupancy* (h y^{-1})	Estimated annual dose (mSv)
Receipt of waste consignments, including QA and monitoring, etc.	2	200	0.4
Transfer and placement of waste in landfill	2	130	0.26
Occupancy of covered waste area	1	130	0.13
Total estimated annual dose			0.79

* Occupancy times and typical dose rates assumed for ENRMF (Eden NE, 2023).

708. Radiation risks to employees from normal operations at the ENRMF have been considered by the HPA (latterly PHE and now UKHSA) since 2009 [Annex C, (Augean, 2009a)], and the most recent assessment from PHE (now UKHSA) (dated November 2017) provided the estimates above (Table 70). A conservative estimate of the dose to workers as a result of three work activities suggests an annual dose of about 0.79 mSv if the same worker undertook waste receipt, monitoring, transfer and placement in the landfill and worked in the covered waste area. PHE considered it unlikely that the same person would be exposed during all the listed work activities. Recorded external doses from workers at the ENRMF involved in waste handling operations have proven to be much lower than estimated by PHE.

709. To examine the dose from all radionuclides, the approach set out in IAEA report SR44 (IAEA, 2005) for calculating external exposure from waste packages and from waste in a landfill was applied to calculate external doses to workers (µSv y^{-1} per Bq g^{-1}) from handling and occupancy of the covered waste area, respectively.

$$E_{Rn,ext} = e_{Rn,ext} t_e f_d e^{-\lambda_{Rn} t_1} \frac{1 - e^{-\lambda_{Rn} t_2}}{\lambda_{Rn} t_2}$$

where:

- $E_{Rn,ext,}$ is the committed effective dose in a year per unit activity concentration in the material for radionuclide Rn (µSv y^{-1} per Bq g^{-1});
- $e_{Rn,\text{ext}}$ is the average effective dose rate per unit activity concentration in the material for radionuclide Rn (scenario dependent) (µSv h^{-1} per Bq g^{-1});
- $\boldsymbol{t_e}$ is the exposure time (h y^{-1})
- $\boldsymbol{f_d}$ is the dilution factor (dimensionless)
- $\boldsymbol{\lambda}_{Rn}$ is the radioactive decay constant for radionuclide Rn (y^{-1})
- $\boldsymbol{t_1}$ is the decay time before the start of the scenario (y); and,
- $\boldsymbol{t_2}$ is the decay time during the scenario (y).

In both exposure cases, it is cautiously assumed that both $\boldsymbol{t_1}$ and $\boldsymbol{t_2}$ are zero.

710. External dose conversion factors are presented in Table 229. External dose from a package was calculated using the external effective dose conversion factors ($e_{Rn,\text{ext}}$) from SR44 for transport (IAEA, 2005). External dose to a worker standing on the covered landfill was calculated using the external effective dose conversion factors ($e_{Rn,\text{ext}}$) from SR44 for a landfill (IAEA, 2005). The dose conversion factor for a semi-infinite slab was used for radionuclides where external effective dose conversion factors for a landfill were not available in SR44.

711. The waste will be covered by at least 0.4 m of material once it has been emplaced. As such the dose from the landfill was reduced to account for attenuation in the cover material.

712. Consistent with Table 70, it is assumed that a worker spends 330 h y^{-1} close to packages during receipt of waste consignments, including QA and monitoring. The remainder of their exposed working time, 130 h y^{-1} is assumed to be as a result of covered waste. Doses assuming the waste contains the maximum activity concentration of each radionuclide were calculated for both cases and are shown in Table 71. The maximum activity concentration is determined from this scenario and from other four scenarios (see Section E.6.5) and used to determine 8 different activity concentration bands. The radionuclide is then assigned to one of these bands.

Table 71 External doses to workers from wastes at maximum activity concentration

Radionuclide	Maximum Activity concentration (Bq g^{-1})	Dose from emplaced waste (mSv)	Dose from handling and emplacement (mSv)	Total dose (mSv)	Handling dose likely to exceed 10 µSv h^{-1}
H-3	5000	0	0	0	
C-14	5000	0	0	0	
Cl-36	5000	0	0	0	
Ca-41	5000	0	0	0	
Mn-54	5000	$4.21\ 10^{-1}$	$5.92\ 10^{1}$	$5.97\ 10^{1}$	Y
Fe-55	5000	0	0	0	
Co-60	200	$9.86\ 10^{-2}$	$7.46\ 10^{0}$	$7.56\ 10^{0}$	Y
Ni-59	5000	0	0	0	
Ni-63	5000	0	0	0	
Zn-65	5000	$4.50\ 10^{-1}$	$4.27\ 10^{1}$	$4.32\ 10^{1}$	Y

Radionuclide	Maximum Activity concentration (Bq g^{-1})	Dose from emplaced waste (mSv)	Dose from handling and emplacement (mSv)	Total dose (mSv)	Handling dose likely to exceed 10 µSv h^{-1}
Se-79	2000	0	0	0	
Sr-90	200	0	0	0	
Mo-93	5000	$2.68\ 10^{-6}$	0	$2.68\ 10^{-6}$	
Zr-93	5000	$4.04\ 10^{-7}$	0	$4.04\ 10^{-7}$	
Nb-93m	5000	$4.08\ 10^{-7}$	0	$4.08\ 10^{-7}$	
Nb-94	100	$1.42\ 10^{-2}$	$2.21\ 10^{0}$	$2.23\ 10^{0}$	
Tc-99	200	$2.29\ 10^{-13}$	$1.41\ 10^{-8}$	$1.41\ 10^{-8}$	
Ru-106	5000	$4.04\ 10^{-2}$	$8.73\ 10^{0}$	$8.77\ 10^{0}$	Y
Ag-108m	100	$9.00\ 10^{-3}$	$2.12\ 10^{0}$	$2.13\ 10^{0}$	
Ag-110m	2000	$6.33\ 10^{-1}$	$7.79\ 10^{1}$	$7.85\ 10^{1}$	Y
Cd-109	5000	$1.27\ 10^{-8}$	$2.01\ 10^{-3}$	$2.01\ 10^{-3}$	
Sb-125	5000	$9.41\ 10^{-2}$	$2.62\ 10^{1}$	$2.63\ 10^{1}$	Y
Sn-119m	5000	$2.09\ 10^{-62}$	nd	$2.09\ 10^{-62}$	
Sn-123	5000	$2.31\ 10^{-2}$	nd	$2.31\ 10^{-2}$	
Sn-126	50	$6.41\ 10^{-3}$	$1.30\ 10^{0}$	$1.31\ 10^{0}$	
Te-127m	5000	$2.50\ 10^{-6}$	$2.71\ 10^{-1}$	$2.71\ 10^{-1}$	
I-129	200	$3.49\ 10^{-26}$	0	$3.49\ 10^{-26}$	
Ba-133	5000	$2.57\ 10^{-2}$	$1.72\ 10^{1}$	$1.72\ 10^{1}$	Y
Cs-134	5000	$5.90\ 10^{-1}$	$1.07\ 10^{2}$	$1.08\ 10^{2}$	Y
Cs-135	5000	0	0	0	
Cs-137	200	$8.10\ 10^{-3}$	$1.62\ 10^{0}$	$1.63\ 10^{0}$	
Ce-144	5000	$7.29\ 10^{-5}$	$2.38\ 10^{0}$	$2.38\ 10^{0}$	
Pm-147	5000	$7.97\ 10^{-11}$	$2.82\ 10^{-5}$	$2.82\ 10^{-5}$	
Sm-147	200	0	nd	0	
Sm-151	5000	$1.27\ 10^{-87}$	0	$1.27\ 10^{-87}$	
Eu-152	2000	$2.79\ 10^{-1}$	$3.08\ 10^{1}$	$3.11\ 10^{1}$	Y
Eu-154	5000	$8.12\ 10^{-1}$	$8.65\ 10^{1}$	$8.73\ 10^{1}$	Y
Eu-155	5000	$3.98\ 10^{-6}$	$8.17\ 10^{-2}$	$8.17\ 10^{-2}$	
Gd-153	5000	$2.34\ 10^{-6}$	$8.81\ 10^{-2}$	$8.81\ 10^{-2}$	
Pb-210	50	$1.03\ 10^{-4}$	nd	$1.03\ 10^{-4}$	
Po-210	2000	$1.76\ 10^{-6}$	nd	$1.76\ 10^{-6}$	
Ra-226	10	$9.94\ 10^{-3}$	nd	$9.94\ 10^{-3}$	
Ra-228	200	$1.89\ 10^{-1}$	nd	$1.89\ 10^{-1}$	
Ac-227	50	$1.18\ 10^{-3}$	nd	$1.18\ 10^{-3}$	
Th-228	200	$1.23\ 10^{-1}$	nd	$1.23\ 10^{-1}$	
Th-229	20	$8.70\ 10^{-4}$	$5.10\ 10^{-2}$	$5.19\ 10^{-2}$	
Th-230	100	$3.80\ 10^{-9}$	nd	$3.80\ 10^{-9}$	
Th-232	10	$9.47\ 10^{-3}$	nd	$9.47\ 10^{-3}$	
Pa-231	10	$3.04\ 10^{-6}$	nd	$3.04\ 10^{-6}$	
U-232	50	$2.69\ 10^{-2}$	$9.54\ 10^{-1}$	$9.81\ 10^{-1}$	
U-233	200	$1.12\ 10^{-6}$	$4.82\ 10^{-3}$	$4.83\ 10^{-3}$	
U-234	200	$1.70\ 10^{-10}$	nd	$1.70\ 10^{-10}$	
U-235	200	$5.63\ 10^{-5}$	nd	$5.63\ 10^{-5}$	
U-236	200	$3.49\ 10^{-10}$	$8.05\ 10^{-8}$	$8.09\ 10^{-8}$	
U-238	200	$1.68\ 10^{-3}$	nd	$1.68\ 10^{-3}$	
Np-237	200	$3.52\ 10^{-4}$	$3.54\ 10^{-1}$	$3.54\ 10^{-1}$	
Pu-238	200	$7.84\ 10^{-12}$	$3.15\ 10^{-9}$	$3.16\ 10^{-9}$	
Pu-239	100	$1.13\ 10^{-8}$	$6.07\ 10^{-6}$	$6.08\ 10^{-6}$	
Pu-240	200	$4.72\ 10^{-13}$	$8.65\ 10^{-12}$	$9.12\ 10^{-12}$	
Pu-241	5000	$1.25\ 10^{-7}$	$1.17\ 10^{-7}$	$2.42\ 10^{-7}$	
Pu-242	200	$4.80\ 10^{-15}$	$1.10\ 10^{-11}$	$1.10\ 10^{-11}$	
Pu-244	200	$3.91\ 10^{-3}$	$6.73\ 10^{-1}$	$6.77\ 10^{-1}$	
Am-241	100	$5.55\ 10^{-12}$	$7.92\ 10^{-8}$	$7.92\ 10^{-8}$	

Radionuclide	Maximum Activity concentration (Bq g^{-1})	Dose from emplaced waste (mSv)	Dose from handling and emplacement (mSv)	Total dose (mSv)	Handling dose likely to exceed 10 µSv h^{-1}
Am-242m	100	1.19 10^{-4}	4.49 10^{-3}	4.61 10^{-3}	
Am-243	200	6.25 10^{-5}	1.57 10^{-1}	1.57 10^{-1}	
Cm-242	2000	7.95 10^{-10}	1.37 10^{-10}	9.31 10^{-10}	
Cm-243	200	4.07 10^{-5}	1.27 10^{-1}	1.27 10^{-1}	
Cm-244	200	1.24 10^{-66}	7.52 10^{-12}	7.52 10^{-12}	
Cm-245	200	2.52 10^{-6}	2.01 10^{-2}	2.01 10^{-2}	
Cm-246	200	2.55 10^{-28}	2.41 10^{-15}	2.41 10^{-15}	
Cm-248	50	7.41 10^{-63}	1.55 10^{-12}	1.55 10^{-12}	

"nd" indicates that no external effective dose conversion factor was available.

713. For the majority of radionuclides, the total dose is less than 1 mSv y^{-1} for waste at the maximum activity concentration (presented in the second column). The exceptions are Mn-54, Co-60, Zn-65, Nb-94, Ru-106, Ag-108m, Ag-110m, Sb-125, Sn-126, Ba-133, Cs-134, Cs-137, Ce-144, Eu-152 and Eu-154 where the total dose exceeds 1 mSv y^{-1}. As stated in the main text the maximum consignment fingerprint accepted for disposal will be 2000 Bq g^{-1} and this will reduce all doses shown above for 5000 Bq g^{-1}.

714. As discussed in Section 7.4.1.2 of the main report, the proposed activity concentration limits vary with radionuclide. The dose to a worker from emplaced of the waste is one of the scenarios used to determine the activity concentration limits, ensuring protection of any workers placing waste in the vicinity of LLW that has already been covered. The dose to a worker from this scenario is therefore 1 mSv or less for all radionuclides. One outcome of using activity concentration bands rather than individual values is that even when a radionuclide is limited by this scenario, the dose for that radionuclide is less than 1 mSv. For example, the emplaced waste scenario suggests a concentration of 3160 Bq g^{-1} of Ag-110m in LLW produces a dose of 1 mSv, but the banding limits the estimated doses to 0.63 mSv y^{-1}.

715. The dose from waste handling and emplacement has not been used to limit the activity concentration limits. This will be controlled by the operational constraints of a 10 µSv h^{-1} dose rate from packages on receipt (procedure PC LLW01), and worker exposure time on the different tasks throughout the year to ensure that the doses to workers do not exceed 1 mSv y^{-1}.

716. The dose to workers during the operational phase can be managed through occupational radiation dose protection practices. Hence the external dose assessment for waste handling and emplacement has not been used to constrain the overall radiological capacity of the site (in MBq).

717. Additional ALARA precautions are that all wastes are handled by machines and operatives generally do not enter the operational area on foot. On most days the only reason to enter the operational area on foot is for final inspection at the end of the day and health physics monitoring. Workplace monitoring will confirm actual doses and enable dose limitation to be managed.

Members of the public

718. This scenario considers a member of the public who stands at a distance in direct line of sight of a waste package/shipment and hence receives direct radiation exposure. Waste acceptance criteria limit consignment surface dose rates to 10 µSv h^{-1} at 1 m from the LLW package on delivery, and that a dose rate criterion of 2 µSv h^{-1} at 1 m

above the covered LLW waste will be applied at Port Clarence. No waste on-site will therefore exceed these criterion.

719. The dose to a member of the public can be estimated by considering the waste as a single point source with a 10 µSv h^{-1} dose rate at 1 m, and assuming that the member of the public is located 50 m from the waste. The dose rate at 50 m can be estimated from:

$$D_1 = D_2 \cdot \frac{{X_2}^2}{{X_1}^2}$$

where:

- D_1 and D_2 are dose rate at positions 1 and 2 (µSv h^{-1}); and,
- X_1 and X_2 are the distances for measured dose rate at positions 1 and 2 (m).

720. The maximum dose rate at 50 m is estimated to be 4 10^{-3} µSv h^{-1} for a package with a surface dose rate of 10 µSv h^{-1}. If the person stands at that location for 8 hours per day and there is waste at the maximum surface dose rate in that location every day then the person would receive 12 µSv y^{-1}; the corresponding dose at a distance of 100 m would be 3 µSv y^{-1}. These are very low doses from calculations that are very conservative. Another scenario could involve a dog walker moving along the site perimeter every day, spending 0.5 h d^{-1} about 120 m from the holding area. In the unlikely event that a consignment was present each time the walker passed by then the annual dose would be about 0.1 µSv.

E.3.4. Exposure from loose tipping of waste

721. The assessment of doses from waste released to atmosphere following the loose tipping of contaminated waste during the operational phase is based on the methodology developed by the IAEA (IAEA, 2005). Members of the exposed group are assumed to be adult, a child or an infant and to be exposed as a result of inhalation of contaminated dust.

722. Exposure of the public to dust has been calculated under the following assumptions:

- a waste tipper tips 15 t of solid waste;
- the tipper is filled with a dry solid;
- the distance to the nearest public is 50 m and the wastes are exposed for 30 minutes after each consignment;
- there are 80 consignments of tipped waste each year;
- the waste is immediately covered after each tip; and,
- the ambient dust loading at the location of the public is comprised of dust from the waste mixed with other clean dust, and the mixing is represented by a dilution factor.

723. The inhalation dose (Sv y^{-1}) was determined as follows:

$$Dose_{Rn,inh} = D_{Rn,inh} \cdot \mathrm{T} \cdot A \cdot Dil \cdot CF \cdot B \cdot M_{inh}$$

where:

- $Dose_{Rn,inh}$ is the dose from inhalation of dust (Sv y^{-1});
- $D_{Rn,inh}$ is the radionuclide specific dose coefficient for inhalation (Sv Bq^{-1}), see Table 225;
- T is the exposure time (h y^{-1});
- A is the activity concentration in contaminated waste (Bq g^{-1});
- Dil is the total dilution factor for the fraction of dust inhaled;
- CF is the concentration factor in fine dust
- B is the inhalation rate (m^3 h^{-1}) see Table 73; and,
- M_{inh} is the dust loading (g m^{-3}).

Table 72 Parameters for inhalation of dust used by the IAEA SR44 model

Parameter	Units	Value	Description
CF		4	Concentration factor in fine dust
M_{inh}	g m^{-3}	1 10^{-3}	Worker Dust loading
		1 10^{-4}	Public Dust loading
Dil		0.01	Total dilution factor

Table 73 Worker and public habit data for exposure to dust and gas: applicable during the Period of Authorisation

Parameter	Units	Value	Comment
Inhalation rate – worker	m^3 h^{-1}	1.69	1 h of heavy (3 m^3/h), 7 h light work (1.5 m^3/h)
Inhalation rate – adult	m^3 h^{-1}	1.21	0.25 h of heavy work (3 m^3/h), 0.75 h light work (1.5 m^3/h) and 1 h sitting (0.54 m^3/h)
Inhalation rate – child	m^3 h^{-1}	0.87	2 h light work (1.12 m^3/h) and 1 h sitting (0.38 m^3/h)
Inhalation rate – infant	m^3 h^{-1}	0.31	0.67 h light work (0.35 m^3/h) and 0.33 h sitting (0.22 m^3/h)
Time in plume – worker	h y^{-1}	40	in close proximity for 30 min during 80 tips
	h y^{-1}	177	10% of 8 hours per day, 220 working days
Time in plume – adult	h y^{-1}	6392	Fraction of year at home = 0.73
Time in plume – child	h y^{-1}	7670	Fraction of year at home = 0.88
Time in plume – infant	h y^{-1}	7305	Fraction of year at home = 0.83

Note: Inhalation rates based on ICRP 66 (ICRP, 1994).

E.3.4.1. Doses from dust released by loose tipping

724. Calculations were performed initially using an activity concentration of 200 Bq g^{-1} in disposed waste. The estimated dose to workers (mSv y^{-1}) is always much higher than that to members of the public (µSv y^{-1}, see Table 74). Applying a dose constraint of 1 mSv y^{-1} to workers and 0.3 mSv y^{-1} to members of the public, Table 74 shows that activity concentrations in loose tipped waste will need to be less than 200 Bq g^{-1} for some radionuclides. The dose to workers is the limiting dose. The dose to a worker from loose tipped waste is one of the scenarios used to determine the radionuclide activity concentration limits for loose tipped waste. These radionuclide activity concentrations will be applied using the sum of fractions approach (see Section 1.5 of main report).

725. Applying the site criterion of 1 mSv y^{-1} for workers, a maximum activity concentration for loose tipped waste was derived (last column of Table 74). In deriving the limiting concentrations, we cautiously assumed that a worker might spend an extended period of time supervising tipping but consider this overly cautious for the small amount of Ac-227, Th-229, Th-232 and Cm-248 recorded (UK RWI) as present in LLW or VLLW (i.e. these waste streams are unlikely to be present in concentrations above 1 Bq/g based on ENRMF consignments).

726. The dose a worker could receive from loose tipping considered the possibility that the projected number of loads accepted could be greater than the 80 loads used in the assessment. A factor was applied based on the assumption that 10% of a worker's time is spent supervising the loose tipping of waste (176 h y^{-1}). This adjustment reduces the limiting activity concentration for loose tipped waste by a factor of about 4.4 (to produce the maximum activity concentration shown in the last column of Table 74) and it is these concentrations that were used to determine the limiting bands containing specific radionuclides in Table 39.

727. Whilst the factored concentrations are below 5 Bq g^{-1}, see Table 74 below (cautious exposure time of 176 h). The un-factored activity concentrations relating to the doses (relating to 40 h exposure) shown in Table 74 for Ac-227 (6.5 Bq/g), Th-229 (14.5 Bq/g), Th-232 (21.8 Bq/g) and Cm-248 (10.3 Bq/g) are above 5 Bq/g and given the low probability of these radionuclides arising in wastes, the lowest band for loose tipped waste (5 Bq/g) was adopted. It is therefore very unlikely that the site constraint of 1 mSv for workers will be exceeded by loose tipping waste containing these radionuclides. The maximum band adopted for loose tipped waste (see Section E.6.5) was 100 Bq g^{-1}.

Table 74 Doses estimated from loose tipping waste at 200 Bq g^{-1} and the maximum activity concentration for loose tipped waste that meets 1 mSv y^{-1} to a worker

Radionuclide	Worker (mSv y^{-1})	Public (µSv y^{-1})			Maximum activity concentration[2] (Bq g^{-1})
		Adult	Child	Infant	
H-3[1]	$1.40\ 10^{-5}$	$1.00\ 10^{-5}$	$1.06\ 10^{-5}$	$9.81\ 10^{-6}$	$3.24\ 10^{6}$
C-14[1]	$3.13\ 10^{-4}$	$2.24\ 10^{-4}$	$2.07\ 10^{-4}$	$1.67\ 10^{-4}$	$1.45\ 10^{5}$
Cl-36	$3.94\ 10^{-4}$	$2.82\ 10^{-4}$	$2.79\ 10^{-4}$	$2.55\ 10^{-4}$	$1.15\ 10^{5}$
Ca-41	$9.72\ 10^{-6}$	$6.96\ 10^{-6}$	$9.22\ 10^{-6}$	$5.89\ 10^{-6}$	$4.68\ 10^{6}$
Mn-54	$8.10\ 10^{-5}$	$5.80\ 10^{-5}$	$6.71\ 10^{-5}$	$6.08\ 10^{-5}$	$5.61\ 10^{5}$
Fe-55	$4.16\ 10^{-5}$	$2.98\ 10^{-5}$	$3.91\ 10^{-5}$	$3.14\ 10^{-5}$	$1.09\ 10^{6}$
Co-60[1]	$1.67\ 10^{-3}$	$1.20\ 10^{-3}$	$1.12\ 10^{-3}$	$8.44\ 10^{-4}$	$2.72\ 10^{4}$
Ni-59	$2.38\ 10^{-5}$	$1.70\ 10^{-5}$	$1.65\ 10^{-5}$	$1.47\ 10^{-5}$	$1.91\ 10^{6}$
Ni-63	$7.02\ 10^{-5}$	$5.02\ 10^{-5}$	$4.75\ 10^{-5}$	$4.22\ 10^{-5}$	$6.48\ 10^{5}$
Zn-65	$1.19\ 10^{-4}$	$8.50\ 10^{-5}$	$1.06\ 10^{-4}$	$9.81\ 10^{-5}$	$3.83\ 10^{5}$
Se-79	$3.67\ 10^{-4}$	$2.63\ 10^{-4}$	$2.43\ 10^{-4}$	$1.96\ 10^{-4}$	$1.24\ 10^{5}$
Sr-90[1]	$8.72\ 10^{-3}$	$6.24\ 10^{-3}$	$5.11\ 10^{-3}$	$4.01\ 10^{-3}$	$5.21\ 10^{3}$
Mo-93	$1.24\ 10^{-4}$	$8.89\ 10^{-5}$	$7.83\ 10^{-5}$	$5.69\ 10^{-5}$	$3.66\ 10^{5}$
Zr-93	$1.35\ 10^{-3}$	$9.66\ 10^{-4}$	$2.71\ 10^{-4}$	$6.28\ 10^{-5}$	$3.37\ 10^{4}$
Nb-93m	$9.72\ 10^{-5}$	$6.96\ 10^{-5}$	$6.99\ 10^{-5}$	$6.38\ 10^{-5}$	$4.68\ 10^{5}$
Nb-94	$2.65\ 10^{-3}$	$1.89\ 10^{-3}$	$1.62\ 10^{-3}$	$1.18\ 10^{-3}$	$1.72\ 10^{4}$
Tc-99[1]	$7.02\ 10^{-4}$	$5.02\ 10^{-4}$	$4.75\ 10^{-4}$	$3.63\ 10^{-4}$	$6.48\ 10^{4}$
Ru-106	$3.56\ 10^{-3}$	$2.55\ 10^{-3}$	$2.54\ 10^{-3}$	$2.26\ 10^{-3}$	$1.28\ 10^{4}$
Ag-108m	$2.00\ 10^{-3}$	$1.43\ 10^{-3}$	$1.23\ 10^{-3}$	$8.54\ 10^{-4}$	$2.28\ 10^{4}$
Ag-110m	$6.48\ 10^{-4}$	$4.64\ 10^{-4}$	$5.03\ 10^{-4}$	$4.02\ 10^{-4}$	$7.01\ 10^{4}$
Cd-109	$4.37\ 10^{-4}$	$3.13\ 10^{-4}$	$3.91\ 10^{-4}$	$3.63\ 10^{-4}$	$1.04\ 10^{5}$

Radionuclide	Worker (mSv y^{-1})	Public (µSv y^{-1})			Maximum activity concentration[2] (Bq g^{-1})
		Adult	Child	Infant	
Sb-125	7.00 10^{-4}	5.01 10^{-4}	4.84 10^{-4}	4.02 10^{-4}	6.50 10^{4}
Sn-119m	1.19 10^{-4}	8.50 10^{-5}	8.66 10^{-5}	7.75 10^{-5}	3.83 10^{5}
Sn-123	4.37 10^{-4}	3.13 10^{-4}	3.35 10^{-4}	3.04 10^{-4}	1.04 10^{5}
Sn-126	1.54 10^{-3}	1.10 10^{-3}	1.17 10^{-3}	1.00 10^{-3}	2.96 10^{4}
Te-127m	5.29 10^{-4}	3.79 10^{-4}	3.91 10^{-4}	3.24 10^{-4}	8.59 10^{4}
I-129	1.94 10^{-3}	1.39 10^{-3}	1.87 10^{-3}	8.44 10^{-4}	2.34 10^{4}
Ba-133	5.40 10^{-4}	3.86 10^{-4}	3.63 10^{-4}	2.85 10^{-4}	8.42 10^{4}
Cs-134	1.08 10^{-3}	7.73 10^{-4}	7.83 10^{-4}	6.18 10^{-4}	4.21 10^{4}
Cs-135	4.64 10^{-4}	3.32 10^{-4}	3.07 10^{-4}	2.36 10^{-4}	9.79 10^{4}
Cs-137[1]	2.11 10^{-3}	1.51 10^{-3}	1.34 10^{-3}	9.81 10^{-4}	2.16 10^{4}
Ce-144	2.86 10^{-3}	2.05 10^{-3}	2.18 10^{-3}	2.65 10^{-3}	1.59 10^{4}
Pm-147	2.70 10^{-4}	1.93 10^{-4}	1.96 10^{-4}	1.77 10^{-4}	1.68 10^{5}
Sm-147	5.18 10^{-1}	3.71 10^{-1}	3.07 10^{-1}	2.26 10^{-1}	8.77 10^{1}
Sm-151	2.16 10^{-4}	1.55 10^{-4}	1.26 10^{-4}	9.81 10^{-5}	2.10 10^{5}
Eu-152	2.27 10^{-3}	1.62 10^{-3}	1.37 10^{-3}	9.81 10^{-4}	2.00 10^{4}
Eu-154	2.86 10^{-3}	2.05 10^{-3}	1.82 10^{-3}	1.47 10^{-3}	1.59 10^{4}
Eu-155	3.73 10^{-4}	2.67 10^{-4}	2.57 10^{-4}	2.26 10^{-4}	1.22 10^{5}
Gd-153	1.13 10^{-4}	8.11 10^{-5}	1.09 10^{-4}	1.18 10^{-4}	4.01 10^{5}
Pb-210	5.40 10^{-1}	3.86 10^{-1}	3.70 10^{-1}	3.17 10^{-1}	8.42 10^{1}
Po-210	2.32 10^{-1}	1.66 10^{-1}	1.65 10^{-1}	1.37 10^{-1}	1.96 10^{2}
Ra-226	1.05 10^{0}	7.54 10^{-1}	7.06 10^{-1}	6.03 10^{-1}	4.31 10^{1}
Ra-228	3.22 10^{0}	2.30 10^{0}	2.23 10^{0}	2.04 10^{0}	1.41 10^{1}
Ac-227	3.07 10^{1}	2.20 10^{1}	2.08 10^{1}	1.62 10^{1}	1.48 10^{0}
Th-228	2.36 10^{0}	1.69 10^{0}	1.67 10^{0}	1.57 10^{0}	1.93 10^{1}
Th-229	1.38 10^{1}	9.90 10^{0}	8.69 10^{0}	5.45 10^{0}	3.29 10^{0}
Th-230	5.40 10^{0}	3.86 10^{0}	3.07 10^{0}	1.96 10^{0}	8.42 10^{0}
Th-232	9.16 10^{0}	6.56 10^{0}	5.86 10^{0}	4.20 10^{0}	4.96 10^{0}
Pa-231	7.56 10^{0}	5.41 10^{0}	4.19 10^{0}	2.26 10^{0}	6.01 10^{0}
U-232	4.35 10^{0}	3.12 10^{0}	2.87 10^{0}	2.52 10^{0}	1.04 10^{1}
U-233	5.18 10^{-1}	3.71 10^{-1}	3.35 10^{-1}	2.94 10^{-1}	8.77 10^{1}
U-234	5.08 10^{-1}	3.63 10^{-1}	3.35 10^{-1}	2.85 10^{-1}	8.95 10^{1}
U-235	4.59 10^{-1}	3.28 10^{-1}	3.07 10^{-1}	2.55 10^{-1}	9.90 10^{1}
U-236	4.70 10^{-1}	3.36 10^{-1}	3.07 10^{-1}	2.65 10^{-1}	9.68 10^{1}
U-238[1]	4.32 10^{-1}	3.09 10^{-1}	2.80 10^{-1}	2.46 10^{-1}	1.05 10^{2}
Np-237	2.70 10^{0}	1.93 10^{0}	1.40 10^{0}	9.13 10^{-1}	1.68 10^{1}
Pu-238	5.94 10^{0}	4.25 10^{0}	3.07 10^{0}	1.86 10^{0}	7.65 10^{0}
Pu-239[1]	6.48 10^{0}	4.64 10^{0}	3.35 10^{0}	1.96 10^{0}	7.01 10^{0}
Pu-240	6.48 10^{0}	4.64 10^{0}	3.35 10^{0}	1.96 10^{0}	7.01 10^{0}
Pu-241	1.24 10^{-1}	8.89 10^{-2}	6.71 10^{-2}	2.85 10^{-2}	3.66 10^{2}
Pu-242	5.94 10^{0}	4.25 10^{0}	3.35 10^{0}	1.86 10^{0}	7.65 10^{0}
Pu-244	5.94 10^{0}	4.25 10^{0}	3.35 10^{0}	1.86 10^{0}	7.65 10^{0}
Am-241[1]	5.18 10^{0}	3.71 10^{0}	2.79 10^{0}	1.77 10^{0}	8.77 10^{0}
Am-242m	6.25 10^{0}	4.48 10^{0}	3.39 10^{0}	1.96 10^{0}	7.27 10^{0}
Am-243	5.18 10^{0}	3.71 10^{0}	2.79 10^{0}	1.67 10^{0}	8.77 10^{0}
Cm-242	3.19 10^{-1}	2.28 10^{-1}	2.29 10^{-1}	2.06 10^{-1}	1.43 10^{2}
Cm-243	3.74 10^{0}	2.68 10^{0}	2.05 10^{0}	1.48 10^{0}	1.22 10^{1}
Cm-244	3.08 10^{0}	2.20 10^{0}	1.70 10^{0}	1.28 10^{0}	1.48 10^{1}
Cm-245	5.35 10^{0}	3.83 10^{0}	2.79 10^{0}	1.77 10^{0}	8.50 10^{0}
Cm-246	5.29 10^{0}	3.79 10^{0}	2.79 10^{0}	1.77 10^{0}	8.59 10^{0}
Cm-248	1.94 10^{1}	1.39 10^{1}	1.03 10^{1}	6.38 10^{0}	2.34 10^{0}

Radionuclide	Worker (mSv y^{-1})	Public (µSv y^{-1})			Maximum activity concentration[2] (Bq g^{-1})
		Adult	Child	Infant	
1 radionuclides included in the Paris convention (NEA, 2017) 2 Based on enhanced exposure					

E.3.5. Exposure to gas during site operations

728. The permit application involves no specific authorised gaseous discharge routes for the RSR permit (gas flaring occurs under an existing non-RSR Permit). During operations, landfill workers on the site would be exposed to gas emanating from disposed waste. Public exposure to gas emanating from the waste would only occur at some distance from the source. These impacts are assessed.

729. Emission of radioactive gases as a result of combustion for power generation or flaring has also been assessed assuming that gas predominantly arises from the non-hazardous landfill. Gas collection and combustion is included in earlier capped cells but these do not contain radioactive waste. Hazardous waste landfill cells containing radioactive waste will contain insufficient material to require flaring.

730. An aerosol pathway does not arise as leachate is not sprayed on to the landfill.

731. Resuspension of dust has only been assessed for loose tipped waste (see sub-Section E.3.4), all other waste is packaged, covered with suitable material before packaging can degrade. A condition for accepting wastes will require low surface contamination of packages and this will be monitored.

732. The dose criteria applied in the assessment are the site criterion of 1 mSv y^{-1} for workers and the dose constraint for the public of 0.3 mSv y^{-1}.

E.3.5.1. Estimating activity concentrations of gas release from disposed waste

733. The assessment of doses from gases released from disposed waste to atmosphere is based on the SNIFFER assessment methodology (SNIFFER, 2006). Members of the exposed groups are assumed to be adults and to be exposed as a result of inhalation.

734. Radioactive gas, i.e., $^{14}CO_2$, $^{14}CH_4$, ^{3}H, and radon can be released to atmosphere from the waste. The first three may be generated through microbial degradation or corrosion of the radioactive waste. However, there will be a limit on the biodegradable content of LLW wastes to reduce this (Augean, 2019). Radon is generated through the decay of Ra-226, which in turn is a decay product of Th-230. The gas pathway has therefore considered radioactive carbon, tritium and radon.

735. Radioactive gases could be inhaled by workers on-site or by members of the public spending time immediately downwind of the site during the operational period and active management period. It could also be inhaled by members of the public living in a house built on the site sometime after the end of the period of authorisation and this is addressed later (see Section E.5.7 and E.5.8). Table 73 details the habit data assumed for the exposed groups during the period of authorisation.

736. During operations, landfill workers on the site would be exposed to gas emanating from disposed waste, public exposure to gas would only occur at some distance from the source. Exposure to gas has been considered for C-14, H-3 and radon.

Gas generation – H-3 and C-14

737. The release rate of radioactive gas for H-3 (in hydrogen, water, or methane) and C-14 (in carbon dioxide or methane), $R_{Rn,gas}$ (Bq y^{-1}), at time t is given by (SNIFFER, 2006):

$$R_{Rn,gas}(t) = \frac{A_{Rn,waste} \cdot e^{-\lambda_{Rn}t} \cdot f_{gas}}{\tau_{gas}}$$

where:

- $R_{Rn,gas}$ is the gaseous release rate of a radionuclide *Rn* (Bq y^{-1});
- $A_{Rn,waste}$ is the initial activity of radionuclide *Rn* in the waste (Bq);
- λ_{Rn} is the decay constant of radionuclide *Rn* (y^{-1});
- f_{gas} is the fraction of the activity associated with gas; and,
- τ_{gas} is the average timescale of gas generation (y).

738. The parameters used in this study are summarised in Table 75 and are from (Augean, 2010). The hazardous waste acceptance criteria at Port Clarence include a restriction on the amount of organic carbon that is disposed (6%). It is this organic carbon that would be subject to microbial action and be released as gas and this limit effectively caps the proportion of C-14 that could be released in a gaseous form. The proposed CfA for radioactive waste permits LLW to contain a greater amount of organic carbon subject to the overall site limit.. Although there is no limit on organic carbon in non-hazardous wastes, disposal of high carbon content waste to the non-hazardous waste landfill is not BAT and is therefore unlikely to occur, high carbon content waste is more likely to be disposed of through incineration. The same gas generation rates have therefore been used for both waste types.

739. The release rate is expected to vary with time. Gas generation within the landfill has been simulated using the GasSim model (Augean, 2010) which shows a rapid build-up in the rate of release after capping followed by an exponential decline. The peak annual gas yield for carbon is less than 10% of the total quantity of gas. The average timescale of gas generation has therefore been set at 10 years during operations.

Table 75 Gas generation parameters

Parameter	Units	Value	Description
$A_{Rn,waste}$	Bq	$1\ 10^{6}$	Initial activity of radionuclide *Rn*
f_{gas}		H-3: $3.9\ 10^{-2}$	Fraction of activity associated with gas
		C-14: $6.0\ 10^{-2}$	
τ_{gas}	y	10	Average timescale of gas generation

From (Augean, 2010)

740. The activity concentration of a radionuclide in air, $C_{Rn,gas,outdoors}$ (Bq m^{-3}), can be approximated by dividing the release rate by the air volume into which the activity released per year is diluted (SNIFFER, 2006):

$$C_{Rn,gas,outdoors} = \frac{R_{Rn,gas}}{(\mathrm{W} \cdot \mathrm{u} \cdot \mathrm{h} \cdot \mathrm{s}_y)}$$

where:

- $C_{Rn,gas,outdoors}$ is the activity concentration of a radionuclide in air (Bq m^{-3});
- $R_{Rn,gas}$ is the release rate of radionuclide Rn in gas (Bq y^{-1}) at the time of interest;
- W is the width of the source perpendicular to the wind direction (m);
- u is the mean wind speed (m s^{-1});
- h is the height for vertical mixing (m); and,
- s_y is the number of seconds in a year, $3.16\ 10^7$ (s y^{-1}).

741. The dose ($Dose_{Rn,gas,outdoors}$; Sv y^{-1}) from gases other than radon is given by (SNIFFER, 2006):

$$Dose_{Rn,gas,outdoors} = C_{Rn,gas,outdoors} \cdot B \cdot O_{out} \cdot D_{Rn,inh}$$

where:

- $Dose_{Rn,gas,outdoors}$ is the dose from gases other than radon (Sv y^{-1});
- O_{out} is the time spent in the gas plume (h y^{-1});
- B is the breathing rate (m^3 h^{-1}); and,
- $D_{Rni,nh}$ is the dose coefficient for inhalation (Sv Bq^{-1}).

742. The dispersion parameter values used in the ESC are given in Table 76, the dose coefficients in Table 225 and the habit data in Table 73.

Table 76 Parameter values used in calculations of doses through the gas pathway during site operations

Parameter	Units	Value	Description
W	m	131	Width of source perpendicular to the wind direction
u	m s^{-1}	4.63	Mean wind speed
h	m	2.0	Height for vertical mixing
s_y	s	$3.16\ 10^7$	Seconds in a year

743. The meterological data for Teeside indicates wind direction and speed (Table 77). This is used to calculate the direction in which the highest impact would occur over the range of recorded wind speeds. These calculations indicate that the highest dose occurs to a group exposed to the south of the site. It assumes that mixing is limited to a height of 2 m and that the width of the source is limited to the narrowest width based on current information for the site (using the average from the two landfills). These assumptions are conservative. Wind data for the meteorological station closest to Port Clarence show that the peak dose, using a combination of wind speed and the

prevailing sector, to a member of the public is about 27% of the value calculated assuming that the exposed group is always downwind of the release point.

Table 77 Wind data from Teeside for 2007 to 2011

Wind direction	Wind speed (m s^{-1}): fraction of year in each direction						
	0.5 – 2	2 - 3	3 – 4	4 – 6	6 - 8	8 – 10	>= 10
N	0.0064	0.0077	0.0073	0.0094	0.0051	0.0022	0.0008
NNE	0.0053	0.0071	0.0068	0.0149	0.0087	0.0028	0.0006
NE	0.0045	0.0062	0.0072	0.0148	0.0082	0.0031	0.0006
ENE	0.0044	0.0044	0.0046	0.0065	0.0042	0.0016	0.0003
E	0.0038	0.0036	0.0027	0.0030	0.0012	0.0004	0.0001
ESE	0.0047	0.0042	0.0026	0.0032	0.0019	0.0006	0.0001
SE	0.0071	0.0073	0.0076	0.0094	0.0031	0.0010	0.0003
SSE	0.0093	0.0138	0.0127	0.0209	0.0126	0.0062	0.0033
S	0.0104	0.0172	0.0198	0.0406	0.0274	0.0100	0.0039
SSW	0.0134	0.0221	0.0212	0.0304	0.0178	0.0084	0.0070
SW	0.0125	0.0183	0.0140	0.0212	0.0186	0.0131	0.0118
WSW	0.0113	0.0134	0.0123	0.0230	0.0202	0.0115	0.0090
W	0.0089	0.0098	0.0116	0.0212	0.0126	0.0068	0.0037
WNW	0.0078	0.0085	0.0085	0.0137	0.0074	0.0028	0.0012
NW	0.0072	0.0076	0.0065	0.0144	0.0080	0.0021	0.0005
NNW	0.0075	0.0089	0.0079	0.0139	0.0071	0.0030	0.0008

Gas generation – Radon

744. Radon (i.e. Rn-222) gas is a short-lived (half-life of 3.82 days) radionuclide that is released as a consequence of the decay of Ra-226. Over long timescales, the ingrowth of Ra-226 through the Cm-246 decay chain (see Figure 12) will also result in radon gas release.

745. Radon decays to a number of very short-lived radioactive decay products, and it is these progeny, rather than radon itself, that present the greater risk. However, conventionally, 'radon' is used as convenient shorthand to include both radon and its progeny (Quintessa Ltd, 2011).

746. The flux of radon, $F_{radon}(t)$ (Bq y^{-1}), through an intact (or partially damaged) cap is calculated according to (SNIFFER, 2006):

$$F_{radon}(t) = \lambda_{Rn-222} \cdot AREA \cdot C_{Ra-226} \cdot e^{-\lambda_{Ra-226} t} \cdot \rho_{waste} \cdot \tau \cdot H_1 \cdot e^{\frac{-h_2}{H_2}}$$

where :

- F_{radon} is the flux of radon through the cap (Bq y^{-1});
- $AREA$ is the plan basal area containing radioactive waste, this is a cautious assumption for a restored site with a maximum pre-settlement slope of 1v:7.7h;
- C_{Ra-226} is the initial ^{226}Ra concentration in the waste (Bq kg^{-1});

- t is the time at which the flux is evaluated;
- ρ_{waste} is the bulk density of the waste (kg m^{-3});
- τ is the emanation factor, the fraction of the radon atoms produced which escape from the solid phase of the waste into the pore spaces;
- H_1 is the effective diffusion relaxation length for the waste (m);
- h_2 is the thickness of the cover (m); and,
- H_2 is the effective relaxation length of the cover (m).

747. The activity concentration of radon in outdoor air is calculated using the equation given in paragraph 740 and the parameters in Table 76. The radon calculations for members of the public are adjusted for the wind direction and speed (see paragraph 743).

748. The release of radon gas is sensitive to the cover depth and the assumption that the complete inventory is only covered with the daily cover depth (0.4 m of material) is not realistic over the operational period. The landfill comprises a series of cells and the average period until a further layer of waste is applied at any location is about two months. It has therefore been assumed that any waste is covered with at least a further 0.6 m of material after 2 months. The dose is therefore a combination of 2 months with 0.4 m cover and 10 months with ≥1 m cover. A cover depth of 1 m or more reduces radon emissions significantly (more than a 97% reduction) so the annual radon dose from each layer is essentially that from the first 2 months.

Table 78 Radon parameters

Parameter	Units	Value	Description	Comment
ρ_{waste}	kg m^{-3}	1,530	Waste density	
τ		0.1	emanation factor	From (HPA, 2007)
H_1	m	0.2	effective diffusion relaxation length for the waste	From (HPA, 2007)
H_2	m	0.2	effective relaxation length of the cover	From (HPA, 2007)
h_2	m	0.4	thickness of cover for first two months	daily cover depth
		1.0	thickness of cover for remaining ten months	
AREA	m^2	265,193	combined landfills	minus inert cover over separation bund

E.3.5.2. Assessment calculation for gas releases

749. The dose (Sv y^{-1}) from gases is given by (SNIFFER, 2006):

$$Dose_{Rn,gas,outdoors} = C_{Rn,gas,outdoors} \cdot B \cdot O_{out} \cdot D_{Rn,inh}$$

where:

- $Dose_{Rn,gas,outdoors}$ is dose from gas exposure outdoors (Sv y^{-1}).
- $C_{Rn,gas,outdoors}$ is the activity concentration of a radionuclide in air (Bq m^{-3});

- O_{out} is the time spent in the gas plume ($h\ y^{-1}$);
- B is the breathing rate ($m^3\ h^{-1}$); and,
- $D_{Rni,nh}$ is the dose coefficient for inhalation ($Sv\ Bq^{-1}$).

750. The dose coefficients for C-14 and H-3 are in Table 225 and the habit data in Table 73.

751. The dose coefficient for radon (Table 79) applied in this ESC accounts for the effect of the daughters of Rn-222 in the body and is taken from the radiological assessment methodology developed by the Environment Agency (Environment Agency, 2022b), Initial Assessment Tool 2022 (Vol 2 - Table B1). Habit data for workers and members of the public are presented in Table 73.

Table 79 Inhalation dose coefficient for use in calculation of radon doses

Parameter	Units	Value	Description
D_{inh}	$Sv\ Bq^{-1}$	$1.20\ 10^{-8}$	Adult
		$2.30\ 10^{-8}$	Child
		$7.00\ 10^{-8}$	Infant

E.3.5.3. Doses from gas releases during operations

752. The release of gases during operations will expose landfill workers on the site. Public exposure to gas would occur at some distance from the source. The calculations assume that there is no radioactive decay (or daughter ingrowth) and that members of the public are always present in the wind direction resulting in the highest dose, for Ra-226 it is also assumed that waste is covered on a daily basis to a depth of 0.4 m and covered again within 2 months. Doses are presented for each age group and site workers in Table 80.

Table 80 Dose estimated for exposure from gas released during operations

Radionuclide	Annual dose (µSv y^{-1} MBq^{-1})				Scenario radiological capacity (MBq)
	Worker	Public - adult	Public - child	Public - infant	
H-3	$3.92\ 10^{-8}$	$5.49\ 10^{-8}$	$6.96\ 10^{-8}$	$6.12\ 10^{-8}$	$4.31\ 10^{9}$
C-14	$1.35\ 10^{-6}$	$1.88\ 10^{-6}$	$2.08\ 10^{-6}$	$1.60\ 10^{-6}$	$1.44\ 10^{8}$
Ra-226	$9.14\ 10^{-6}$	$1.28\ 10^{-5}$	$2.12\ 10^{-5}$	$2.16\ 10^{-5}$	$1.39\ 10^{7}$

753. The dose estimates indicate that the worst case is for Ra-226 disposal for both workers and members of the public (the highest dose is to a child or an infant member of the public). The results are independent of the eventual Ra-226 placement depth in the site since this scenario assesses the dose immediately after emplacement. This scenario does not limit disposals at Port Clarence.

754. The doses calculated using illustrative inventories are considered further in Appendix D.

E.3.5.4. Exposure to gases collected from capped cells

755. The site operates a system for management of landfill gas. The landfill gas generation and utilisation for the year 2018 CE at Port Clarence is summarised in Table 81 [Pers. Comm. [redacted] to [redacted], "Port Clarence", 04/04/2019 – no more recent

information available]. The most recent gas generation data has been impacted by various works at the site in recent years leading to lower and variable values. The data below represent a cautious basis to estimate doses.

Table 81 Landfill gas generation and utilisation for the year 2018 CE at Port Clarence

Area	Landfill gas generated (t)	Proportion used for power generation (%)	Proportion vented passively (%)
Port Clarence Hazardous landfill	146	0	100
Port Clarence Non-hazardous landfill	4807	65	35

756. A facility has been installed at Port Clarence that generates electricity from the landfill gas. The radiological assessment of that facility assumes conversion of CH_4 into CO_2 and H_2O.

757. The LLW wastes that will be disposed of at the site have a generally low level of organic matter and are only slowly degradable. The levels of radioactivity in LLW are too low to give rise to a risk from radiolytic hydrogen gas evolution.

758. PC-CREAM 08 provides the assessment of gaseous tritium and C-14 releases, generally keeping the default parameters. PC-CREAM 08 implements a Gaussian Plume model for atmospheric dispersion of gases and a combination of assessment models, including Plume, Farmland, Granis and Resus (Smith & Simmonds, 2015).

759. The methodology uses the disposed inventory and a gas release rate to give the activity released in a year. Hence, the gas generation values in Table 81 are not used directly in the radiological assessment but can subsequently be used to derive an activity concentration in the generated gas. The tritium release rate was taken from the LLWR assessment for the period of authorisation (Penfold & Paulley, 2011) as 0.01 y^{-1}. The C-14 release rate was taken from the C-14 assessment undertaken for LLWR (LLWR Ltd, 2013b) as 0.0316 y^{-1}, which, which is appropriately cautious for mixed waste containing various materials. Decreases of activity through release and decay were not taken into account, the assessment is based on the maximum release rate, which occurs when the site is just filled completely. The stack height for releases is 10 m.

760. The weather conditions were based on annual data from 2007 to 2011 published by the Meteorological Office (Table 77). The average wind speed is 4.6 m s^{-1}. It should be noted that the weather data is presented as wind blowing from directions, while PC-CREAM implements wind blowing to directions in the meteorological data files.

761. PC-CREAM 08 uses a Pasquill weather classification system. The UK generally has a mix of Categories C and D. The Radioactivity in Food and the Environment (RIFE) report for 2023 (RIFE, 2024) advises 70% as the frequency of Pasquill stability category D for Hartlepool, which is used as surrogate for Middlesbrough and PC-CREAM uses 10% rain as a default. This was implemented as 27% Category C, 63% Category D, 3% Category C Rain and 7% Category D Rain. We note that the PC Cream help file indicates that a factor or 1.5 is applied to ICRP inhalation dose coefficients for tritiated vapour in order to account for a skin absorption component. For example, the ICRP value for adults is 1.8 10^{-11} Sv Bq^{-1}, that is multiplied by 1.5 before being used in the PC Cream module ASSESSOR (2.7 10^{-11} Sv Bq^{-1}).

762. Three receptor locations were chosen to represent:

- the greatest dose at the site boundary;
- the nearest downwind residential site (Greatham); and,
- the nearest residential site (South Bank).

763. Table 82 summarises the results of the gaseous dispersion assessment for H-3 and C-14, where the disposed radionuclide inventory has been assumed to be 1 MBq for both H-3 and C-14.

Table 82 Calculated annual dose for gaseous dispersion following disposal of 1 MBq of H-3 and C-14 and dose at maximum inventory

Receptor		Annual dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	
Location	Age group	H-3	C-14
Site boundary (390 m, 37 degrees)	Adult	$4.91\ 10^{-11}$	$1.15\ 10^{-8}$
	Child	$4.52\ 10^{-11}$	$1.16\ 10^{-8}$
	Infant	$3.36\ 10^{-11}$	$9.74\ 10^{-9}$
Greatham (4858 m, 337 degrees)	Adult	$2.52\ 10^{-11}$	$2.03\ 10^{-8}$
	Child	$2.47\ 10^{-11}$	$2.03\ 10^{-8}$
	Infant	$4.33\ 10^{-11}$	$2.60\ 10^{-8}$
South Bank (1544 m, 143 degrees)	Adult	$4.35\ 10^{-11}$	$1.65\ 10^{-8}$
	Child	$3.77\ 10^{-11}$	$1.51\ 10^{-8}$
	Infant	$3.40\ 10^{-11}$	$1.48\ 10^{-8}$
Scenario radiological capacity (MBq)		$6.11\ 10^{12}$	$1.15\ 10^{10}$

764. These results are lower than for the operational assessment (see Table 80) by more than an order of magnitude. This scenario would only apply to the non-hazardous waste cells and due to the low doses will not constrain the radiological capacity of Port Clarence.

E.3.6. Exposures from non-hazardous waste landfill fire

765. Fires at landfill sites can disperse material from the waste and hence a fire at Port Clarence would create the potential for exposure to radioactive material dispersed in the air. The disposal of organic carbon to the hazardous waste site at Port Clarence is limited to 6% total organic carbon and a fire is very unlikely in hazardous waste cells. Hence, no fire assessment has been made for the hazardous landfill at Port Clarence. However, there is no limit on total organic carbon for the non-hazardous waste landfill at Port Clarence and hence a cautious assessment has been undertaken. Note that the disposal of wastes that are high in organic carbon, and which could therefore ignite, is unlikely because BAT disposal of these wastes would be incineration.

766. The assessment uses the same approach adopted by PHE for the NORM waste assessments at Port Clarence (Jones, et al., 2014). The approach taken by PHE simplifies the processes involved and gives an illustrative value for the resulting dose; doses from a real fire depend heavily on environmental and meteorological factors at the time.

767. Doses are calculated for members of the public, who are assumed to be working 250 m downwind of the fire. It is assumed that the fire burns for one hour at ground level, and consumes 100 m^3 of the waste (SNIFFER, 2006).

768. The dose criteria used in the assessment are 1 mSv y^{-1} for workers at the site and the dose constraint for the public of 0.3 mSv y^{-1}.

E.3.6.1. Assessment calculation for releases to air from a fire

769. An element-specific fraction of the burnt material is lifted with the plume (Asselineau et al., 1995), which is neutrally buoyant and non-depleting.

770. The exposure pathways are inhalation of and external exposure to radionuclides in the smoke plume for the duration of the fire. The dose (Sv) from one fire is given by:

$$Dose_{fire} = Dose_{Inh} + Dose_{ext,cloud}$$

where:

- $Dose_{fire}$ is total dose from a fire (Sv);
- $Dose_{Inh}$ is the dose from inhalation (Sv); and,
- $Dose_{ext,cloud}$ is the dose from external exposure from the passing cloud (Sv).

771. The dose (Sv) from inhalation is given by:

$$Dose_{Rn,Inh} = C_{Rn,smoke} \cdot T_{fire} \cdot R_{Inh} \cdot D_{Rn,Inh}$$

where:

- $Dose_{Rn,Inh}$ is the dose from inhalation for radionuclide *Rn* (Sv);
- $C_{Rn,smoke}$ is the activity concentration in the smoke plume for radionuclide *Rn* (Bq m^{-3});
- T_{fire} is the duration of the fire (h) and exposure time;
- R_{Inh} is the inhalation rate (m^3 h^{-1}); and,
- $D_{Rn,Inh}$ is the inhalation dose coefficient for radionuclide *Rn* (Sv Bq^{-1}), see Table 225.

772. The dose (Sv) from external exposure is given by:

$$Dose_{Rn,ext,cloud} = C_{Rn,smoke} \cdot T_{fire} \cdot D_{Rn,ext,cloud}$$

where:

- $Dose_{Rn,ext,cloud}$ is the external dose from the plume for radionuclide *Rn* (Sv);
- $C_{Rn,smoke}$ is the activity concentration in the smoke plume for radionuclide *Rn* (Bq m^{-3});
- T_{fire} is the duration of the fire (h) and exposure time; and,
- $D_{Rn,ext,cloud}$ is the external dose coefficient for radionuclide *Rn* (Sv Bq^{-1} h^{-1} m^3), see Table 226.

773. The activity concentration in the smoke (SNIFFER, 2006) is given by:

$$C_{Rn,smoke} = \frac{V_{fire}}{V_{landfill}} \cdot RF \cdot A_{landfill} \cdot \frac{C_{TIAC} \cdot CF}{T_{fire}}$$

where:

- $C_{Rn,smoke}$ is the activity concentration in the smoke plume for radionuclide *Rn* (Bq m^{-3});
- V_{fire} is the volume of waste consumed by the fire (m^3);
- $V_{landfill}$ is the volume of the landfill (m^3);
- *RF* is the fraction of the radionuclide consumed in the fire that reaches the plume (dimensionless, see Table 224);
- $A_{landfill}$ is the activity disposed of into the landfill (Bq);
- C_{TIAC} is the time-integrated activity concentration in air at the receptor point from a 30 minute release (Bq h m^{-3} Bq^{-1});
- *CF* correction factor for a 60 minute release (dimensionless);
- T_{fire} is the duration of the fire (h).

774. It is assumed that there are two fires per year and hence the dose is multiplied by two. The time-integrated activity concentration is based on a Pasquill stability category F stable from a source at zero stack elevation 250 m downwind of the fire. The NRPB R91 scheme (Clarke, 1979) covers categories from A to G representing increasing atmospheric stability – where G is the most stable. These are therefore very cautious assumptions for a coastal location (see Figure 11 of NRPB R91, that shows coastal impact on stability category distribution), i.e. we have cautiously used an assumption of stable conditions in an area unlikely to experience stable conditions.

775. Parameter values used in the calculations are summarised in Table 83. Inhalation rates for members of the public are presented in Table 73.

Table 83 Parameters for use in calculation of doses from fires

Parameter	Units	Value	Reference
T_{fire}	H	1	(SNIFFER, 2006)
V_{fire}	m^3	100	(SNIFFER, 2006)
C_{TIAC}	Bq h m^{-3} Bq^{-1}	2.8 10^{-7}	(Clarke, 1979)
CF		0.7	(Jones, et al., 2014)

E.3.6.2. Doses from a fire in the non-hazardous waste landfill

776. The calculated doses shown below for each of the assessed groups are per MBq input to Port Clarence (Table 84). The radiological capacity (MBq) associated with the limiting age group for each radionuclide is shown in the fourth column. This scenario has the potential to constrain the radiological capacity of the non-hazardous landfill at Port Clarence.

Table 84 Doses estimated for two fires in a non-hazardous waste cell in one year

Radionuclide	Public dose (mSv y-1) per MBq disposed			Scenario radiological capacity (MBq)
	Adult	Child	Infant	
H-3	$7.40\ 10^{-12}$	$7.82\ 10^{-12}$	$7.23\ 10^{-12}$	$3.83\ 10^{10}$
C-14	$1.65\ 10^{-10}$	$1.52\ 10^{-10}$	$1.23\ 10^{-10}$	$1.82\ 10^{9}$
Cl-36	$2.08\ 10^{-10}$	$2.06\ 10^{-10}$	$1.88\ 10^{-10}$	$1.44\ 10^{9}$
Ca-41	$5.12\ 10^{-15}$	$6.79\ 10^{-15}$	$4.34\ 10^{-15}$	$4.42\ 10^{13}$
Mn-54	$4.59\ 10^{-14}$	$5.26\ 10^{-14}$	$4.80\ 10^{-14}$	$5.70\ 10^{12}$
Fe-55	$2.19\ 10^{-14}$	$2.88\ 10^{-14}$	$2.31\ 10^{-14}$	$1.04\ 10^{13}$
Co-60	$8.92\ 10^{-13}$	$8.34\ 10^{-13}$	$6.32\ 10^{-13}$	$3.36\ 10^{11}$
Ni-59	$1.25\ 10^{-14}$	$1.21\ 10^{-14}$	$1.08\ 10^{-14}$	$2.40\ 10^{13}$
Ni-63	$3.70\ 10^{-14}$	$3.50\ 10^{-14}$	$3.11\ 10^{-14}$	$8.11\ 10^{12}$
Zn-65	$6.49\ 10^{-12}$	$8.05\ 10^{-12}$	$7.46\ 10^{-12}$	$3.73\ 10^{10}$
Se-79	$1.94\ 10^{-10}$	$1.79\ 10^{-10}$	$1.45\ 10^{-10}$	$1.55\ 10^{9}$
Sr-90	$4.60\ 10^{-12}$	$3.76\ 10^{-12}$	$2.96\ 10^{-12}$	$6.53\ 10^{10}$
Mo-93	$6.55\ 10^{-14}$	$5.76\ 10^{-14}$	$4.19\ 10^{-14}$	$4.58\ 10^{12}$
Zr-93	$7.12\ 10^{-13}$	$2.00\ 10^{-13}$	$4.63\ 10^{-14}$	$4.22\ 10^{11}$
Nb-93m	$5.12\ 10^{-14}$	$5.15\ 10^{-14}$	$4.70\ 10^{-14}$	$5.83\ 10^{12}$
Nb-94	$1.40\ 10^{-12}$	$1.20\ 10^{-12}$	$8.74\ 10^{-13}$	$2.14\ 10^{11}$
Tc-99	$3.70\ 10^{-13}$	$3.50\ 10^{-13}$	$2.68\ 10^{-13}$	$8.11\ 10^{11}$
Ru-106	$1.88\ 10^{-10}$	$1.87\ 10^{-10}$	$1.66\ 10^{-10}$	$1.60\ 10^{9}$
Ag-108m	$1.06\ 10^{-11}$	$9.12\ 10^{-12}$	$6.35\ 10^{-12}$	$2.83\ 10^{10}$
Ag-110m	$3.52\ 10^{-12}$	$3.81\ 10^{-12}$	$3.07\ 10^{-12}$	$7.87\ 10^{10}$
Cd-109	$2.31\ 10^{-13}$	$2.88\ 10^{-13}$	$2.68\ 10^{-13}$	$1.04\ 10^{12}$
Sb-125	$3.70\ 10^{-11}$	$3.58\ 10^{-11}$	$2.98\ 10^{-11}$	$8.10\ 10^{9}$
Sn-119m	$6.26\ 10^{-14}$	$6.38\ 10^{-14}$	$5.71\ 10^{-14}$	$4.70\ 10^{12}$
Sn-123	$2.31\ 10^{-13}$	$2.47\ 10^{-13}$	$2.24\ 10^{-13}$	$1.21\ 10^{12}$
Sn-126	$8.18\ 10^{-13}$	$8.67\ 10^{-13}$	$7.47\ 10^{-13}$	$3.46\ 10^{11}$
Te-127m	$2.79\ 10^{-11}$	$2.88\ 10^{-11}$	$2.39\ 10^{-11}$	$1.04\ 10^{10}$
I-129	$1.02\ 10^{-9}$	$1.38\ 10^{-9}$	$6.22\ 10^{-10}$	$2.17\ 10^{8}$
Ba-133	$2.86\ 10^{-13}$	$2.69\ 10^{-13}$	$2.11\ 10^{-13}$	$1.05\ 10^{12}$
Cs-134	$5.75\ 10^{-11}$	$5.82\ 10^{-11}$	$4.61\ 10^{-11}$	$5.15\ 10^{9}$
Cs-135	$2.45\ 10^{-11}$	$2.26\ 10^{-11}$	$1.74\ 10^{-11}$	$1.23\ 10^{10}$
Cs-137	$1.11\ 10^{-10}$	$9.90\ 10^{-11}$	$7.25\ 10^{-11}$	$2.70\ 10^{9}$
Ce-144	$1.51\ 10^{-12}$	$1.61\ 10^{-12}$	$1.95\ 10^{-12}$	$1.54\ 10^{11}$
Pm-147	$1.42\ 10^{-13}$	$1.44\ 10^{-13}$	$1.30\ 10^{-13}$	$2.08\ 10^{12}$
Sm-147	$2.73\ 10^{-10}$	$2.26\ 10^{-10}$	$1.66\ 10^{-10}$	$1.10\ 10^{9}$
Sm-151	$1.14\ 10^{-13}$	$9.26\ 10^{-14}$	$7.23\ 10^{-14}$	$2.63\ 10^{12}$
Eu-152	$1.20\ 10^{-12}$	$1.01\ 10^{-12}$	$7.27\ 10^{-13}$	$2.50\ 10^{11}$
Eu-154	$1.51\ 10^{-12}$	$1.34\ 10^{-12}$	$1.09\ 10^{-12}$	$1.98\ 10^{11}$
Eu-155	$1.97\ 10^{-13}$	$1.90\ 10^{-13}$	$1.66\ 10^{-13}$	$1.53\ 10^{12}$
Gd-153	$6.00\ 10^{-14}$	$8.05\ 10^{-14}$	$8.70\ 10^{-14}$	$3.45\ 10^{12}$
Pb-210	$1.42\ 10^{-7}$	$1.36\ 10^{-7}$	$1.17\ 10^{-7}$	$2.11\ 10^{6}$
Po-210	$1.22\ 10^{-10}$	$1.21\ 10^{-10}$	$1.01\ 10^{-10}$	$2.45\ 10^{9}$
Ra-226	$5.56\ 10^{-10}$	$5.20\ 10^{-10}$	$4.44\ 10^{-10}$	$5.40\ 10^{8}$
Ra-228	$1.70\ 10^{-9}$	$1.64\ 10^{-9}$	$1.50\ 10^{-9}$	$1.77\ 10^{8}$
Ac-227	$1.62\ 10^{-8}$	$1.53\ 10^{-8}$	$1.20\ 10^{-8}$	$1.85\ 10^{7}$
Th-228	$1.24\ 10^{-9}$	$1.23\ 10^{-9}$	$1.16\ 10^{-9}$	$2.42\ 10^{8}$
Th-229	$7.29\ 10^{-9}$	$6.40\ 10^{-9}$	$4.01\ 10^{-9}$	$4.11\ 10^{7}$
Th-230	$2.85\ 10^{-9}$	$2.26\ 10^{-9}$	$1.45\ 10^{-9}$	$1.05\ 10^{8}$
Th-232	$4.83\ 10^{-9}$	$4.32\ 10^{-9}$	$3.09\ 10^{-9}$	$6.21\ 10^{7}$
Pa-231	$3.99\ 10^{-9}$	$3.09\ 10^{-9}$	$1.66\ 10^{-9}$	$7.53\ 10^{7}$

Radionuclide	Public dose (mSv y^{-1}) per MBq disposed			Scenario radiological capacity (MBq)
	Adult	Child	Infant	
U-232	$2.29\ 10^{-9}$	$2.11\ 10^{-9}$	$1.86\ 10^{-9}$	$1.31\ 10^{8}$
U-233	$2.73\ 10^{-10}$	$2.47\ 10^{-10}$	$2.17\ 10^{-10}$	$1.10\ 10^{9}$
U-234	$2.68\ 10^{-10}$	$2.47\ 10^{-10}$	$2.10\ 10^{-10}$	$1.12\ 10^{9}$
U-235	$2.42\ 10^{-10}$	$2.26\ 10^{-10}$	$1.88\ 10^{-10}$	$1.24\ 10^{9}$
U-236	$2.48\ 10^{-10}$	$2.26\ 10^{-10}$	$1.95\ 10^{-10}$	$1.21\ 10^{9}$
U-238	$2.28\ 10^{-10}$	$2.06\ 10^{-10}$	$1.81\ 10^{-10}$	$1.32\ 10^{9}$
Np-237	$1.42\ 10^{-9}$	$1.03\ 10^{-9}$	$6.72\ 10^{-10}$	$2.11\ 10^{8}$
Pu-238	$3.13\ 10^{-9}$	$2.26\ 10^{-9}$	$1.37\ 10^{-9}$	$9.58\ 10^{7}$
Pu-239	$3.42\ 10^{-9}$	$2.47\ 10^{-9}$	$1.45\ 10^{-9}$	$8.78\ 10^{7}$
Pu-240	$3.42\ 10^{-9}$	$2.47\ 10^{-9}$	$1.45\ 10^{-9}$	$8.78\ 10^{7}$
Pu-241	$6.55\ 10^{-11}$	$4.94\ 10^{-11}$	$2.10\ 10^{-11}$	$4.58\ 10^{9}$
Pu-242	$3.13\ 10^{-9}$	$2.47\ 10^{-9}$	$1.37\ 10^{-9}$	$9.58\ 10^{7}$
Pu-244	$3.13\ 10^{-9}$	$2.47\ 10^{-9}$	$1.37\ 10^{-9}$	$9.58\ 10^{7}$
Am-241	$2.73\ 10^{-9}$	$2.06\ 10^{-9}$	$1.30\ 10^{-9}$	$1.10\ 10^{8}$
Am-242m	$3.30\ 10^{-9}$	$2.50\ 10^{-9}$	$1.45\ 10^{-9}$	$9.10\ 10^{7}$
Am-243	$2.73\ 10^{-9}$	$2.06\ 10^{-9}$	$1.23\ 10^{-9}$	$1.10\ 10^{8}$
Cm-242	$1.68\ 10^{-10}$	$1.69\ 10^{-10}$	$1.52\ 10^{-10}$	$1.78\ 10^{9}$
Cm-243	$1.97\ 10^{-9}$	$1.51\ 10^{-9}$	$1.09\ 10^{-9}$	$1.52\ 10^{8}$
Cm-244	$1.62\ 10^{-9}$	$1.26\ 10^{-9}$	$9.40\ 10^{-10}$	$1.85\ 10^{8}$
Cm-245	$2.82\ 10^{-9}$	$2.06\ 10^{-9}$	$1.30\ 10^{-9}$	$1.06\ 10^{8}$
Cm-246	$2.79\ 10^{-9}$	$2.06\ 10^{-9}$	$1.30\ 10^{-9}$	$1.08\ 10^{8}$
Cm-248	$1.02\ 10^{-8}$	$7.62\ 10^{-9}$	$4.70\ 10^{-9}$	$2.93\ 10^{7}$

E.3.7. Exposures from leachate processing

777. The permit application involves no specific authorised radioactive liquid discharge routes. The leachate collected at the landfill is currently used at the WRP treatment facilities or sent off-site during maintenance periods. An assessment has been made of the radiological impact arising from off-site treatment of contaminated leachate at an industrial liquid waste treatment plant, at a reed-bed facility and from on-site treatment at the WRP. An EPR Radioactive Substances Permit would be required for off-site disposal of leachate containing radionuclides.

778. A GoldSim groundwater model for the whole site provides an estimate of the annual leachate from the facility and an estimate of the maximum activity concentration in the leachate; the activity concentrations are used to assess the impact of leachate treatment. The radiological assessment considers:

- the treatment of contaminated leachate at an off-site hazardous waste treatment facility followed by discharge of liquid effluent to an estuary and use of sludge from the treatment works digestors as a soil improver;
- the treatment of contaminated leachate at an off-site reed bed facility; and,
- the treatment of contaminated leachate at the WRP and placement of stabilised APCR in the Port Clarence landfill.

779. The off-site hazardous waste treatment facility assessments consider the radiation exposure of workers at the treatment facility, anglers fishing in the estuary into which the treatment works discharge and a farming family assumed to grow crops on land fertilised with sludge from the aerobic digestors. The assessment is based on the Environment Agency initial radiological assessment tool (Environment Agency, 2022a)

that has been implemented in Excel to consider all radionuclides listed in Table 6. The initial radiological assessment methodology for a sewage treatment works is used here as a proxy for a hazardous waste processing facility taking into account an appropriate total input flow rate. It is assumed that worker doses at the hazardous waste treatment facility would be similar to worker doses at a sewage treatment facility. The methodology accounts for radionuclide-specific partitioning of activity between treated sewage effluent and sewage solids.

780. The Reed Bed assessment considers contamination of the total area of the Reed Beds (49,000 m^2) and accumulation over 7 years which is the anticipated operating life of the beds. This dose assessment considers external exposure to this contaminated area as irradiation from a semi-infinite slab. The treated leachate is then discharged to the estuary via Billingham Beck. Disposal of the reed bed is not considered in this assessment but would be required to support an application for authorised discharges of leachate containing radionuclides from LLW disposals to the reed bed facility.

781. There is a waste stabilisation process at the WRP where lime and leachate are used. The ESC assesses doses to workers who may be involved in the process using leachate at the WRP. Leachate used in the lime stabilisation process is introduced to an enclosed and abated mixing system, after treatment the resultant materials are disposed of to landfill. Potential exposure occurs due to proximity to the stored leachate and during facility clean down. The leachate utilised in the treatment process will be monitored in accordance with the permit conditions prior to use in the stabilisation process, therefore any leachate with higher activity concentrations would be detected prior to removal from the cell and would not be used unwittingly in the treatment process.

782. Stabilised material is then placed in the landfill. Any impacts associated with the disposal of stabilised material in the landfill will be limited by the initial disposal of LLW because there is no additional radioactivity introduced to the landfill or increase in chemical availability. There is therefore no new radioactivity, no enhanced transfer within the environment and no impact on radiological capacity.

783. The stabilised material will be loose tipped and the approach used ensures that this material will have radionuclide concentrations below the limits proposed for loose tipping of waste. In addition, the dose rate measurements above disposed LLW will ensure that landfill workers will be protected. Augean have appropriate procedures in place to monitor activity concentrations in the leachate and the disposal process.

784. The dose criteria used in the assessment are 1 mSv y^{-1} for workers in the on-site facility and for off-site treatment the dose constraint for the public of 0.3 mSv y^{-1} is used.

E.3.7.1. Estimating activity concentrations in leachate

785. The flux of radionuclides to the treatment works (Bq y^{-1}) uses the peak leachate activity concentrations (per MBq input to the landfill) at 60 years after closure and the leachate export rate (3,778 m^3 y^{-1}) from the site. The ingrowth of daughters is modelled using GoldSim and the activity concentrations of the daughters are propagated through the model and the dose contributions summed.

Table 85 Projected leachate activity concentration and input to treatment works

Radionuclide	Leachate activity concentration (Bq m^{-3}/MBq)	Flux to treatment works (Bq y^{-1}/MBq)
H-3	5.56 10^{-1}	2.10 10^{3}
C-14	1.80 10^{-3}	6.82 10^{0}
Cl-36	3.56 10^{-1}	1.35 10^{3}
Ca-41	2.20 10^{-2}	8.32 10^{1}
Mn-54	7.21 10^{-5}	2.72 10^{-1}
Fe-55	1.61 10^{-4}	6.07 10^{-1}
Co-60	3.31 10^{-4}	1.25 10^{0}
Ni-59	6.45 10^{-4}	2.44 10^{0}
Ni-63	6.41 10^{-4}	2.42 10^{0}
Zn-65	7.56 10^{-5}	2.86 10^{-1}
Se-79	9.03 10^{-4}	3.41 10^{0}
Sr-90	3.38 10^{-3}	1.28 10^{1}
Mo-93	4.50 10^{-3}	1.70 10^{1}
Zr-93	4.41 10^{-4}	1.67 10^{0}
Nb-93m	1.16 10^{-4}	4.36 10^{-1}
Nb-94	1.21 10^{-4}	4.55 10^{-1}
Tc-99	9.84 10^{-2}	3.72 10^{2}
Ru-106	3.58 10^{-4}	1.35 10^{0}
Ag-108m	4.75 10^{-4}	1.79 10^{0}
Ag-110m	1.93 10^{-4}	7.28 10^{-1}
Cd-109	7.22 10^{-4}	2.73 10^{0}
Sb-125	2.28 10^{-3}	8.61 10^{0}
Sn-119m	5.17 10^{-5}	1.95 10^{-1}
Sn-123	2.29 10^{-5}	8.67 10^{-2}
Sn-126	1.13 10^{-4}	4.27 10^{-1}
Te-127m	6.03 10^{-5}	2.28 10^{-1}
I-129	2.54 10^{-2}	9.61 10^{1}
Ba-133	2.79 10^{-1}	1.05 10^{3}
Cs-134	1.09 10^{-4}	4.12 10^{-1}
Cs-135	1.51 10^{-4}	5.69 10^{-1}
Cs-137	1.47 10^{-4}	5.56 10^{-1}
Ce-144	6.74 10^{-5}	2.55 10^{-1}
Pm-147	3.11 10^{-4}	1.17 10^{0}
Sm-147	1.94 10^{-4}	7.34 10^{-1}
Sm-151	1.93 10^{-4}	7.29 10^{-1}
Eu-152	7.16 10^{-4}	2.70 10^{0}
Eu-154	6.95 10^{-4}	2.63 10^{0}
Eu-155	6.53 10^{-4}	2.47 10^{0}
Gd-153	1.46 10^{-4}	5.50 10^{-1}
Pb-210	8.77 10^{-5}	3.31 10^{-1}

Radionuclide	Leachate activity concentration (Bq m^{-3}/MBq)	Flux to treatment works (Bq y^{-1}/MBq)
Po-210	$1.91\ 10^{-4}$	$7.20\ 10^{-1}$
Ra-226	$7.23\ 10^{-5}$	$2.73\ 10^{-1}$
Ra-228	$6.42\ 10^{-5}$	$2.43\ 10^{-1}$
Ac-227	$1.03\ 10^{-4}$	$3.89\ 10^{-1}$
Th-228	$6.73\ 10^{-5}$	$2.54\ 10^{-1}$
Th-229	$9.52\ 10^{-5}$	$3.60\ 10^{-1}$
Th-230	$9.52\ 10^{-5}$	$3.60\ 10^{-1}$
Th-232	$9.52\ 10^{-5}$	$3.60\ 10^{-1}$
Pa-231	$9.04\ 10^{-5}$	$3.42\ 10^{-1}$
U-232	$8.94\ 10^{-4}$	$3.38\ 10^{0}$
U-233	$9.03\ 10^{-4}$	$3.41\ 10^{0}$
U-234	$9.03\ 10^{-4}$	$3.41\ 10^{0}$
U-235	$9.03\ 10^{-4}$	$3.41\ 10^{0}$
U-236	$9.03\ 10^{-4}$	$3.41\ 10^{0}$
U-238	$9.03\ 10^{-4}$	$3.41\ 10^{0}$
Np-237	$5.14\ 10^{-3}$	$1.94\ 10^{1}$
Pu-238	$2.42\ 10^{-4}$	$9.16\ 10^{-1}$
Pu-239	$2.44\ 10^{-4}$	$9.23\ 10^{-1}$
Pu-240	$2.44\ 10^{-4}$	$9.23\ 10^{-1}$
Pu-241	$2.33\ 10^{-4}$	$8.80\ 10^{-1}$
Pu-242	$2.44\ 10^{-4}$	$9.23\ 10^{-1}$
Pu-244	$2.44\ 10^{-4}$	$9.23\ 10^{-1}$
Am-241	$6.94\ 10^{-5}$	$2.62\ 10^{-1}$
Am-242m	$6.92\ 10^{-5}$	$2.62\ 10^{-1}$
Am-243	$6.96\ 10^{-5}$	$2.63\ 10^{-1}$
Cm-242	$5.23\ 10^{-6}$	$1.97\ 10^{-2}$
Cm-243	$1.90\ 10^{-5}$	$7.17\ 10^{-2}$
Cm-244	$1.87\ 10^{-5}$	$7.07\ 10^{-2}$
Cm-245	$1.94\ 10^{-5}$	$7.35\ 10^{-2}$
Cm-246	$1.94\ 10^{-5}$	$7.35\ 10^{-2}$
Cm-248	$1.94\ 10^{-5}$	$7.35\ 10^{-2}$

E.3.7.2. Assessment calculations for off-site leachate treatment

786. The pathways for exposure to radiation of the hazardous waste treatment facility worker and the sewage treatment plant worker are assumed to be similar and the dose assessment is based on the EA Initial Radiological Assessment Tool (Environment Agency, 2022a) and (Environment Agency, 2022b) for discharge to a sewage treatment plant. The default EA IRAT calculations are based on generic data and provide a cautious estimate of the radiation dose arising to various exposed groups. The EA IRAT model assumes a default volume throughput at the sewage works of 60 m^3 day^{-1}. This is based on a small sewage treatment works serving about 500 people. In contrast, the Bran Sands treatment facility has a throughput of about

$3\ 10^5\ m^3\ day^{-1}$. This means that the radionuclide activity concentrations in the discharges and sewage sludge would be substantially lower than those assumed in the default case. The facility processing hazardous leachate processes up to 9,600 $m^3\ day^{-1}$ and this lower volume is used for treatment facility workers. These values have been represented in the calculations (see equations below).

787. The list of radionuclides in EA IRAT is missing several radionuclides considered in the Port Clarence ESC and this has required the development of a suitable approach to gap fill the EA IRAT dataset for the farming and angler scenarios. For Ca-41, Ni-59, Se-79, Nb-93m, Nb-94, Zr-63, Ag-108m, Ba-133, Cs-135, Sm-147, Sm-151, Ac-227, Ra-228, Th-228, Th-229, U-232, U-233, U-236, Pu-244, Am-242m, Cm-245, Cm-246 and Cm-248 the EA IRAT dataset includes isotopes of the same element. In each case, the DPUR calculated for external, inhalation and ingestion pathways is adjusted by the ratio of the dose coefficients for the two radionuclides, for example Ca-41 is missing from IRAT, but includes Ca-45 and on the basis that the element determines environmental and biological behaviour, scaling the DPUR will provide a reasonable estimate over pathways involving short timescales.

788. There are a further 10 radionuclides where an analogue was been selected from the radionuclides listed in EA IRAT. The basis for the selection is provided in Table 86.

Table 86 Filling data gaps in EA IRAT

Missing radionuclide	Analogue used	Comment
Mo-93	Nb-95	These elements are adjacent in the periodic table.
Cd-109	Zn-65	Both elements are in Group 12 of the periodic table.
Sn-119m	I-129	Assume Iodine due to methyl Tin.
Sn-123	I-129	
Sn-126	I-129	
Te-127m	Se-75	Both elements are in Group 16 of the periodic table.
Sm-147	Ce-144	Both elements are lanthanides. Biochemical and biokinetic behaviour of all the lanthanides is very similar.
Sm-151	Ce-144	
Gd-153	Ce-144	Both elements are lanthanides. Biochemical and biokinetic behaviour of all the lanthanides is very similar
Pa-231	Th-232	Elements are adjacent actinides in the periodic table.

Treatment Facility Worker

789. Members of the exposed group are assumed to be adults working at a treatment plant and to be exposed as a result of:

- external radiation from radionuclides in raw effluent and sludge;
- inadvertent inhalation of raw effluent and sludge; and,
- inadvertent ingestion of raw effluent and sludge.

790. The EA methodology was used to produce tables of Dose Per Unit Release (DPUR; μSv y^{-1} per Bq y^{-1} discharge) that are then used to obtain doses from discharges. The assessment model is described below and plant worker characteristics are presented in Table 87. It uses leachate contamination levels derived from the GoldSim groundwater model (see Section E.4.4) and a realistic throughput for the treatment works.

Table 87 Treatment plant worker characteristics

Parameter	Value	Comment
Time at plant (h y^{-1})	2000	Standard assumption in [(Environment Agency, 2022a; Environment Agency, 2022b)].
Proportion near treatment tanks	0.25	
Dust in air from sewage/sludge (kg m^{-3})	1 10^{-7}	
Inadvertent sludge ingestion (mg h^{-1})	5	
Inhalation rate (m^3 h^{-1})	1.2	
Adopted Inhalation rate (m^3 h^{-1})	1.69	1 h of heavy (3 m^3/h), 7 h light work (1.5 m^3/h)

Note: Inhalation rate based on ICRP 66 (ICRP, 1994).

791. The radiation dose (Sv y^{-1}) incurred by an adult treatment plant worker for each radionuclide ($Dose_{Rn,worker}$) is given by:

$$Dose_{Rn,worker} = F_{Rn} \cdot DF_{Rn,worker} \cdot Dil$$

where:

- $Dose_{Rn,worker}$ is the dose to a treatment plant worker (Sv y^{-1});
- F_{Rn} is the flux of the radionuclide to the treatment works (Bq y^{-1});
- $DF_{Rn,\ worker}$ is the dose per unit flux to the given exposed group (Sv y^{-1} per Bq y^{-1}) based on default assumptions – Total DPUR calculated using EA methodology and reproduced in Table 88 (adult sewage worker); and,
- Dil is a dilution factor that is a product of the ratio of the default and actual treatment throughputs, and a factor to account for the ratio of the default and assumed inhalation rates.

Table 88 Dose per unit release factors for effluent treatment workers – leachate to treatment facility scenario (μSv/y per Bq/y of discharge to leachate) calculated using the EA IRAT methodology

Radionuclide	External irradiation DPUR (μSv/y per Bq/y)	Inadvertent ingestion and inhalation DPUR (μSv/y per Bq/y)	Total DPUR (μSv/y per Bq/y)
H-3	5.04 10^{-16}	9.16 10^{-16}	1.42 10^{-15}
C-14	4.64 10^{-13}	2.66 10^{-14}	4.91 10^{-13}
Cl-36	4.50 10^{-12}	2.77 10^{-14}	4.52 10^{-12}
Ca-41	0	3.40 10^{-14}	3.40 10^{-14}
Mn-54	1.11 10^{-9}	8.15 10^{-14}	1.11 10^{-9}
Fe-55	2.55 10^{-19}	6.89 10^{-14}	6.89 10^{-14}
Co-60	5.61 10^{-9}	7.68 10^{-13}	5.61 10^{-9}
Ni-59	1.97 10^{-14}	8.49 10^{-15}	2.82 10^{-14}

Radionuclide	External irradiation DPUR (µSv/y per Bq/y)	Inadvertent ingestion and inhalation DPUR (µSv/y per Bq/y)	Total DPUR (µSv/y per Bq/y)
Ni-63	$1.78\ 10^{-13}$	$2.12\ 10^{-14}$	$1.99\ 10^{-13}$
Zn-65	$7.96\ 10^{-10}$	$4.23\ 10^{-13}$	$7.96\ 10^{-10}$
Se-79	$1.52\ 10^{-12}$	$3.41\ 10^{-13}$	$1.86\ 10^{-12}$
Sr-90	$2.69\ 10^{-11}$	$8.50\ 10^{-13}$	$2.78\ 10^{-11}$
Mo-93	$1.82\ 10^{-14}$	$7.48\ 10^{-14}$	$9.29\ 10^{-14}$
Zr-93	$3.70\ 10^{-13}$	$3.79\ 10^{-13}$	$7.48\ 10^{-13}$
Nb-93m	$1.32\ 10^{-14}$	$1.97\ 10^{-14}$	$3.29\ 10^{-14}$
Nb-94	$2.10\ 10^{-9}$	$3.66\ 10^{-13}$	$2.10\ 10^{-9}$
Tc-99	$1.08\ 10^{-12}$	$2.54\ 10^{-14}$	$1.10\ 10^{-12}$
Ru-106	$1.07\ 10^{-10}$	$2.14\ 10^{-13}$	$1.07\ 10^{-10}$
Ag-108m	$3.64\ 10^{-9}$	$6.91\ 10^{-13}$	$3.64\ 10^{-9}$
Ag-110m	$6.47\ 10^{-9}$	$6.10\ 10^{-13}$	$6.47\ 10^{-9}$
Cd-109	$6.76\ 10^{-13}$	$5.29\ 10^{-14}$	$7.28\ 10^{-13}$
Sb-125	$8.35\ 10^{-10}$	$2.99\ 10^{-13}$	$8.35\ 10^{-10}$
Sn-119m	$4.91\ 10^{-13}$	$4.43\ 10^{-14}$	$5.36\ 10^{-13}$
Sn-123	$5.21\ 10^{-11}$	$2.48\ 10^{-13}$	$5.24\ 10^{-11}$
Sn-126	$2.61\ 10^{-9}$	$6.58\ 10^{-13}$	$2.61\ 10^{-9}$
Te-127m	$1.18\ 10^{-12}$	$2.72\ 10^{-13}$	$1.45\ 10^{-12}$
I-129	$1.49\ 10^{-12}$	$5.00\ 10^{-12}$	$6.48\ 10^{-12}$
Ba-133	$1.03\ 10^{-10}$	$4.32\ 10^{-14}$	$1.03\ 10^{-10}$
Cs-134	$1.28\ 10^{-9}$	$1.29\ 10^{-12}$	$1.28\ 10^{-9}$
Cs-135	$2.28\ 10^{-12}$	$1.52\ 10^{-13}$	$2.43\ 10^{-12}$
Cs-137	$4.65\ 10^{-10}$	$9.49\ 10^{-13}$	$4.66\ 10^{-10}$
Ce-144	$1.80\ 10^{-11}$	$7.47\ 10^{-13}$	$1.88\ 10^{-11}$
Pm-147	$2.08\ 10^{-12}$	$4.65\ 10^{-14}$	$2.13\ 10^{-12}$
Sm-147	0	$4.07\ 10^{-11}$	$4.07\ 10^{-11}$
Sm-151	$2.41\ 10^{-13}$	$2.54\ 10^{-14}$	$2.66\ 10^{-13}$
Eu-152	$1.57\ 10^{-9}$	$3.07\ 10^{-13}$	$1.57\ 10^{-9}$
Eu-154	$1.71\ 10^{-9}$	$4.13\ 10^{-13}$	$1.71\ 10^{-9}$
Eu-155	$4.10\ 10^{-11}$	$6.01\ 10^{-14}$	$4.11\ 10^{-11}$
Gd-153	$5.02\ 10^{-11}$	$3.63\ 10^{-14}$	$5.02\ 10^{-11}$
Pb-210	$5.35\ 10^{-11}$	$4.34\ 10^{-10}$	$4.87\ 10^{-10}$
Po-210	$2.20\ 10^{-14}$	$2.51\ 10^{-10}$	$2.51\ 10^{-10}$
Ra-226	$6.56\ 10^{-9}$	$3.09\ 10^{-10}$	$6.87\ 10^{-9}$
Ra-228	$3.39\ 10^{-9}$	$3.10\ 10^{-10}$	$3.70\ 10^{-9}$
Ac-227	$8.70\ 10^{-10}$	$3.97\ 10^{-9}$	$4.84\ 10^{-9}$
Th-228	$3.83\ 10^{-9}$	$3.12\ 10^{-10}$	$4.14\ 10^{-9}$
Th-229	$6.77\ 10^{-10}$	$1.81\ 10^{-9}$	$2.48\ 10^{-9}$
Th-230	$4.74\ 10^{-13}$	$6.99\ 10^{-10}$	$6.99\ 10^{-10}$
Th-232	$5.97\ 10^{-9}$	$1.32\ 10^{-9}$	$7.30\ 10^{-9}$
Pa-231	$6.49\ 10^{-11}$	$1.06\ 10^{-9}$	$1.12\ 10^{-9}$

Radionuclide	External irradiation DPUR (µSv/y per Bq/y)	Inadvertent ingestion and inhalation DPUR (µSv/y per Bq/y)	Total DPUR (µSv/y per Bq/y)
U-232	$1.35\ 10^{-9}$	$7.52\ 10^{-11}$	$1.42\ 10^{-9}$
U-233	$5.26\ 10^{-14}$	$8.83\ 10^{-12}$	$8.89\ 10^{-12}$
U-234	$2.01\ 10^{-14}$	$8.63\ 10^{-12}$	$8.65\ 10^{-12}$
U-235	$4.30\ 10^{-11}$	$7.87\ 10^{-12}$	$5.09\ 10^{-11}$
U-236	$9.95\ 10^{-15}$	$8.02\ 10^{-12}$	$8.03\ 10^{-12}$
U-238	$2.80\ 10^{-11}$	$7.51\ 10^{-12}$	$3.55\ 10^{-11}$
Np-237	$2.54\ 10^{-10}$	$1.96\ 10^{-10}$	$4.50\ 10^{-10}$
Pu-238	$2.30\ 10^{-14}$	$4.31\ 10^{-10}$	$4.31\ 10^{-10}$
Pu-239	$6.40\ 10^{-14}$	$4.70\ 10^{-10}$	$4.70\ 10^{-10}$
Pu-240	$2.38\ 10^{-14}$	$4.70\ 10^{-10}$	$4.70\ 10^{-10}$
Pu-241	$3.27\ 10^{-15}$	$8.99\ 10^{-12}$	$9.00\ 10^{-12}$
Pu-242	$1.34\ 10^{-13}$	$4.32\ 10^{-10}$	$4.32\ 10^{-10}$
Pu-244	$5.16\ 10^{-10}$	$4.32\ 10^{-10}$	$9.48\ 10^{-10}$
Am-241	$1.68\ 10^{-11}$	$6.70\ 10^{-10}$	$6.87\ 10^{-10}$
Am-242m	$4.22\ 10^{-11}$	$8.09\ 10^{-10}$	$8.51\ 10^{-10}$
Am-243	$3.64\ 10^{-10}$	$6.71\ 10^{-10}$	$1.03\ 10^{-9}$
Cm-242	$4.37\ 10^{-14}$	$3.97\ 10^{-11}$	$3.98\ 10^{-11}$
Cm-243	$2.20\ 10^{-10}$	$4.85\ 10^{-10}$	$7.05\ 10^{-10}$
Cm-244	$7.63\ 10^{-14}$	$3.98\ 10^{-10}$	$3.98\ 10^{-10}$
Cm-245	$1.48\ 10^{-10}$	$6.92\ 10^{-10}$	$8.40\ 10^{-10}$
Cm-246	$9.55\ 10^{-12}$	$6.86\ 10^{-10}$	$6.95\ 10^{-10}$
Cm-248	$3.48\ 10^{-9}$	$2.52\ 10^{-9}$	$6.00\ 10^{-9}$

792. The doses to leachate treatment facility workers are presented in Section E.3.7.3.

Farming family (soil treated with sludge)

793. Farm land is assumed to be treated repeatedly with contaminated sludge from the treatment works. The assessment of doses to a farming family using the treated land is based on the EA IRAT (Environment Agency, 2022a) and (Environment Agency, 2022b). Members of the exposed group are assumed to be adults, children and infants and the exposure pathways considered are:

- consumption of food produced on land conditioned with sludge and incorporating radionuclides, including milk, green vegetables, root vegetables and cow and sheep meat;
- external irradiation from radionuclides incorporated in surface layers of sludge conditioned soil when outdoors and when shielded indoors;
- inadvertent inhalation of contaminated dust whilst outdoors; and,
- inadvertent ingestion of contaminated soil.

794. The characteristics of the group are based on the EA methodology, with some modification to allow for more realistic rates of sludge application and food consumption.

795. The organic matter content of soil is an important part of its fertility. Farmers aim to enhance soil organic matter by reducing losses, minimising cultivations and adding organic carbon. Application of sewage sludge (commonly referred to as 'biosolids') to agricultural land is one method of maintaining soil organic matter but it is highly regulated. The application of solid or liquid sewage sludge is limited by many factors, including time of year, pH, potentially toxic element content, use of land and proximity to watercourses. It is common for the rate of application of biosolids to be limited in total to around 50 t ha^{-1} y^{-1}, equivalent to 5 kg m^{-2} y^{-1} (Defra, 2009). It is assumed that this rate also applies to sludge from the treatment facility.

796. Parameters characterising the application of treated sludge to agricultural land are summarised in Table 89. The area of land treated is not defined but is assumed to be sufficient to support food production at the levels implied by intake rates presented in Table 90.

Table 89 Parameters characterising the application of treated sludge to agricultural land: applicable during the Period of Authorisation

Parameter	Value	Comment
Rate of application of treated sludge (kg m^{-2} y^{-1})	5	Amended from the EA IRAT default value of 8 kg m^{-2} y^{-1} to comply with UK practice.
Delay between spreading sludge and animal grazing (d)	21	Standard assumption in (Environment Agency, 2022a; Environment Agency, 2022b).
Delay between spreading sludge and crop harvest (d)	304	
Density of soil (kg m^{-3})	1,250	
Transfer of strontium to next soil layer (y^{-1})	0.464	
Transfer of other radionuclides to next soil layer (y^{-1})	0.243	
Dust in air (kg m^{-3})	1 10^{-7}	

797. Habit data for the farming family are summarised in Table 90. The habit data values used in the ESC for the inhalation and external exposure pathways differ from those in the EA IRAT, except for the child and infant inhalation rates. Scaling factors (F_P) were determined by dividing the ESC value by the value used in the EA IRAT approach to derive DPUR values. This approach is applied to all parameters listed in Table 83.

798. The assessment uses the leachate contamination levels derived from the GoldSim groundwater model (see Section E.4.4) and a realistic throughput for the treatment works.

799. Consumption rates assumed for the farming family using biosolids from the treatment facility are consistent with the approach used throughout this report: the two most limiting pathways use consumption rates at the 97.5th percentile rate and mean rates are used for consumption of all other foods. The EA IRAT models adopted 97.5th percentile consumption rates for all foods and hence they use different values, see Table 90. Scaling factors for consumption (F_P) have been determined by dividing the assumed consumption rates by the EA IRAT default consumption rates and scaling is only applied to the pathways ranked third and below. The values for the mean and 97.5th percentile consumption rates are the generalised intake rates produced by the NRPB (Smith & Jones, 2003).

800. A biosolids application rate of 8 kg m^{-2} y^{-1} was used as the default value in the EA IRAT methodology and hence the results are scaled to the assumed application rate of 5 kg m^{-2} y^{-1} (F_{SAR} = 0.625) as discussed above (paragraph 795).

Table 90 Farming family habits data

Habit data	Adult			Child			Infant		
	EA IRAT basis	Mean	97.5th	EA IRAT basis	Mean	97.5th	EA IRAT basis	Mean	97.5th
Green vegetables (kg y^{-1})	80	35	80	35	15	35	15	5	15
Root vegetables (kg y^{-1})	130	60	130	95	50	95	45	15	45
Cow meat (kg y^{-1})	45	15	45	30	15	30	10	3	10
Sheep meat (kg y^{-1})	25	8	25	10	4	10	3	0.8	3
Milk (kg y^{-1})	240	95	240	240	110	240	320	130	320
Soil ingestion (inadvertent) (kg y^{-1})	7 10^{-5}	3.7 10^{-3}	8.3 10^{-3}	5.96 10^{-5}	1.1 10^{-2}	1.8 10^{-2}	7.36 10^{-5}	3.7 10^{-2}	4.4 10^{-2}
Inhalation rate (m^3 h^{-1})	0.92	1.69		0.64	0.87		0.22	0.31	
Outdoor occupancy	0.5	0.28		0.2	0.16		0.1	0.09	

Note: Adjusted inhalation rates based on ICRP 66 (ICRP, 1994), see Table 73 for derivation.

801. The radiation dose (Sv y^{-1}) incurred by a farmer for each radionuclide ($Dose_{Rn,farmer}$) is given by:

$$Dose_{Rn,farmer,P} = F_{Rn} \cdot DF_{Rn,farmer} \cdot Dil \cdot F_{SAR} \cdot F_P \cdot (1 - F_E)$$

$$Dose_{Rn,farmer} = \sum_P Dose_{Rn,farmer,P}$$

where:

- $Dose_{Rn,farmer}$ is the total dose summed over all pathways (Sv y^{-1});
- $Dose_{Rn,farmer,P}$ is the dose for the specific pathway P (Sv y^{-1});
- F_{Rn} is the flux of the radionuclide to the treatment works (Bq y^{-1}), assuming no loss during leachate treatment;
- $DF_{Rn,\ farmer}$ is the dose per unit flux to the given exposed group (Sv y^{-1} per Bq y^{-1}) using default values – as indicated in Table 91, Table 92 and Table 93 for adult, child and infant respectively from (Environment Agency, 2022b);
- Dil is a dilution factor that is given by the ratio of the assumed and actual throughputs;
- F_{SAR} is the scaling factor for the sewage application rate;

- F_P is the scaling factor for the specific pathway P, as appropriate these are the ratios relating to the change in consumption, soil ingestion, inhalation or occupancy; and,
- F_E is the fraction (Table 95) from raw sewage that is disposed in liquid effluent (the rest is disposed with biosolids).

802. The doses to each member of a farming family are presented in Section E.3.7.3.

803. The dose per unit release factors for members of the farming family (Table 91 to Table 93) for leachate release to the treatment facility scenario (μSv y^{-1} per Bq y^{-1}) are given in the EA IRAT methodology (Environment Agency, 2022b). To maintain consistency across all models only the Cow and sheep meat pathways were used for the doses associated with livestock food products.

Table 91 Dose per unit release factors for adult member of the farming family – leachate release to treatment facility scenario (µSv y^{-1} per Bq y^{-1}) given in the EA IRAT methodology

Radionuclide$	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. ingestion
H-3	0	0	$1.90\ 10^{-12}$	$7.50\ 10^{-13}$	$2.20\ 10^{-12}$	$4.90\ 10^{-13}$	$1.40\ 10^{-11}$	0	$1.10\ 10^{-17}$	$1.80\ 10^{-18}$
C-14	$1.80\ 10^{-8}$	$2.40\ 10^{-8}$	$3.30\ 10^{-9}$	$1.30\ 10^{-9}$	$3.70\ 10^{-9}$	$8.30\ 10^{-10}$	$9.70\ 10^{-9}$	0	$1.40\ 10^{-13}$	$6.70\ 10^{-15}$
Cl-36	$5.10\ 10^{-8}$	$6.90\ 10^{-8}$	$5.40\ 10^{-8}$	$2.90\ 10^{-8}$	$8.20\ 10^{-8}$	$1.80\ 10^{-8}$	$8.80\ 10^{-8}$	$9.30\ 10^{-11}$	$7.10\ 10^{-13}$	$1.60\ 10^{-14}$
Ca-41	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Mn-54	$2.10\ 10^{-10}$	$3.30\ 10^{-10}$	$5.30\ 10^{-10}$	$4.60\ 10^{-8}$	$5.10\ 10^{-10}$	$3.70\ 10^{-8}$	$2.00\ 10^{-10}$	$3.40\ 10^{-7}$	$7.00\ 10^{-14}$	$5.70\ 10^{-15}$
Fe-55	$2.90\ 10^{-10}$	$2.00\ 10^{-12}$	$1.30\ 10^{-11}$	$1.50\ 10^{-10}$	$1.80\ 10^{-10}$	$1.20\ 10^{-8}$	$9.80\ 10^{-12}$	$2.80\ 10^{-12}$	$4.70\ 10^{-14}$	$7.00\ 10^{-15}$
Co-60	$3.10\ 10^{-9}$	$4.50\ 10^{-9}$	$1.90\ 10^{-9}$	$6.20\ 10^{-8}$	$8.70\ 10^{-10}$	$4.50\ 10^{-8}$	$1.40\ 10^{-9}$	$4.10\ 10^{-6}$	$2.30\ 10^{-12}$	$1.30\ 10^{-13}$
Ni-59	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ni-63	$1.30\ 10^{-9}$	$5.00\ 10^{-10}$	$2.20\ 10^{-13}$	$8.80\ 10^{-13}$	$1.60\ 10^{-12}$	$3.50\ 10^{-12}$	$2.50\ 10^{-9}$	0	$5.00\ 10^{-13}$	$2.70\ 10^{-14}$
Zn-65	$2.60\ 10^{-10}$	$8.60\ 10^{-11}$	$6.20\ 10^{-10}$	$1.10\ 10^{-10}$	$4.30\ 10^{-8}$	$1.20\ 10^{-10}$	$9.20\ 10^{-9}$	$1.90\ 10^{-8}$	$6.00\ 10^{-15}$	$2.50\ 10^{-15}$
Se-79	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sr-90	$1.50\ 10^{-7}$	$2.50\ 10^{-7}$	$1.20\ 10^{-8}$	$4.90\ 10^{-9}$	$3.90\ 10^{-8}$	$8.80\ 10^{-9}$	$9.80\ 10^{-7}$	$2.00\ 10^{-14}$	$1.20\ 10^{-11}$	$1.60\ 10^{-12}$
Mo-93	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Zr-93	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Nb-93m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Nb-94	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Tc-99	$8.50\ 10^{-8}$	$8.70\ 10^{-8}$	$1.30\ 10^{-6}$	$1.50\ 10^{-6}$	$7.10\ 10^{-8}$	$6.30\ 10^{-8}$	$3.80\ 10^{-7}$	0	$1.90\ 10^{-13}$	$5.10\ 10^{-15}$
Ru-106	$1.50\ 10^{-10}$	$1.10\ 10^{-11}$	$1.60\ 10^{-11}$	$3.00\ 10^{-11}$	$2.30\ 10^{-10}$	$1.60\ 10^{-11}$	$6.60\ 10^{-12}$	$1.00\ 10^{-8}$	$1.50\ 10^{-13}$	$6.50\ 10^{-15}$
Ag-108m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ag-110m	$3.30\ 10^{-10}$	$3.10\ 10^{-12}$	$8.10\ 10^{-11}$	$2.00\ 10^{-7}$	$2.40\ 10^{-9}$	$2.20\ 10^{-7}$	$4.50\ 10^{-7}$	$8.60\ 10^{-7}$	$2.60\ 10^{-13}$	$1.70\ 10^{-14}$
Cd-109	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Radionuclide$	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. ingestion
Sb-125	$3.10\ 10^{-11}$	$4.80\ 10^{-13}$	$5.40\ 10^{-11}$	$2.10\ 10^{-9}$	$4.30\ 10^{-11}$	$8.00\ 10^{-10}$	$7.60\ 10^{-12}$	$5.00\ 10^{-8}$	$6.60\ 10^{-14}$	$2.60\ 10^{-15}$
Sn-119m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sn-123	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sn-126	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Te-127m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
I-129	$1.30\ 10^{-7}$	$2.00\ 10^{-7}$	$8.80\ 10^{-8}$	$3.50\ 10^{-8}$	$2.70\ 10^{-8}$	$6.10\ 10^{-9}$	$2.10\ 10^{-7}$	$3.20\ 10^{-9}$	$1.00\ 10^{-11}$	$5.30\ 10^{-12}$
Ba-133	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cs-134	$7.20\ 10^{-10}$	$1.10\ 10^{-9}$	$2.60\ 10^{-8}$	$1.00\ 10^{-8}$	$2.60\ 10^{-8}$	$5.70\ 10^{-9}$	$2.70\ 10^{-8}$	$1.40\ 10^{-7}$	$7.00\ 10^{-14}$	$3.40\ 10^{-14}$
Cs-135	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cs-137	$1.80\ 10^{-9}$	$4.40\ 10^{-9}$	$3.20\ 10^{-8}$	$1.30\ 10^{-8}$	$2.70\ 10^{-8}$	$6.10\ 10^{-9}$	$2.80\ 10^{-8}$	$2.60\ 10^{-7}$	$3.90\ 10^{-13}$	$1.90\ 10^{-13}$
Ce-144	$3.80\ 10^{-10}$	$1.50\ 10^{-11}$	$1.40\ 10^{-12}$	$4.60\ 10^{-9}$	$1.20\ 10^{-10}$	$5.50\ 10^{-9}$	$2.10\ 10^{-10}$	$9.10\ 10^{-9}$	$7.90\ 10^{-13}$	$2.00\ 10^{-14}$
Pm-147	$7.30\ 10^{-11}$	$3.20\ 10^{-11}$	$1.50\ 10^{-11}$	$3.60\ 10^{-11}$	$1.90\ 10^{-11}$	$3.40\ 10^{-11}$	$3.00\ 10^{-12}$	$1.90\ 10^{-12}$	$3.30\ 10^{-13}$	$3.00\ 10^{-15}$
Sm-147	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sm-151	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Eu-152	$4.20\ 10^{-10}$	$3.40\ 10^{-10}$	$1.60\ 10^{-10}$	$3.90\ 10^{-10}$	$3.10\ 10^{-10}$	$5.60\ 10^{-10}$	$2.80\ 10^{-11}$	$1.80\ 10^{-6}$	$1.20\ 10^{-11}$	$6.70\ 10^{-14}$
Eu-154	$5.10\ 10^{-10}$	$3.30\ 10^{-10}$	$2.10\ 10^{-10}$	$5.00\ 10^{-10}$	$3.70\ 10^{-10}$	$6.50\ 10^{-10}$	$3.60\ 10^{-11}$	$1.60\ 10^{-6}$	$1.00\ 10^{-11}$	$6.70\ 10^{-14}$
Eu-155	$6.40\ 10^{-11}$	$3.00\ 10^{-11}$	$2.70\ 10^{-11}$	$6.40\ 10^{-11}$	$4.10\ 10^{-11}$	$7.30\ 10^{-11}$	$4.70\ 10^{-12}$	$3.80\ 10^{-8}$	$8.10\ 10^{-13}$	$6.50\ 10^{-15}$
Gd-153	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Pb-210	$9.10\ 10^{-7}$	$4.20\ 10^{-7}$	$7.80\ 10^{-7}$	$8.80\ 10^{-7}$	$1.90\ 10^{-6}$	$1.20\ 10^{-6}$	$3.20\ 10^{-6}$	$2.30\ 10^{-9}$	$7.40\ 10^{-10}$	$7.90\ 10^{-11}$
Po-210	$7.90\ 10^{-8}$	$8.00\ 10^{-8}$	$7.20\ 10^{-7}$	$3.50\ 10^{-6}$	$4.30\ 10^{-7}$	$2.60\ 10^{-6}$	$2.10\ 10^{-7}$	$1.50\ 10^{-12}$	$6.40\ 10^{-11}$	$4.00\ 10^{-12}$
Ra-226	$3.90\ 10^{-7}$	$8.50\ 10^{-7}$	$1.60\ 10^{-7}$	$6.40\ 10^{-8}$	$7.30\ 10^{-7}$	$4.70\ 10^{-8}$	$8.80\ 10^{-7}$	$5.40\ 10^{-6}$	$2.40\ 10^{-9}$	$3.20\ 10^{-11}$
Ra-228	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ac-227	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Th-228	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Radionuclide[$]	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. ingestion
Th-229	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Th-230	6.90 10^{-8}	1.30 10^{-8}	1.00 10^{-8}	4.20 10^{-8}	7.10 10^{-8}	6.90 10^{-8}	1.20 10^{-8}	9.80 10^{-6}	1.80 10^{-8}	4.50 10^{-11}
Th-232	7.60 10^{-8}	1.50 10^{-8}	1.10 10^{-8}	4.50 10^{-8}	7.80 10^{-8}	7.50 10^{-8}	1.40 10^{-8}	6.90 10^{-6}	3.10 10^{-8}	5.00 10^{-11}
Pa-231	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U-232	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U-233	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U-234	4.30 10^{-9}	3.70 10^{-9}	1.30 10^{-9}	5.40 10^{-10}	2.40 10^{-9}	2.70 10^{-10}	6.00 10^{-8}	8.10 10^{-9}	4.90 10^{-10}	1.20 10^{-12}
U-235	4.10 10^{-9}	3.50 10^{-9}	1.30 10^{-9}	5.20 10^{-10}	2.30 10^{-9}	2.60 10^{-10}	5.70 10^{-8}	8.20 10^{-8}	4.30 10^{-10}	1.10 10^{-12}
U-236	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U-238	3.90 10^{-9}	3.40 10^{-9}	1.20 10^{-9}	4.90 10^{-10}	2.20 10^{-9}	2.50 10^{-10}	5.50 10^{-8}	1.30 10^{-8}	4.10 10^{-10}	1.10 10^{-12}
Np-237	1.20 10^{-8}	2.10 10^{-8}	7.80 10^{-10}	2.20 10^{-8}	2.40 10^{-9}	6.50 10^{-8}	2.30 10^{-10}	1.20 10^{-7}	3.20 10^{-9}	2.60 10^{-12}
Pu-238	7.60 10^{-9}	6.60 10^{-10}	8.10 10^{-10}	2.30 10^{-8}	9.30 10^{-10}	2.50 10^{-8}	8.90 10^{-11}	6.60 10^{-11}	5.40 10^{-9}	4.60 10^{-12}
Pu-239	8.40 10^{-9}	8.60 10^{-10}	9.10 10^{-10}	2.60 10^{-8}	1.10 10^{-9}	2.90 10^{-8}	1.00 10^{-10}	8.20 10^{-8}	7.00 10^{-9}	6.00 10^{-12}
Pu-240	8.40 10^{-9}	8.60 10^{-10}	9.10 10^{-10}	2.60 10^{-8}	1.10 10^{-9}	2.90 10^{-8}	1.00 10^{-10}	4.70 10^{-11}	7.00 10^{-9}	6.00 10^{-12}
Pu-241	1.50 10^{-10}	6.40 10^{-12}	1.40 10^{-11}	4.00 10^{-10}	1.50 10^{-11}	4.00 10^{-10}	1.40 10^{-12}	5.50 10^{-9}	5.00 10^{-11}	4.60 10^{-14}
Pu-242	8.10 10^{-9}	8.20 10^{-10}	8.70 10^{-10}	2.50 10^{-8}	1.00 10^{-9}	2.80 10^{-8}	9.90 10^{-11}	1.30 10^{-8}	6.70 10^{-9}	5.80 10^{-12}
Pu-244	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Am-241	3.40 10^{-8}	5.50 10^{-9}	5.50 10^{-9}	1.60 10^{-7}	1.30 10^{-8}	3.60 10^{-7}	1.30 10^{-9}	6.10 10^{-7}	2.80 10^{-8}	2.30 10^{-11}
Am-242m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Am-243	3.40 10^{-8}	5.70 10^{-9}	5.50 10^{-9}	1.60 10^{-7}	1.40 10^{-8}	3.70 10^{-7}	1.30 10^{-9}	4.90 10^{-7}	2.90 10^{-8}	2.40 10^{-11}
Cm-242	8.20 10^{-10}	2.90 10^{-12}	2.90 10^{-11}	8.30 10^{-10}	1.70 10^{-11}	4.60 10^{-10}	1.70 10^{-12}	1.70 10^{-10}	1.20 10^{-10}	4.70 10^{-14}
Cm-243	4.60 10^{-8}	5.90 10^{-9}	4.40 10^{-9}	1.30 10^{-7}	5.00 10^{-9}	1.30 10^{-7}	4.80 10^{-10}	1.30 10^{-6}	2.30 10^{-8}	1.90 10^{-11}
Cm-244	3.60 10^{-8}	3.70 10^{-9}	3.30 10^{-9}	9.50 10^{-8}	3.60 10^{-9}	9.80 10^{-8}	3.50 10^{-10}	8.70 10^{-10}	1.60 10^{-8}	1.20 10^{-11}
Cm-245	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Radionuclide$	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. ingestion
Cm-246	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cm-248	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Note: $ Radionuclides that are not considered in EA IRAT are shown with no data (nd).

Table 92 Dose per unit release factors for child member of the farming family – leachate release to treatment facility scenario (μSv y^{-1} per Bq y^{-1}) given in the EA IRAT methodology

Radionuclide$	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. Ingestion
H-3	0	0	$9.50\ 10^{-13}$	$4.80\ 10^{-13}$	$1.90\ 10^{-12}$	$3.10\ 10^{-13}$	$1.70\ 10^{-11}$	0	$3.80\ 10^{-18}$	$2.00\ 10^{-18}$
C-14	$1.10\ 10^{-8}$	$2.40\ 10^{-8}$	$1.80\ 10^{-9}$	$9.10\ 10^{-10}$	$3.40\ 10^{-9}$	$5.70\ 10^{-10}$	$1.30\ 10^{-8}$	0	$5.30\ 10^{-14}$	$8.10\ 10^{-15}$
Cl-36	$4.50\ 10^{-8}$	$1.00\ 10^{-7}$	$4.40\ 10^{-8}$	$3.00\ 10^{-8}$	$1.10\ 10^{-7}$	$1.90\ 10^{-8}$	$1.80\ 10^{-7}$	$4.70\ 10^{-11}$	$2.70\ 10^{-13}$	$2.80\ 10^{-14}$
Ca-41	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Mn-54	$1.70\ 10^{-10}$	$4.40\ 10^{-10}$	$3.90\ 10^{-10}$	$4.30\ 10^{-8}$	$6.20\ 10^{-10}$	$3.40\ 10^{-8}$	$3.70\ 10^{-10}$	$1.70\ 10^{-7}$	$3.10\ 10^{-14}$	$9.10\ 10^{-15}$
Fe-55	$4.20\ 10^{-10}$	$4.90\ 10^{-12}$	$1.70\ 10^{-11}$	$2.50\ 10^{-10}$	$4.00\ 10^{-10}$	$1.90\ 10^{-8}$	$3.30\ 10^{-11}$	$1.40\ 10^{-12}$	$2.10\ 10^{-14}$	$2.00\ 10^{-14}$
Co-60	$4.30\ 10^{-9}$	$1.10\ 10^{-8}$	$2.40\ 10^{-9}$	$1.00\ 10^{-7}$	$1.90\ 10^{-9}$	$7.20\ 10^{-8}$	$4.60\ 10^{-9}$	$2.10\ 10^{-6}$	$9.40\ 10^{-13}$	$3.70\ 10^{-13}$
Ni-59	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ni-63	$1.00\ 10^{-9}$	$6.80\ 10^{-10}$	$1.60\ 10^{-13}$	$8.20\ 10^{-13}$	$2.00\ 10^{-12}$	$3.30\ 10^{-12}$	$4.70\ 10^{-9}$	0	$2.00\ 10^{-13}$	$4.40\ 10^{-14}$
Zn-65	$1.90\ 10^{-10}$	$1.00\ 10^{-10}$	$4.10\ 10^{-10}$	$9.00\ 10^{-11}$	$4.70\ 10^{-8}$	$9.80\ 10^{-11}$	$1.50\ 10^{-8}$	$9.80\ 10^{-9}$	$2.50\ 10^{-15}$	$3.60\ 10^{-15}$
Se-79	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sr-90	$1.40\ 10^{-7}$	$4.00\ 10^{-7}$	$1.10\ 10^{-8}$	$5.30\ 10^{-9}$	$5.60\ 10^{-8}$	$9.40\ 10^{-9}$	$2.10\ 10^{-6}$	$1.00\ 10^{-14}$	$4.80\ 10^{-12}$	$3.00\ 10^{-12}$
Mo-93	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Zr-93	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Radionuclide$	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. Ingestion
Nb-93m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Nb-94	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Tc-99	7.60 10^{-8}	1.30 10^{-7}	1.00 10^{-6}	1.60 10^{-6}	9.60 10^{-8}	6.40 10^{-8}	7.70 10^{-7}	0	7.40 10^{-14}	9.00 10^{-15}
Ru-106	1.40 10^{-10}	1.70 10^{-11}	1.40 10^{-11}	3.20 10^{-11}	3.30 10^{-10}	1.70 10^{-11}	1.40 10^{-11}	5.20 10^{-9}	6.20 10^{-14}	1.20 10^{-14}
Ag-108m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ag-110m	2.70 10^{-10}	4.20 10^{-12}	6.00 10^{-11}	1.90 10^{-7}	3.00 10^{-9}	2.00 10^{-7}	8.40 10^{-7}	4.40 10^{-7}	1.20 10^{-13}	2.70 10^{-14}
Cd-109	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sb-125	2.60 10^{-11}	6.70 10^{-13}	4.10 10^{-11}	2.00 10^{-9}	5.50 10^{-11}	7.70 10^{-10}	1.40 10^{-11}	2.50 10^{-8}	2.60 10^{-14}	4.30 10^{-15}
Sn-119m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sn-123	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sn-126	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Te-127m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
I-129	9.70 10^{-8}	2.60 10^{-7}	6.10 10^{-8}	3.00 10^{-8}	3.10 10^{-8}	5.20 10^{-9}	3.70 10^{-7}	1.70 10^{-9}	5.20 10^{-12}	7.90 10^{-12}
Ba-133	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cs-134	2.30 10^{-10}	5.90 10^{-10}	7.60 10^{-9}	3.80 10^{-9}	1.30 10^{-8}	2.10 10^{-9}	2.00 10^{-8}	7.30 10^{-8}	1.60 10^{-14}	2.20 10^{-14}
Cs-135	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cs-137	6.20 10^{-10}	2.50 10^{-9}	9.90 10^{-9}	5.00 10^{-9}	1.40 10^{-8}	2.30 10^{-9}	2.20 10^{-8}	1.30 10^{-7}	8.60 10^{-14}	1.20 10^{-13}
Ce-144	3.50 10^{-10}	2.40 10^{-11}	1.20 10^{-12}	4.90 10^{-9}	1.70 10^{-10}	5.80 10^{-9}	4.50 10^{-10}	4.60 10^{-9}	3.40 10^{-13}	3.60 10^{-14}
Pm-147	7.00 10^{-11}	5.20 10^{-11}	1.30 10^{-11}	3.90 10^{-11}	2.80 10^{-11}	3.80 10^{-11}	6.50 10^{-12}	9.60 10^{-13}	1.30 10^{-13}	5.70 10^{-15}
Sm-147	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sm-151	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Eu-152	3.50 10^{-10}	4.60 10^{-10}	1.20 10^{-10}	3.60 10^{-10}	3.90 10^{-10}	5.20 10^{-10}	5.20 10^{-11}	9.20 10^{-7}	3.80 10^{-12}	1.10 10^{-13}
Eu-154	4.50 10^{-10}	5.00 10^{-10}	1.70 10^{-10}	5.10 10^{-10}	5.00 10^{-10}	6.70 10^{-10}	7.30 10^{-11}	8.00 10^{-7}	3.50 10^{-12}	1.20 10^{-13}
Eu-155	5.90 10^{-11}	4.60 10^{-11}	2.30 10^{-11}	6.80 10^{-11}	5.80 10^{-11}	7.70 10^{-11}	1.00 10^{-11}	1.90 10^{-8}	3.00 10^{-13}	1.20 10^{-14}

Radionuclide$	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. Ingestion
Gd-153	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Pb-210	$1.10\ 10^{-6}$	$8.50\ 10^{-7}$	$8.60\ 10^{-7}$	$1.20\ 10^{-6}$	$3.40\ 10^{-6}$	$1.60\ 10^{-6}$	$8.90\ 10^{-6}$	$1.20\ 10^{-9}$	$2.80\ 10^{-10}$	$1.90\ 10^{-10}$
Po-210	$7.50\ 10^{-8}$	$1.30\ 10^{-7}$	$6.30\ 10^{-7}$	$3.80\ 10^{-6}$	$6.30\ 10^{-7}$	$2.80\ 10^{-6}$	$4.50\ 10^{-7}$	$7.50\ 10^{-13}$	$2.50\ 10^{-11}$	$7.50\ 10^{-12}$
Ra-226	$4.90\ 10^{-7}$	$1.80\ 10^{-6}$	$1.80\ 10^{-7}$	$9.20\ 10^{-8}$	$1.40\ 10^{-6}$	$6.80\ 10^{-8}$	$2.50\ 10^{-6}$	$2.80\ 10^{-6}$	$9.20\ 10^{-10}$	$8.00\ 10^{-11}$
Ra-228	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ac-227	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Th-228	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Th-229	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Th-230	$3.50\ 10^{-8}$	$1.10\ 10^{-8}$	$4.70\ 10^{-9}$	$2.40\ 10^{-8}$	$5.40\ 10^{-8}$	$3.90\ 10^{-8}$	$1.40\ 10^{-8}$	$5.00\ 10^{-6}$	$5.60\ 10^{-9}$	$4.50\ 10^{-11}$
Th-232	$4.20\ 10^{-8}$	$1.30\ 10^{-8}$	$5.70\ 10^{-9}$	$2.90\ 10^{-8}$	$6.50\ 10^{-8}$	$4.70\ 10^{-8}$	$1.70\ 10^{-8}$	$3.50\ 10^{-6}$	$9.10\ 10^{-9}$	$5.40\ 10^{-11}$
Pa-231	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U-232	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U-233	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U-234	$2.80\ 10^{-9}$	$4.00\ 10^{-9}$	$8.10\ 10^{-10}$	$4.10\ 10^{-10}$	$2.40\ 10^{-9}$	$2.10\ 10^{-10}$	$9.00\ 10^{-8}$	$4.10\ 10^{-9}$	$1.90\ 10^{-10}$	$1.50\ 10^{-12}$
U-235	$2.70\ 10^{-9}$	$3.90\ 10^{-9}$	$7.80\ 10^{-10}$	$3.90\ 10^{-10}$	$2.30\ 10^{-9}$	$2.00\ 10^{-10}$	$8.70\ 10^{-8}$	$4.20\ 10^{-8}$	$1.70\ 10^{-10}$	$1.50\ 10^{-12}$
U-236	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U-238	$2.60\ 10^{-9}$	$3.70\ 10^{-9}$	$7.50\ 10^{-10}$	$3.70\ 10^{-10}$	$2.20\ 10^{-9}$	$1.90\ 10^{-10}$	$8.30\ 10^{-8}$	$6.60\ 10^{-9}$	$1.60\ 10^{-10}$	$1.40\ 10^{-12}$
Np-237	$5.10\ 10^{-9}$	$1.60\ 10^{-8}$	$3.10\ 10^{-10}$	$1.10\ 10^{-8}$	$1.60\ 10^{-9}$	$3.20\ 10^{-8}$	$2.30\ 10^{-10}$	$6.00\ 10^{-8}$	$8.60\ 10^{-10}$	$2.30\ 10^{-12}$
Pu-238	$3.50\ 10^{-9}$	$5.00\ 10^{-10}$	$3.40\ 10^{-10}$	$1.20\ 10^{-8}$	$6.50\ 10^{-10}$	$1.30\ 10^{-8}$	$9.30\ 10^{-11}$	$3.30\ 10^{-11}$	$1.40\ 10^{-9}$	$4.20\ 10^{-12}$
Pu-239	$4.00\ 10^{-9}$	$6.80\ 10^{-10}$	$3.90\ 10^{-10}$	$1.40\ 10^{-8}$	$7.70\ 10^{-10}$	$1.60\ 10^{-8}$	$1.10\ 10^{-10}$	$4.20\ 10^{-8}$	$1.90\ 10^{-9}$	$5.60\ 10^{-12}$
Pu-240	$4.00\ 10^{-9}$	$6.80\ 10^{-10}$	$3.90\ 10^{-10}$	$1.40\ 10^{-8}$	$7.70\ 10^{-10}$	$1.60\ 10^{-8}$	$1.10\ 10^{-10}$	$2.40\ 10^{-11}$	$1.90\ 10^{-9}$	$5.60\ 10^{-12}$
Pu-241	$7.00\ 10^{-11}$	$4.90\ 10^{-12}$	$6.00\ 10^{-12}$	$2.10\ 10^{-10}$	$1.00\ 10^{-11}$	$2.10\ 10^{-10}$	$1.50\ 10^{-12}$	$2.80\ 10^{-9}$	$1.30\ 10^{-11}$	$4.20\ 10^{-14}$
Pu-242	$3.80\ 10^{-9}$	$6.50\ 10^{-10}$	$3.80\ 10^{-10}$	$1.40\ 10^{-8}$	$7.40\ 10^{-10}$	$1.50\ 10^{-8}$	$1.10\ 10^{-10}$	$6.80\ 10^{-9}$	$1.80\ 10^{-9}$	$5.40\ 10^{-12}$
Pu-244	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Radionuclide$	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. Ingestion
Am-241	1.60 10^{-8}	4.40 10^{-9}	2.40 10^{-9}	8.60 10^{-8}	9.70 10^{-9}	2.00 10^{-7}	1.40 10^{-9}	3.10 10^{-7}	7.50 10^{-9}	2.20 10^{-11}
Am-242m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Am-243	1.70 10^{-8}	4.60 10^{-9}	2.40 10^{-9}	8.70 10^{-8}	1.00 10^{-8}	2.00 10^{-7}	1.40 10^{-9}	2.50 10^{-7}	7.80 10^{-9}	2.30 10^{-11}
Cm-242	7.20 10^{-10}	4.20 10^{-12}	2.40 10^{-11}	8.30 10^{-10}	2.30 10^{-11}	4.60 10^{-10}	3.30 10^{-12}	8.70 10^{-11}	4.60 10^{-11}	8.10 10^{-14}
Cm-243	2.20 10^{-8}	4.60 10^{-9}	1.90 10^{-9}	6.70 10^{-8}	3.50 10^{-9}	7.20 10^{-8}	5.10 10^{-10}	6.60 10^{-7}	6.50 10^{-9}	1.80 10^{-11}
Cm-244	1.80 10^{-8}	3.10 10^{-9}	1.60 10^{-9}	5.60 10^{-8}	2.80 10^{-9}	5.70 10^{-8}	4.00 10^{-10}	4.40 10^{-10}	4.40 10^{-9}	1.20 10^{-11}
Cm-245	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cm-246	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cm-248	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Note: $ Radionuclides that are not considered in EA IRAT are shown with no data (nd).

Table 93 Dose per unit release factors for infant member of the farming family – leachate release to treatment facility scenario (μSv y^{-1} per Bq y^{-1}) given in the EA IRAT methodology

Radionuclide$	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. Ingestion
H-3	0	0	6.00 10^{-13}	5.50 10^{-13}	1.30 10^{-12}	3.60 10^{-13}	4.80 10^{-11}	0	1.40 10^{-18}	5.20 10^{-18}
C-14	9.40 10^{-9}	2.30 10^{-8}	1.10 10^{-9}	1.00 10^{-9}	2.30 10^{-9}	6.30 10^{-10}	3.60 10^{-8}	0	2.10 10^{-14}	2.00 10^{-14}
Cl-36	6.40 10^{-8}	1.60 10^{-7}	4.40 10^{-8}	5.40 10^{-8}	1.20 10^{-7}	3.40 10^{-8}	7.90 10^{-7}	3.20 10^{-11}	1.20 10^{-13}	1.10 10^{-13}
Ca-41	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Mn-54	1.70 10^{-10}	5.00 10^{-10}	2.80 10^{-10}	5.60 10^{-8}	4.90 10^{-10}	4.50 10^{-8}	1.20 10^{-9}	1.20 10^{-7}	1.40 10^{-14}	2.60 10^{-14}
Fe-55	3.90 10^{-10}	5.00 10^{-12}	1.10 10^{-11}	3.00 10^{-10}	2.90 10^{-10}	2.30 10^{-8}	9.50 10^{-11}	9.70 10^{-13}	8.30 10^{-15}	5.40 10^{-14}

Radionuclide$	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. Ingestion
Co-60	$4.50\ 10^{-9}$	$1.20\ 10^{-8}$	$1.80\ 10^{-9}$	$1.30\ 10^{-7}$	$1.50\ 10^{-9}$	$9.80\ 10^{-8}$	$1.50\ 10^{-8}$	$1.40\ 10^{-6}$	$3.70\ 10^{-13}$	$1.10\ 10^{-12}$
Ni-59	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ni-63	$1.30\ 10^{-9}$	$9.70\ 10^{-10}$	$1.50\ 10^{-13}$	$1.40\ 10^{-12}$	$2.00\ 10^{-12}$	$5.50\ 10^{-12}$	$1.90\ 10^{-8}$	0	$9.50\ 10^{-14}$	$1.60\ 10^{-13}$
Zn-65	$2.00\ 10^{-10}$	$1.20\ 10^{-10}$	$3.00\ 10^{-10}$	$1.20\ 10^{-10}$	$3.90\ 10^{-8}$	$1.30\ 10^{-10}$	$5.00\ 10^{-8}$	$6.70\ 10^{-9}$	$1.20\ 10^{-15}$	$1.10\ 10^{-14}$
Se-79	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sr-90	$7.50\ 10^{-8}$	$2.30\ 10^{-7}$	$3.80\ 10^{-9}$	$3.50\ 10^{-9}$	$2.30\ 10^{-8}$	$6.30\ 10^{-9}$	$3.40\ 10^{-6}$	$7.00\ 10^{-15}$	$1.80\ 10^{-12}$	$4.50\ 10^{-12}$
Mo-93	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Zr-93	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Nb-93m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Nb-94	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Tc-99	$1.20\ 10^{-7}$	$2.30\ 10^{-7}$	$1.20\ 10^{-6}$	$3.20\ 10^{-6}$	$1.20\ 10^{-7}$	$1.30\ 10^{-7}$	$3.80\ 10^{-6}$	0	$2.90\ 10^{-14}$	$4.10\ 10^{-14}$
Ru-106	$2.00\ 10^{-10}$	$2.60\ 10^{-11}$	$1.30\ 10^{-11}$	$5.80\ 10^{-11}$	$3.60\ 10^{-10}$	$3.00\ 10^{-11}$	$6.10\ 10^{-11}$	$3.50\ 10^{-9}$	$2.90\ 10^{-14}$	$4.80\ 10^{-14}$
Ag-108m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ag-110m	$3.10\ 10^{-10}$	$5.30\ 10^{-12}$	$4.90\ 10^{-11}$	$2.80\ 10^{-7}$	$2.70\ 10^{-9}$	$3.00\ 10^{-7}$	$3.00\ 10^{-6}$	$3.00\ 10^{-7}$	$4.70\ 10^{-14}$	$8.90\ 10^{-14}$
Cd-109	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sb-125	$3.30\ 10^{-11}$	$9.20\ 10^{-13}$	$3.60\ 10^{-11}$	$3.30\ 10^{-9}$	$5.30\ 10^{-11}$	$1.20\ 10^{-9}$	$5.60\ 10^{-11}$	$1.70\ 10^{-8}$	$1.10\ 10^{-14}$	$1.50\ 10^{-14}$
Sn-119m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sn-123	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sn-126	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Te-127m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
I-129	$4.80\ 10^{-8}$	$1.40\ 10^{-7}$	$2.10\ 10^{-8}$	$1.90\ 10^{-8}$	$1.20\ 10^{-8}$	$3.30\ 10^{-9}$	$5.70\ 10^{-7}$	$1.10\ 10^{-9}$	$1.20\ 10^{-12}$	$1.10\ 10^{-11}$
Ba-133	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cs-134	$1.10\ 10^{-10}$	$3.20\ 10^{-10}$	$2.60\ 10^{-9}$	$2.40\ 10^{-9}$	$4.80\ 10^{-9}$	$1.30\ 10^{-9}$	$3.10\ 10^{-8}$	$4.90\ 10^{-8}$	$3.70\ 10^{-15}$	$3.10\ 10^{-14}$
Cs-135	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Radionuclide[$]	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. Ingestion
Cs-137	$3.20\ 10^{-10}$	$1.40\ 10^{-9}$	$3.60\ 10^{-9}$	$3.30\ 10^{-9}$	$5.60\ 10^{-9}$	$1.50\ 10^{-9}$	$3.50\ 10^{-8}$	$9.10\ 10^{-8}$	$2.20\ 10^{-14}$	$1.80\ 10^{-13}$
Ce-144	$5.30\ 10^{-10}$	$4.00\ 10^{-11}$	$1.30\ 10^{-12}$	$9.60\ 10^{-9}$	$2.00\ 10^{-10}$	$1.10\ 10^{-8}$	$2.10\ 10^{-9}$	$3.10\ 10^{-9}$	$1.70\ 10^{-13}$	$1.60\ 10^{-13}$
Pm-147	$1.00\ 10^{-10}$	$8.20\ 10^{-11}$	$1.30\ 10^{-11}$	$7.20\ 10^{-11}$	$3.10\ 10^{-11}$	$6.90\ 10^{-11}$	$2.90\ 10^{-11}$	$6.50\ 10^{-13}$	$5.70\ 10^{-14}$	$2.30\ 10^{-14}$
Sm-147	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sm-151	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Eu-152	$4.20\ 10^{-10}$	$6.10\ 10^{-10}$	$1.00\ 10^{-10}$	$5.70\ 10^{-10}$	$3.70\ 10^{-10}$	$8.10\ 10^{-10}$	$2.00\ 10^{-10}$	$6.30\ 10^{-7}$	$1.30\ 10^{-12}$	$3.80\ 10^{-13}$
Eu-154	$5.70\ 10^{-10}$	$6.90\ 10^{-10}$	$1.50\ 10^{-10}$	$8.30\ 10^{-10}$	$4.90\ 10^{-10}$	$1.10\ 10^{-9}$	$2.90\ 10^{-10}$	$5.40\ 10^{-7}$	$1.40\ 10^{-12}$	$4.30\ 10^{-13}$
Eu-155	$8.20\ 10^{-11}$	$7.10\ 10^{-11}$	$2.20\ 10^{-11}$	$1.20\ 10^{-10}$	$6.30\ 10^{-11}$	$1.40\ 10^{-10}$	$4.30\ 10^{-11}$	$1.30\ 10^{-8}$	$1.30\ 10^{-13}$	$4.70\ 10^{-14}$
Gd-153	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Pb-210	$8.90\ 10^{-7}$	$7.60\ 10^{-7}$	$4.90\ 10^{-7}$	$1.30\ 10^{-6}$	$2.20\ 10^{-6}$	$1.70\ 10^{-6}$	$2.20\ 10^{-5}$	$7.90\ 10^{-10}$	$1.20\ 10^{-10}$	$4.40\ 10^{-10}$
Po-210	$1.10\ 10^{-7}$	$2.00\ 10^{-7}$	$6.40\ 10^{-7}$	$7.00\ 10^{-6}$	$7.10\ 10^{-7}$	$5.20\ 10^{-6}$	$2.00\ 10^{-6}$	$5.10\ 10^{-13}$	$1.00\ 10^{-11}$	$3.10\ 10^{-11}$
Ra-226	$2.50\ 10^{-7}$	$1.00\ 10^{-6}$	$6.60\ 10^{-8}$	$6.10\ 10^{-8}$	$5.50\ 10^{-7}$	$4.50\ 10^{-8}$	$4.00\ 10^{-6}$	$1.90\ 10^{-6}$	$3.60\ 10^{-10}$	$1.20\ 10^{-10}$
Ra-228	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ac-227	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Th-228	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Th-229	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Th-230	$2.50\ 10^{-8}$	$9.00\ 10^{-9}$	$2.40\ 10^{-9}$	$2.20\ 10^{-8}$	$3.10\ 10^{-8}$	$3.70\ 10^{-8}$	$3.20\ 10^{-8}$	$3.40\ 10^{-6}$	$2.10\ 10^{-9}$	$9.40\ 10^{-11}$
Th-232	$2.80\ 10^{-8}$	$9.90\ 10^{-9}$	$2.70\ 10^{-9}$	$2.40\ 10^{-8}$	$3.40\ 10^{-8}$	$4.00\ 10^{-8}$	$3.50\ 10^{-8}$	$2.40\ 10^{-6}$	$3.00\ 10^{-9}$	$1.00\ 10^{-10}$
Pa-231	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U-232	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U-233	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U-234	$2.10\ 10^{-9}$	$3.40\ 10^{-9}$	$4.30\ 10^{-10}$	$3.90\ 10^{-10}$	$1.40\ 10^{-9}$	$2.00\ 10^{-10}$	$2.10\ 10^{-7}$	$2.80\ 10^{-9}$	$7.40\ 10^{-11}$	$3.30\ 10^{-12}$
U-235	$2.10\ 10^{-9}$	$3.40\ 10^{-9}$	$4.30\ 10^{-10}$	$3.90\ 10^{-10}$	$1.40\ 10^{-9}$	$2.00\ 10^{-10}$	$2.10\ 10^{-7}$	$2.80\ 10^{-8}$	$6.70\ 10^{-11}$	$3.30\ 10^{-12}$
U-236	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Radionuclide[$]	Green vegetable	Root vegetable	Sheep meat	Sheep liver	Cow meat	Cow liver	Milk	External irradiation	Inadv. Inhalation	Inadv. Ingestion
U-238	$2.00\ 10^{-9}$	$3.10\ 10^{-9}$	$4.00\ 10^{-10}$	$3.60\ 10^{-10}$	$1.30\ 10^{-9}$	$1.90\ 10^{-10}$	$2.00\ 10^{-7}$	$4.50\ 10^{-9}$	$6.30\ 10^{-11}$	$3.10\ 10^{-12}$
Np-237	$4.20\ 10^{-9}$	$1.40\ 10^{-8}$	$1.80\ 10^{-10}$	$1.20\ 10^{-8}$	$1.00\ 10^{-9}$	$3.40\ 10^{-8}$	$5.80\ 10^{-10}$	$4.00\ 10^{-8}$	$2.70\ 10^{-10}$	$5.30\ 10^{-12}$
Pu-238	$2.50\ 10^{-9}$	$3.90\ 10^{-10}$	$1.70\ 10^{-10}$	$1.10\ 10^{-8}$	$3.60\ 10^{-10}$	$1.20\ 10^{-8}$	$2.10\ 10^{-10}$	$2.30\ 10^{-11}$	$4.10\ 10^{-10}$	$8.50\ 10^{-12}$
Pu-239	$2.60\ 10^{-9}$	$5.00\ 10^{-10}$	$1.80\ 10^{-10}$	$1.20\ 10^{-8}$	$4.00\ 10^{-10}$	$1.30\ 10^{-8}$	$2.30\ 10^{-10}$	$2.80\ 10^{-8}$	$5.10\ 10^{-10}$	$1.10\ 10^{-11}$
Pu-240	$2.60\ 10^{-9}$	$5.00\ 10^{-10}$	$1.80\ 10^{-10}$	$1.20\ 10^{-8}$	$4.00\ 10^{-10}$	$1.30\ 10^{-8}$	$2.30\ 10^{-10}$	$1.60\ 10^{-11}$	$5.10\ 10^{-10}$	$1.10\ 10^{-11}$
Pu-241	$3.30\ 10^{-11}$	$2.60\ 10^{-12}$	$2.00\ 10^{-12}$	$1.30\ 10^{-10}$	$3.90\ 10^{-12}$	$1.30\ 10^{-10}$	$2.20\ 10^{-12}$	$1.90\ 10^{-9}$	$2.60\ 10^{-12}$	$5.80\ 10^{-14}$
Pu-242	$2.50\ 10^{-9}$	$4.70\ 10^{-10}$	$1.70\ 10^{-10}$	$1.10\ 10^{-8}$	$3.80\ 10^{-10}$	$1.30\ 10^{-8}$	$2.20\ 10^{-10}$	$4.60\ 10^{-9}$	$4.90\ 10^{-10}$	$1.00\ 10^{-11}$
Pu-244	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Am-241	$1.20\ 10^{-8}$	$3.50\ 10^{-9}$	$1.20\ 10^{-9}$	$7.90\ 10^{-8}$	$5.50\ 10^{-9}$	$1.80\ 10^{-7}$	$3.20\ 10^{-9}$	$2.10\ 10^{-7}$	$2.20\ 10^{-9}$	$4.50\ 10^{-11}$
Am-242m	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Am-243	$1.20\ 10^{-8}$	$3.60\ 10^{-9}$	$1.20\ 10^{-9}$	$8.10\ 10^{-8}$	$5.60\ 10^{-9}$	$1.90\ 10^{-7}$	$3.20\ 10^{-9}$	$1.70\ 10^{-7}$	$2.30\ 10^{-9}$	$4.70\ 10^{-11}$
Cm-242	$9.70\ 10^{-10}$	$6.30\ 10^{-12}$	$2.20\ 10^{-11}$	$1.40\ 10^{-9}$	$2.40\ 10^{-11}$	$8.00\ 10^{-10}$	$1.40\ 10^{-11}$	$5.90\ 10^{-11}$	$1.90\ 10^{-11}$	$3.10\ 10^{-13}$
Cm-243	$1.90\ 10^{-8}$	$4.50\ 10^{-9}$	$1.20\ 10^{-9}$	$7.70\ 10^{-8}$	$2.40\ 10^{-9}$	$8.20\ 10^{-8}$	$1.40\ 10^{-9}$	$4.50\ 10^{-7}$	$2.20\ 10^{-9}$	$4.50\ 10^{-11}$
Cm-244	$1.60\ 10^{-8}$	$3.10\ 10^{-9}$	$9.70\ 10^{-10}$	$6.30\ 10^{-8}$	$1.90\ 10^{-9}$	$6.50\ 10^{-8}$	$1.10\ 10^{-9}$	$3.00\ 10^{-10}$	$1.60\ 10^{-9}$	$3.10\ 10^{-11}$
Cm-245	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cm-246	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cm-248	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Note: $ Radionuclides that are not considered in EA IRAT are shown with no data (nd).

Anglers (discharge from treatment plant)

804. The assessment of doses to a coastal angler fishing in an estuary that receives discharges from the treatment plant is based on the EA IRAT (Environment Agency, 2022a; Environment Agency, 2022b). Members of the exposed group are assumed to comprise adults, children and infants consuming fish and spending time on the banks of the estuary where water from the treatment works is discharged.

805. Habit data assumed for the angler family are summarised in Table 94. Representative person adult consumption rates are taken from Table 31 of NRPB W41 (Smith & Jones, 2003), as are the infant and child 97.5th percentile rates. The infant and child mean consumption rates were derived from the 97.5th rates assuming that the mean consumption rate is one third of the critical consumption rate, based on (Thorne, 2006). Beach occupancies are those assumed in (Environment Agency, 2022b). The use of consumption rates assumed for the angler family are consistent with the approach used throughout this report: the two most limiting pathways use consumption rates at the 97.5th percentile rate and mean rates are used for consumption of all other foods.

Table 94 Habit data for the angling family: applicable during the Period of Authorisation

Pathway	Adult			Child			Infant		
	DPUR basis	mean	97.5th	DPUR basis	mean	97.5th	DPUR basis	mean	97.5th
Fish consumption (kg y^{-1})	100	33.33	100	20	6.67	20	5	1.67	5
Crustacean consumption (kg y^{-1})	20	6.67	20	5	1.67	5	0	0	0
Molluscs consumption (kg y^{-1})	20	6.67	20	5	1.67	5	0	0	0
Occupancy on beach (h y^{-1})	2000	2000		300	300		30	30	

806. The radiation dose (Sv y^{-1}) incurred by an angling family for each radionuclide ($Dose_{Rn,fisherman}$) is given by:

$$Dose_{Rn,fisherman} = F_{Rn} \cdot DF_{Rn,fisherman} \cdot Dil \cdot F_E \cdot F_p \cdot F_{exchange}$$

where:

- $Dose_{Rn,fisherman}$ is the dose to an adult, child or infant member of the angling family (Sv y^{-1});
- F_{Rn} is the flux of the radionuclide to the treatment works (Bq y^{-1});
- $DF_{Rn,\ fisherman}$ is the dose per unit flux to the given exposed group (Sv y^{-1} per Bq y^{-1}) using default values – Total DPUR taken from EA methodology and given in Table 95, Table 96 and Table 97 for adult, child and infant members of the fishing family respectively;
- Dil is a dilution factor that is given by the ratio of the assumed and actual treatment throughputs, i.e. 60/3 10^{5};

- F_E is the fraction from raw effluent that is disposed in liquid effluent;
- F_p is the consumption scaling factor; and,
- $F_{exchange}$ is the estuary exchange rate scaling factor, i.e. 100/51, to adjust for the assumed exchange rate in the Tees Estuary of 51 $m^3 s^{-1}$ (Dewar, et al., 2011).

Table 95 Dose per unit release factors for an adult member of the fishing family – leachate release to treatment facility scenario (µSv/y per Bq/y of discharge to sewer) given in the EA IRAT methodology

Radionuclide$	Fraction to effluent (F_E)	Fish	Crustacea	Molluscs	External irradiation
H-3	8.50 10^{-1}	2.90 10^{-16}	1.10 10^{-16}	1.10 10^{-16}	0
C-14	8.50 10^{-1}	1.80 10^{-10}	7.20 10^{-11}	7.20 10^{-11}	2.10 10^{-16}
Cl-36	9.00 10^{-1}	9.10 10^{-16}	3.60 10^{-16}	3.00 10^{-16}	5.60 10^{-17}
Ca-41	nd	nd	nd	nd	nd
Mn-54	5.00 10^{-2}	1.60 10^{-13}	3.20 10^{-13}	3.20 10^{-12}	3.10 10^{-10}
Fe-55	1.00 10^{-1}	1.60 10^{-14}	1.10 10^{-13}	1.10 10^{-13}	0
Co-60	1.00 10^{-1}	3.70 10^{-12}	1.50 10^{-11}	4.20 10^{-11}	3.60 10^{-9}
Ni-59	nd	nd	nd	nd	nd
Ni-63	1.00 10^{-1}	1.60 10^{-12}	6.20 10^{-13}	1.20 10^{-12}	0
Zn-65	9.00 10^{-1}	1.80 10^{-11}	2.10 10^{-9}	5.60 10^{-10}	1.30 10^{-10}
Se-79	nd	nd	nd	nd	nd
Sr-90	6.00 10^{-1}	1.40 10^{-12}	9.00 10^{-13}	1.80 10^{-12}	5.30 10^{-15}
Mo-93	nd	nd	nd	nd	nd
Zr-93	nd	nd	nd	nd	nd
Nb-93m	nd	nd	nd	nd	nd
Nb-94	nd	nd	nd	nd	nd
Tc-99	9.00 10^{-1}	8.40 10^{-13}	4.10 10^{-12}	2.00 10^{-12}	1.80 10^{-16}
Ru-106	9.00 10^{-1}	9.20 10^{-14}	1.80 10^{-12}	9.20 10^{-12}	5.50 10^{-11}
Ag-108m	nd	nd	nd	nd	nd
Ag-110m	1.00 10^{-1}	3.20 10^{-10}	2.60 10^{-9}	7.70 10^{-10}	2.20 10^{-10}
Cd-109	nd	nd	nd	nd	nd
Sb-125	9.00 10^{-1}	1.10 10^{-11}	2.20 10^{-12}	2.20 10^{-12}	2.60 10^{-11}
Sn-119m	nd	nd	nd	nd	nd
Sn-123	nd	nd	nd	nd	nd
Sn-126	nd	nd	nd	nd	nd
Te-127m	nd	nd	nd	nd	nd
I-129	8.00 10^{-1}	1.60 10^{-11}	2.10 10^{-12}	7.00 10^{-12}	1.10 10^{-14}
Ba-133	nd	nd	nd	nd	nd
Cs-134	9.00 10^{-1}	2.70 10^{-11}	5.30 10^{-12}	6.30 10^{-12}	1.50 10^{-10}
Cs-135	nd	nd	nd	nd	nd

Radionuclide$	Fraction to effluent (F_E)	Fish	Crustacea	Molluscs	External irradiation
Cs-137	$9.00\ 10^{-1}$	$1.90\ 10^{-11}$	$3.70\ 10^{-12}$	$4.50\ 10^{-12}$	$1.70\ 10^{-10}$
Ce-144	$5.00\ 10^{-1}$	$3.90\ 10^{-14}$	$3.10\ 10^{-13}$	$6.20\ 10^{-13}$	$2.00\ 10^{-11}$
Pm-147	$5.00\ 10^{-1}$	$1.90\ 10^{-14}$	$9.90\ 10^{-14}$	$1.70\ 10^{-13}$	$8.00\ 10^{-15}$
Sm-147	nd	nd	nd	nd	nd
Sm-151	nd	nd	nd	nd	nd
Eu-152	$5.00\ 10^{-1}$	$1.10\ 10^{-13}$	$6.10\ 10^{-13}$	$1.10\ 10^{-12}$	$2.80\ 10^{-9}$
Eu-154	$5.00\ 10^{-1}$	$1.60\ 10^{-13}$	$8.40\ 10^{-13}$	$1.50\ 10^{-12}$	$2.50\ 10^{-9}$
Eu-155	$5.00\ 10^{-1}$	$2.40\ 10^{-14}$	$1.30\ 10^{-13}$	$2.20\ 10^{-13}$	$4.70\ 10^{-11}$
Gd-153	nd	nd	nd	nd	nd
Pb-210	$1.00\ 10^{-1}$	$5.80\ 10^{-10}$	$1.00\ 10^{-7}$	$5.80\ 10^{-8}$	$3.10\ 10^{-12}$
Po-210	$1.00\ 10^{-1}$	$5.30\ 10^{-11}$	$2.10\ 10^{-10}$	$2.10\ 10^{-10}$	$1.50\ 10^{-15}$
Ra-226	$5.00\ 10^{-1}$	$4.30\ 10^{-10}$	$1.70\ 10^{-10}$	$1.70\ 10^{-10}$	$3.30\ 10^{-10}$
Ra-228	nd	nd	nd	nd	nd
Ac-227	nd	nd	nd	nd	nd
Th-228	nd	nd	nd	nd	nd
Th-229	nd	nd	nd	nd	nd
Th-230	$1.00\ 10^{-1}$	$2.90\ 10^{-11}$	$1.90\ 10^{-11}$	$1.90\ 10^{-11}$	$2.30\ 10^{-11}$
Th-232	$1.00\ 10^{-1}$	$1.30\ 10^{-9}$	$8.50\ 10^{-10}$	$8.50\ 10^{-10}$	$4.50\ 10^{-9}$
Pa-231	nd	nd	nd	nd	nd
U-232	nd	nd	nd	nd	nd
U-233	nd	nd	nd	nd	nd
U-234	$9.00\ 10^{-1}$	$7.80\ 10^{-13}$	$3.00\ 10^{-12}$	$9.10\ 10^{-12}$	$6.70\ 10^{-15}$
U-235	$9.00\ 10^{-1}$	$7.50\ 10^{-13}$	$2.90\ 10^{-12}$	$8.80\ 10^{-12}$	$1.30\ 10^{-11}$
U-236	nd	nd	nd	nd	nd
U-238	$9.00\ 10^{-1}$	$7.20\ 10^{-13}$	$2.80\ 10^{-12}$	$8.40\ 10^{-12}$	$2.30\ 10^{-12}$
Np-237	$9.00\ 10^{-1}$	$1.70\ 10^{-12}$	$6.80\ 10^{-11}$	$2.70\ 10^{-10}$	$1.80\ 10^{-11}$
Pu-238	$9.00\ 10^{-1}$	$1.00\ 10^{-10}$	$8.00\ 10^{-11}$	$1.20\ 10^{-9}$	$5.90\ 10^{-14}$
Pu-239	$9.00\ 10^{-1}$	$1.10\ 10^{-10}$	$8.90\ 10^{-11}$	$1.30\ 10^{-9}$	$1.40\ 10^{-13}$
Pu-240	$9.00\ 10^{-1}$	$1.10\ 10^{-10}$	$8.80\ 10^{-11}$	$1.30\ 10^{-9}$	$6.10\ 10^{-14}$
Pu-241	$9.00\ 10^{-1}$	$2.00\ 10^{-12}$	$1.60\ 10^{-12}$	$2.40\ 10^{-11}$	$2.20\ 10^{-13}$
Pu-242	$9.00\ 10^{-1}$	$1.10\ 10^{-10}$	$8.50\ 10^{-11}$	$1.30\ 10^{-9}$	$5.40\ 10^{-14}$
Pu-244	nd	nd	nd	nd	nd
Am-241	$5.00\ 10^{-1}$	$6.00\ 10^{-12}$	$9.60\ 10^{-12}$	$2.40\ 10^{-11}$	$2.60\ 10^{-11}$
Am-242m	nd	nd	nd	nd	nd
Am-243	$5.00\ 10^{-1}$	$6.10\ 10^{-12}$	$9.70\ 10^{-12}$	$2.40\ 10^{-11}$	$5.80\ 10^{-10}$
Cm-242	$1.00\ 10^{-1}$	$4.00\ 10^{-13}$	$6.30\ 10^{-13}$	$1.60\ 10^{-12}$	$5.40\ 10^{-15}$
Cm-243	$1.00\ 10^{-1}$	$4.30\ 10^{-12}$	$6.80\ 10^{-12}$	$1.70\ 10^{-11}$	$3.00\ 10^{-10}$
Cm-244	$1.00\ 10^{-1}$	$3.40\ 10^{-12}$	$5.40\ 10^{-12}$	$1.30\ 10^{-11}$	$4.80\ 10^{-14}$
Cm-245	nd	nd	nd	nd	nd

Radionuclide$	Fraction to effluent (F_E)	Fish	Crustacea	Molluscs	External irradiation
Cm-246	nd	nd	nd	nd	nd
Cm-248	nd	nd	nd	nd	nd

Note: $ Radionuclides that are not considered in EA IRAT are shown with no data (nd).

Table 96 Dose per unit release factors for a child member of the fishing family – leachate release to treatment facility scenario (μSv/y per Bq/y of discharge to sewer) given in the EA IRAT methodology

Radionuclide$	Fraction to effluent	Fish	Crustacea	Molluscs	External irradiation
H-3	$8.50\ 10^{-1}$	$7.50\ 10^{-17}$	$3.70\ 10^{-17}$	$3.70\ 10^{-17}$	0
C-14	$8.50\ 10^{-1}$	$5.10\ 10^{-11}$	$2.50\ 10^{-11}$	$2.50\ 10^{-11}$	$3.10\ 10^{-17}$
Cl-36	$9.00\ 10^{-1}$	$3.70\ 10^{-16}$	$1.80\ 10^{-16}$	$1.50\ 10^{-16}$	$8.40\ 10^{-18}$
Ca-41	nd	nd	nd	nd	nd
Mn-54	$5.00\ 10^{-2}$	$5.80\ 10^{-14}$	$1.50\ 10^{-13}$	$1.50\ 10^{-12}$	$4.70\ 10^{-11}$
Fe-55	$1.00\ 10^{-1}$	$1.10\ 10^{-14}$	$8.90\ 10^{-14}$	$8.90\ 10^{-14}$	0
Co-60	$1.00\ 10^{-1}$	$2.40\ 10^{-12}$	$1.20\ 10^{-11}$	$3.40\ 10^{-11}$	$5.40\ 10^{-10}$
Ni-59	nd	nd	nd	nd	nd
Ni-63	$1.00\ 10^{-1}$	$5.80\ 10^{-13}$	$2.90\ 10^{-13}$	$5.80\ 10^{-13}$	0
Zn-65	$9.00\ 10^{-1}$	$5.80\ 10^{-12}$	$8.70\ 10^{-10}$	$2.30\ 10^{-10}$	$1.90\ 10^{-11}$
Se-79	nd	nd	nd	nd	nd
Sr-90	$6.00\ 10^{-1}$	$5.90\ 10^{-13}$	$4.80\ 10^{-13}$	$9.60\ 10^{-13}$	$8.00\ 10^{-16}$
Mo-93	nd	nd	nd	nd	nd
Zr-93	nd	nd	nd	nd	nd
Nb-93m	nd	nd	nd	nd	nd
Nb-94	nd	nd	nd	nd	nd
Tc-99	$9.00\ 10^{-1}$	$3.40\ 10^{-13}$	$2.10\ 10^{-12}$	$1.00\ 10^{-12}$	$2.80\ 10^{-17}$
Ru-106	$9.00\ 10^{-1}$	$3.90\ 10^{-14}$	$9.80\ 10^{-13}$	$4.90\ 10^{-12}$	$8.30\ 10^{-12}$
Ag-108m	nd	nd	nd	nd	nd
Ag-110m	$1.00\ 10^{-1}$	$1.20\ 10^{-10}$	$1.20\ 10^{-9}$	$3.60\ 10^{-10}$	$3.30\ 10^{-11}$
Cd-109	nd	nd	nd	nd	nd
Sb-125	$9.00\ 10^{-1}$	$4.30\ 10^{-12}$	$1.00\ 10^{-12}$	$1.00\ 10^{-12}$	$3.90\ 10^{-12}$
Sn-119m	nd	nd	nd	nd	nd
Sn-123	nd	nd	nd	nd	nd
Sn-126	nd	nd	nd	nd	nd
Te-127m	nd	nd	nd	nd	nd
I-129	$8.00\ 10^{-1}$	$5.60\ 10^{-12}$	$9.10\ 10^{-13}$	$3.00\ 10^{-12}$	$1.70\ 10^{-15}$
Ba-133	nd	nd	nd	nd	nd
Cs-134	$9.00\ 10^{-1}$	$3.90\ 10^{-12}$	$9.70\ 10^{-13}$	$1.20\ 10^{-12}$	$2.20\ 10^{-11}$

Radionuclide[$]	Fraction to effluent	Fish	Crustacea	Molluscs	External irradiation
Cs-135	nd	nd	nd	nd	nd
Cs-137	$9.00\ 10^{-1}$	$2.90\ 10^{-12}$	$7.20\ 10^{-13}$	$8.60\ 10^{-13}$	$2.50\ 10^{-11}$
Ce-144	$5.00\ 10^{-1}$	$1.60\ 10^{-14}$	$1.60\ 10^{-13}$	$3.30\ 10^{-13}$	$3.00\ 10^{-12}$
Pm-147	$5.00\ 10^{-1}$	$8.20\ 10^{-15}$	$5.40\ 10^{-14}$	$9.50\ 10^{-14}$	$1.20\ 10^{-15}$
Sm-147	nd	nd	nd	nd	nd
Sm-151	nd	nd	nd	nd	nd
Eu-152	$5.00\ 10^{-1}$	$4.20\ 10^{-14}$	$2.80\ 10^{-13}$	$4.90\ 10^{-13}$	$4.10\ 10^{-10}$
Eu-154	$5.00\ 10^{-1}$	$6.50\ 10^{-14}$	$4.30\ 10^{-13}$	$7.50\ 10^{-13}$	$3.70\ 10^{-10}$
Eu-155	$5.00\ 10^{-1}$	$1.00\ 10^{-14}$	$6.80\ 10^{-14}$	$1.20\ 10^{-13}$	$7.10\ 10^{-12}$
Gd-153	nd	nd	nd	nd	nd
Pb-210	$1.00\ 10^{-1}$	$3.20\ 10^{-10}$	$7.20\ 10^{-8}$	$4.00\ 10^{-8}$	$4.60\ 10^{-13}$
Po-210	$1.00\ 10^{-1}$	$2.30\ 10^{-11}$	$1.10\ 10^{-10}$	$1.10\ 10^{-10}$	$2.20\ 10^{-16}$
Ra-226	$5.00\ 10^{-1}$	$2.50\ 10^{-10}$	$1.20\ 10^{-10}$	$1.20\ 10^{-10}$	$5.00\ 10^{-11}$
Ra-228	nd	nd	nd	nd	nd
Ac-227	nd	nd	nd	nd	nd
Th-228	nd	nd	nd	nd	nd
Th-229	nd	nd	nd	nd	nd
Th-230	$1.00\ 10^{-1}$	$7.90\ 10^{-12}$	$6.50\ 10^{-12}$	$6.50\ 10^{-12}$	$3.50\ 10^{-12}$
Th-232	$1.00\ 10^{-1}$	$1.50\ 10^{-9}$	$1.20\ 10^{-9}$	$1.20\ 10^{-9}$	$6.80\ 10^{-10}$
Pa-231	nd	nd	nd	nd	nd
U-232	nd	nd	nd	nd	nd
U-233	nd	nd	nd	nd	nd
U-234	$9.00\ 10^{-1}$	$2.40\ 10^{-13}$	$1.20\ 10^{-12}$	$3.50\ 10^{-12}$	$1.00\ 10^{-15}$
U-235	$9.00\ 10^{-1}$	$2.30\ 10^{-13}$	$1.10\ 10^{-12}$	$3.30\ 10^{-12}$	$1.90\ 10^{-12}$
U-236	nd	nd	nd	nd	nd
U-238	$9.00\ 10^{-1}$	$2.20\ 10^{-13}$	$1.10\ 10^{-12}$	$3.20\ 10^{-12}$	$3.50\ 10^{-13}$
Np-237	$9.00\ 10^{-1}$	$3.50\ 10^{-13}$	$1.70\ 10^{-11}$	$6.80\ 10^{-11}$	$2.70\ 10^{-12}$
Pu-238	$9.00\ 10^{-1}$	$2.10\ 10^{-11}$	$2.10\ 10^{-11}$	$3.10\ 10^{-10}$	$8.80\ 10^{-15}$
Pu-239	$9.00\ 10^{-1}$	$2.40\ 10^{-11}$	$2.40\ 10^{-11}$	$3.60\ 10^{-10}$	$2.10\ 10^{-14}$
Pu-240	$9.00\ 10^{-1}$	$2.40\ 10^{-11}$	$2.40\ 10^{-11}$	$3.60\ 10^{-10}$	$9.20\ 10^{-15}$
Pu-241	$9.00\ 10^{-1}$	$4.20\ 10^{-13}$	$4.20\ 10^{-13}$	$6.30\ 10^{-12}$	$3.40\ 10^{-14}$
Pu-242	$9.00\ 10^{-1}$	$2.30\ 10^{-11}$	$2.30\ 10^{-11}$	$3.50\ 10^{-10}$	$8.20\ 10^{-15}$
Pu-244	nd	nd	nd	nd	nd
Am-241	$5.00\ 10^{-1}$	$1.30\ 10^{-12}$	$2.60\ 10^{-12}$	$6.60\ 10^{-12}$	$3.90\ 10^{-12}$
Am-242m	nd	nd	nd	nd	nd
Am-243	$5.00\ 10^{-1}$	$1.30\ 10^{-12}$	$2.70\ 10^{-12}$	$6.60\ 10^{-12}$	$8.60\ 10^{-11}$
Cm-242	$1.00\ 10^{-1}$	$1.30\ 10^{-13}$	$2.60\ 10^{-13}$	$6.60\ 10^{-13}$	$8.20\ 10^{-16}$
Cm-243	$1.00\ 10^{-1}$	$9.10\ 10^{-13}$	$1.80\ 10^{-12}$	$4.60\ 10^{-12}$	$4.60\ 10^{-11}$
Cm-244	$1.00\ 10^{-1}$	$7.80\ 10^{-13}$	$1.60\ 10^{-12}$	$3.90\ 10^{-12}$	$7.10\ 10^{-15}$

Radionuclide$	Fraction to effluent	Fish	Crustacea	Molluscs	External irradiation
Cm-245	nd	nd	nd	nd	nd
Cm-246	nd	nd	nd	nd	nd
Cm-248	nd	nd	nd	nd	nd

Note: $ Radionuclides that are not considered in EA IRAT are shown with no data (nd).

Table 97 Dose per unit release factors for an infant member of the fishing family – leachate release to treatment facility scenario (μSv/y per Bq/y of discharge to sewer) given in the EA IRAT methodology

Radionuclide$	Fraction to effluent	Fish	Crustacea	Molluscs	External irradiation
H-3	8.50 10^{-1}	3.90 10^{-17}	0	0	0
C-14	8.50 10^{-1}	2.50 10^{-11}	0	0	3.10 10^{-18}
Cl-36	9.00 10^{-1}	3.10 10^{-16}	0	0	8.40 10^{-19}
Ca-41	nd	nd	nd	nd	nd
Mn-54	5.00 10^{-2}	3.50 10^{-14}	0	0	4.70 10^{-12}
Fe-55	1.00 10^{-1}	5.80 10^{-15}	0	0	0
Co-60	1.00 10^{-1}	1.50 10^{-12}	0	0	5.40 10^{-11}
Ni-59	nd	nd	nd	nd	nd
Ni-63	1.00 10^{-1}	4.40 10^{-13}	0	0	0
Zn-65	9.00 10^{-1}	3.60 10^{-12}	0	0	1.90 10^{-12}
Se-79	nd	nd	nd	nd	nd
Sr-90	6.00 10^{-1}	1.80 10^{-13}	0	0	8.00 10^{-17}
Mo-93	nd	nd	nd	nd	nd
Zr-93	nd	nd	nd	nd	nd
Nb-93m	nd	nd	nd	nd	nd
Nb-94	nd	nd	nd	nd	nd
Tc-99	9.00 10^{-1}	3.10 10^{-13}	0	0	2.80 10^{-18}
Ru-106	9.00 10^{-1}	3.20 10^{-14}	0	0	8.30 10^{-13}
Ag-108m	nd	nd	nd	nd	nd
Ag-110m	1.00 10^{-1}	8.00 10^{-11}	0	0	3.30 10^{-12}
Cd-109	nd	nd	nd	nd	nd
Sb-125	9.00 10^{-1}	3.20 10^{-12}	0	0	3.90 10^{-13}
Sn-119m	nd	nd	nd	nd	nd
Sn-123	nd	nd	nd	nd	nd
Sn-126	nd	nd	nd	nd	nd
Te-127m	nd	nd	nd	nd	nd
I-129	8.00 10^{-1}	1.60 10^{-12}	0	0	1.70 10^{-16}
Ba-133	nd	nd	nd	nd	nd

Radionuclide$	Fraction to effluent	Fish	Crustacea	Molluscs	External irradiation
Cs-134	$9.00\ 10^{-1}$	$1.10\ 10^{-12}$	0	0	$2.20\ 10^{-12}$
Cs-135	nd	nd	nd	nd	nd
Cs-137	$9.00\ 10^{-1}$	$8.70\ 10^{-13}$	0	0	$2.50\ 10^{-12}$
Ce-144	$5.00\ 10^{-1}$	$1.50\ 10^{-14}$	0	0	$3.00\ 10^{-13}$
Pm-147	$5.00\ 10^{-1}$	$6.80\ 10^{-15}$	0	0	$1.20\ 10^{-16}$
Sm-147	nd	nd	nd	nd	nd
Sm-151	nd	nd	nd	nd	nd
Eu-152	$5.00\ 10^{-1}$	$3.00\ 10^{-14}$	0	0	$4.10\ 10^{-11}$
Eu-154	$5.00\ 10^{-1}$	$4.70\ 10^{-14}$	0	0	$3.70\ 10^{-11}$
Eu-155	$5.00\ 10^{-1}$	$8.30\ 10^{-15}$	0	0	$7.10\ 10^{-13}$
Gd-153	nd	nd	nd	nd	nd
Pb-210	$1.00\ 10^{-1}$	$1.50\ 10^{-10}$	0	0	$4.60\ 10^{-14}$
Po-210	$1.00\ 10^{-1}$	$1.90\ 10^{-11}$	0	0	$2.20\ 10^{-17}$
Ra-226	$5.00\ 10^{-1}$	$7.40\ 10^{-11}$	0	0	$5.00\ 10^{-12}$
Ra-228	nd	nd	nd	nd	nd
Ac-227	nd	nd	nd	nd	nd
Th-228	nd	nd	nd	nd	nd
Th-229	nd	nd	nd	nd	nd
Th-230	$1.00\ 10^{-1}$	$3.10\ 10^{-12}$	0	0	$3.50\ 10^{-13}$
Th-232	$1.00\ 10^{-1}$	$5.30\ 10^{-10}$	0	0	$6.80\ 10^{-11}$
Pa-231	nd	nd	nd	nd	nd
U-232	nd	nd	nd	nd	nd
U-233	nd	nd	nd	nd	nd
U-234	$9.00\ 10^{-1}$	$1.00\ 10^{-13}$	0	0	$1.00\ 10^{-16}$
U-235	$9.00\ 10^{-1}$	$1.00\ 10^{-13}$	0	0	$1.90\ 10^{-13}$
U-236	nd	nd	nd	nd	nd
U-238	$9.00\ 10^{-1}$	$9.50\ 10^{-14}$	0	0	$3.50\ 10^{-14}$
Np-237	$9.00\ 10^{-1}$	$1.70\ 10^{-13}$	0	0	$2.70\ 10^{-13}$
Pu-238	$9.00\ 10^{-1}$	$8.70\ 10^{-12}$	0	0	$8.80\ 10^{-16}$
Pu-239	$9.00\ 10^{-1}$	$9.30\ 10^{-12}$	0	0	$2.10\ 10^{-15}$
Pu-240	$9.00\ 10^{-1}$	$9.30\ 10^{-12}$	0	0	$9.20\ 10^{-16}$
Pu-241	$9.00\ 10^{-1}$	$1.20\ 10^{-13}$	0	0	$3.40\ 10^{-15}$
Pu-242	$9.00\ 10^{-1}$	$8.90\ 10^{-12}$	0	0	$8.20\ 10^{-16}$
Pu-244	nd	nd	nd	nd	nd
Am-241	$5.00\ 10^{-1}$	$5.60\ 10^{-13}$	0	0	$3.90\ 10^{-13}$
Am-242m	nd	nd	nd	nd	nd
Am-243	$5.00\ 10^{-1}$	$5.60\ 10^{-13}$	0	0	$8.60\ 10^{-12}$
Cm-242	$1.00\ 10^{-1}$	$9.50\ 10^{-14}$	0	0	$8.20\ 10^{-17}$
Cm-243	$1.00\ 10^{-1}$	$4.70\ 10^{-13}$	0	0	$4.60\ 10^{-12}$

Radionuclide$	Fraction to effluent	Fish	Crustacea	Molluscs	External irradiation
Cm-244	1.00 10^{-1}	4.00 10^{-13}	0	0	7.10 10^{-16}
Cm-245	nd	nd	nd	nd	nd
Cm-246	nd	nd	nd	nd	nd
Cm-248	nd	nd	nd	nd	nd

Note: $ Radionuclides that are not considered in EA IRAT are shown with no data (nd).

Reed bed facility worker

807. An assessment has been made of the radiological impact arising from treatment of contaminated leachate using a Reed Bed facility. The Billingham Reed Beds is used for leachate treatment (Scott Bros. Ltd) and under current normal operating circumstances approximately 3,800 m^3 y^{-1} of leachate is sent for off-site treatment (averaged over the last 6 years). The treated leachate is then discharged to the estuary via Billingham Beck.

808. Output from a GoldSim groundwater model of the site provides an estimate of the maximum leachate activity concentration and this is used to assess the potential doses arising from leachate treatment. The calculations are conservative because they do not take into account sorption of radionuclides within waste materials whereas in reality the waste received at Port Clarence is likely to provide sorption sites within waste cells. The flux of radionuclides to off-site treatment (Bq y^{-1}) uses the peak leachate activity concentrations (per MBq input to the landfill) during the active control period (60 years after capping) and the leachate export rate (3,778 m^3 y^{-1}) from the site. The ingrowth of daughters is modelled using GoldSim and the activity concentrations of the daughters are propagated through the model and the dose contributions summed.

809. The radiological assessment considers worker exposure to contamination of the Reed Beds (49,000 m^2 to a depth of 0.6 m) and accumulation over 7 years which is the anticipated operating life of the beds.

810. The reed bed operative receives a dose (Sv y^{-1}) from external irradiation (SNIFFER, 2006):

$$Dose_{reed\ bed\ operator} = \left(\frac{D_{irr,slab}^{Rn}}{8766}\right) T C_{Rn,\text{reed bed}}$$

where:

- $Dose_{reed\ bed\ operator}$ is the dose to a reed bed operative (Sv y^{-1});
- T is the time that the operative is exposed to the material (104 h y^{-1});
- $D_{irr,slab}$, is the dose coefficient for radionuclide *Rn* (Sv y^{-1} Bq^{-1} kg^{-1});
- 8766 is the number of hours in a year (h y^{-1});

- $C_{Rn,waste}$ is the activity concentration of radionuclide *Rn* (Bq kg^{-1}) integrated over a period of 7 years, *t*:

$$C_{Rn,\text{reed bed}} = \frac{A_{Rn}(t)}{V_{reed\ bed}\rho_{reed\ bed}}$$

- $V_{reed\ bed}$ is the volume of the reed bed in which the activity is assumed to be concentrated (29,400 m^3); and,
- $\rho_{reed\ bed}$ is the density of the reed bed substrate (1680 kg m^{-3}).

E.3.7.3. Doses from leachate treatment

Dose per MBq Deposited at Port Clarence – Leachate Treatment

811. The calculated doses shown below for each of the assessed groups are per MBq input to Port Clarence landfills. The scenario radiological capacity is presented in the right hand column.

Table 98 Dose for exposure from the off-site treatment of leachate per MBq input to Port Clarence

Radionuclide	Leachate treatment worker ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Reed bed treatment worker ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Farming family ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Limiting age group on farm	Fishing family ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Limiting age group fishing	Scenario radiological capacity (MBq)
H-3	$2.98\ 10^{-12}$	$1.42\ 10^{-11}$	$8.25\ 10^{-12}$	Adult	$1.77\ 10^{-15}$	Adult	$2.12\ 10^{13}$
C-14	$3.35\ 10^{-12}$	$1.47\ 10^{-10}$	$8.08\ 10^{-12}$	Infant	$3.64\ 10^{-12}$	Adult	$2.03\ 10^{12}$
Cl-36	$6.09\ 10^{-9}$	$3.92\ 10^{-7}$	$1.73\ 10^{-8}$	Infant	$3.93\ 10^{-15}$	Adult	$7.65\ 10^{8}$
Ca-41	$2.83\ 10^{-12}$	0	$8.75\ 10^{-11}$	Infant	$4.85\ 10^{-16}$	Child	$3.42\ 10^{12}$
Mn-54	$3.02\ 10^{-10}$	$1.00\ 10^{-10}$	$5.11\ 10^{-13}$	Adult	$9.71\ 10^{-15}$	Adult	$9.95\ 10^{11}$
Fe-55	$4.18\ 10^{-14}$	$9.28\ 10^{-20}$	$4.47\ 10^{-13}$	Child	$2.10\ 10^{-17}$	Adult	$1.84\ 10^{14}$
Co-60	$7.01\ 10^{-9}$	$9.03\ 10^{-9}$	$3.72\ 10^{-10}$	Adult	$1.04\ 10^{-12}$	Adult	$3.32\ 10^{10}$
Ni-59	$6.87\ 10^{-14}$	$7.62\ 10^{-13}$	$2.28\ 10^{-12}$	Infant	$6.96\ 10^{-16}$	Adult	$1.31\ 10^{14}$
Ni-63	$4.82\ 10^{-13}$	$5.60\ 10^{-12}$	$5.64\ 10^{-12}$	Infant	$1.66\ 10^{-15}$	Adult	$5.32\ 10^{13}$
Zn-65	$2.27\ 10^{-10}$	$5.93\ 10^{-11}$	$4.08\ 10^{-13}$	Infant	$1.64\ 10^{-12}$	Adult	$1.32\ 10^{12}$
Se-79	$6.35\ 10^{-12}$	$8.23\ 10^{-11}$	$3.29\ 10^{-10}$	Infant	$2.18\ 10^{-12}$	Child	$3.01\ 10^{11}$
Sr-90	$3.55\ 10^{-10}$	$1.18\ 10^{-8}$	$2.34\ 10^{-9}$	Infant	$6.11\ 10^{-14}$	Adult	$2.54\ 10^{10}$
Mo-93	$1.58\ 10^{-12}$	$1.99\ 10^{-11}$	$4.43\ 10^{-17}$	Child	$3.80\ 10^{-16}$	Adult	$1.51\ 10^{13}$
Zr-93	$1.25\ 10^{-12}$	$5.57\ 10^{-12}$	$6.26\ 10^{-17}$	Adult	$8.74\ 10^{-17}$	Adult	$5.38\ 10^{13}$
Nb-93m	$1.44\ 10^{-14}$	$3.29\ 10^{-14}$	$6.56\ 10^{-18}$	Infant	$1.52\ 10^{-17}$	Adult	$9.13\ 10^{15}$
Nb-94	$9.56\ 10^{-10}$	$1.52\ 10^{-8}$	$5.48\ 10^{-13}$	Adult	$3.45\ 10^{-14}$	Adult	$1.98\ 10^{10}$
Tc-99	$4.10\ 10^{-10}$	$2.60\ 10^{-8}$	$2.41\ 10^{-8}$	Infant	$4.86\ 10^{-12}$	Adult	$8.49\ 10^{9}$
Ru-106	$1.44\ 10^{-10}$	$2.32\ 10^{-10}$	$2.47\ 10^{-13}$	Adult	$1.83\ 10^{-13}$	Adult	$1.29\ 10^{12}$
Ag-108m	$6.54\ 10^{-9}$	$5.63\ 10^{-8}$	$4.07\ 10^{-12}$	Adult	$4.93\ 10^{-13}$	Adult	$5.33\ 10^{9}$
Ag-110m	$4.72\ 10^{-9}$	$7.18\ 10^{-10}$	$4.96\ 10^{-12}$	Adult	$6.13\ 10^{-13}$	Adult	$6.36\ 10^{10}$
Cd-109	$1.99\ 10^{-12}$	$3.66\ 10^{-12}$	$2.26\ 10^{-13}$	Infant	$8.00\ 10^{-13}$	Adult	$8.20\ 10^{13}$

Radionuclide	Leachate treatment worker ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Reed bed treatment worker ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Farming family ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Limiting age group on farm	Fishing family ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Limiting age group fishing	Scenario radiological capacity (MBq)
Sb-125	$7.19\ 10^{-9}$	$4.86\ 10^{-9}$	$3.48\ 10^{-12}$	Adult	$7.04\ 10^{-13}$	Adult	$4.17\ 10^{10}$
Sn-119m	$1.05\ 10^{-13}$	$3.00\ 10^{-14}$	$2.07\ 10^{-11}$	Infant	$1.31\ 10^{-14}$	Adult	$1.44\ 10^{13}$
Sn-123	$4.54\ 10^{-12}$	$6.37\ 10^{-13}$	$1.59\ 10^{-10}$	Infant	$1.10\ 10^{-13}$	Adult	$1.87\ 10^{12}$
Sn-126	$1.12\ 10^{-9}$	$1.77\ 10^{-8}$	$3.80\ 10^{-9}$	Adult	$1.66\ 10^{-12}$	Adult	$1.69\ 10^{10}$
Te-127m	$3.30\ 10^{-13}$	$3.14\ 10^{-14}$	$2.11\ 10^{-10}$	Infant	$1.68\ 10^{-12}$	Adult	$4.69\ 10^{11}$
I-129	$6.23\ 10^{-10}$	$5.24\ 10^{-9}$	$1.78\ 10^{-9}$	Infant	$4.15\ 10^{-12}$	Adult	$5.73\ 10^{10}$
Ba-133	$1.08\ 10^{-7}$	$1.74\ 10^{-6}$	$5.39\ 10^{-10}$	Adult	$1.57\ 10^{-11}$	Adult	$1.72\ 10^{8}$
Cs-134	$5.28\ 10^{-10}$	$6.72\ 10^{-10}$	$2.97\ 10^{-11}$	Adult	$1.56\ 10^{-13}$	Adult	$4.46\ 10^{11}$
Cs-135	$1.38\ 10^{-12}$	$3.31\ 10^{-11}$	$4.70\ 10^{-13}$	Adult	$5.28\ 10^{-15}$	Adult	$9.06\ 10^{12}$
Cs-137	$2.59\ 10^{-10}$	$3.58\ 10^{-9}$	$4.18\ 10^{-12}$	Adult	$2.22\ 10^{-13}$	Adult	$8.38\ 10^{10}$
Ce-144	$4.78\ 10^{-12}$	$1.39\ 10^{-12}$	$3.19\ 10^{-14}$	Infant	$6.07\ 10^{-15}$	Adult	$6.28\ 10^{13}$
Pm-147	$2.50\ 10^{-12}$	$2.46\ 10^{-12}$	$1.70\ 10^{-14}$	Infant	$3.79\ 10^{-16}$	Adult	$1.20\ 10^{14}$
Sm-147	$2.99\ 10^{-11}$	0	$2.27\ 10^{-13}$	Adult	$1.57\ 10^{-13}$	Adult	$1.00\ 10^{13}$
Sm-151	$1.94\ 10^{-13}$	$2.23\ 10^{-12}$	$5.23\ 10^{-16}$	Infant	$3.13\ 10^{-16}$	Adult	$1.34\ 10^{14}$
Eu-152	$4.24\ 10^{-9}$	$2.09\ 10^{-8}$	$1.95\ 10^{-10}$	Adult	$8.62\ 10^{-12}$	Adult	$1.43\ 10^{10}$
Eu-154	$4.49\ 10^{-9}$	$1.46\ 10^{-8}$	$1.68\ 10^{-10}$	Adult	$7.47\ 10^{-12}$	Adult	$2.05\ 10^{10}$
Eu-155	$1.01\ 10^{-10}$	$1.85\ 10^{-10}$	$4.17\ 10^{-12}$	Adult	$1.33\ 10^{-13}$	Adult	$1.63\ 10^{12}$
Gd-153	$2.76\ 10^{-11}$	$7.10\ 10^{-12}$	$1.47\ 10^{-15}$	Infant	$1.62\ 10^{-14}$	Adult	$1.09\ 10^{13}$
Pb-210	$1.61\ 10^{-10}$	$7.25\ 10^{-11}$	$1.21\ 10^{-9}$	Infant	$1.22\ 10^{-11}$	Adult	$2.18\ 10^{11}$
Po-210	$1.81\ 10^{-10}$	$1.36\ 10^{-15}$	$1.29\ 10^{-10}$	Infant	$4.88\ 10^{-14}$	Adult	$7.12\ 10^{11}$
Ra-226	$1.88\ 10^{-9}$	$2.81\ 10^{-8}$	$3.38\ 10^{-10}$	Child	$1.07\ 10^{-11}$	Adult	$1.07\ 10^{10}$
Ra-228	$8.99\ 10^{-10}$	$1.81\ 10^{-9}$	$2.63\ 10^{-10}$	Child	$6.10\ 10^{-12}$	Child	$1.66\ 10^{11}$
Ac-227	$1.89\ 10^{-9}$	$1.37\ 10^{-9}$	$9.00\ 10^{-13}$	Adult	$1.38\ 10^{-13}$	Adult	$1.59\ 10^{11}$
Th-228	$1.05\ 10^{-9}$	$4.09\ 10^{-10}$	$1.17\ 10^{-10}$	Adult	$2.65\ 10^{-13}$	Adult	$2.85\ 10^{11}$

Radionuclide	Leachate treatment worker ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Reed bed treatment worker ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Farming family ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Limiting age group on farm	Fishing family ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Limiting age group fishing	Scenario radiological capacity (MBq)
Th-229	$8.92\ 10^{-10}$	$2.20\ 10^{-9}$	$2.66\ 10^{-11}$	Adult	$1.56\ 10^{-13}$	Adult	$1.37\ 10^{11}$
Th-230	$2.51\ 10^{-10}$	$1.54\ 10^{-12}$	$2.65\ 10^{-10}$	Adult	$1.90\ 10^{-13}$	Adult	$1.13\ 10^{12}$
Th-232	$2.62\ 10^{-9}$	$1.94\ 10^{-8}$	$1.88\ 10^{-10}$	Adult	$5.67\ 10^{-13}$	Adult	$1.54\ 10^{10}$
Pa-231	$3.84\ 10^{-10}$	$2.01\ 10^{-10}$	$8.17\ 10^{-12}$	Adult	$1.37\ 10^{-13}$	Adult	$7.81\ 10^{11}$
U-232	$4.80\ 10^{-9}$	$2.21\ 10^{-7}$	$1.67\ 10^{-10}$	Infant	$3.68\ 10^{-12}$	Adult	$1.36\ 10^{9}$
U-233	$3.03\ 10^{-11}$	$1.16\ 10^{-11}$	$9.76\ 10^{-12}$	Infant	$9.01\ 10^{-14}$	Adult	$9.89\ 10^{12}$
U-234	$2.95\ 10^{-11}$	$4.44\ 10^{-12}$	$9.48\ 10^{-12}$	Infant	$8.65\ 10^{-14}$	Adult	$1.02\ 10^{13}$
U-235	$1.74\ 10^{-10}$	$9.51\ 10^{-9}$	$1.04\ 10^{-11}$	Infant	$1.74\ 10^{-13}$	Adult	$3.15\ 10^{10}$
U-236	$2.74\ 10^{-11}$	$2.20\ 10^{-12}$	$9.06\ 10^{-12}$	Infant	$8.29\ 10^{-14}$	Adult	$1.09\ 10^{13}$
U-238	$1.21\ 10^{-10}$	$6.19\ 10^{-9}$	$8.97\ 10^{-12}$	Infant	$9.60\ 10^{-14}$	Adult	$4.85\ 10^{10}$
Np-237	$8.74\ 10^{-9}$	$7.83\ 10^{-8}$	$3.20\ 10^{-11}$	Adult	$1.42\ 10^{-11}$	Adult	$3.83\ 10^{9}$
Pu-238	$3.94\ 10^{-10}$	$2.67\ 10^{-13}$	$6.49\ 10^{-12}$	Infant	$2.49\ 10^{-12}$	Adult	$7.61\ 10^{11}$
Pu-239	$4.34\ 10^{-10}$	$9.37\ 10^{-13}$	$9.46\ 10^{-12}$	Infant	$2.72\ 10^{-12}$	Adult	$6.92\ 10^{11}$
Pu-240	$4.34\ 10^{-10}$	$3.47\ 10^{-13}$	$3.47\ 10^{-13}$	Adult	$2.72\ 10^{-12}$	Adult	$6.92\ 10^{11}$
Pu-241	$7.92\ 10^{-12}$	$1.49\ 10^{-14}$	$2.33\ 10^{-13}$	Adult	$4.87\ 10^{-14}$	Adult	$3.79\ 10^{13}$
Pu-242	$3.99\ 10^{-10}$	$1.97\ 10^{-12}$	$8.90\ 10^{-13}$	Infant	$2.72\ 10^{-12}$	Adult	$7.53\ 10^{11}$
Pu-244	$8.75\ 10^{-10}$	$7.57\ 10^{-9}$	$2.06\ 10^{-8}$	Adult	$4.76\ 10^{-12}$	Adult	$1.45\ 10^{10}$
Am-241	$1.80\ 10^{-10}$	$3.80\ 10^{-11}$	$9.34\ 10^{-12}$	Adult	$1.86\ 10^{-14}$	Adult	$1.66\ 10^{12}$
Am-242m	$2.23\ 10^{-10}$	$8.64\ 10^{-11}$	$1.96\ 10^{-11}$	Adult	$3.26\ 10^{-14}$	Adult	$1.35\ 10^{12}$
Am-243	$2.72\ 10^{-10}$	$8.63\ 10^{-10}$	$1.74\ 10^{-12}$	Adult	$1.89\ 10^{-13}$	Adult	$3.47\ 10^{11}$
Cm-242	$7.85\ 10^{-13}$	$8.68\ 10^{-17}$	$4.24\ 10^{-13}$	Adult	$1.21\ 10^{-14}$	Adult	$3.82\ 10^{14}$
Cm-243	$5.06\ 10^{-11}$	$7.61\ 10^{-11}$	$2.49\ 10^{-10}$	Adult	$7.71\ 10^{-15}$	Adult	$3.94\ 10^{12}$
Cm-244	$2.82\ 10^{-11}$	$1.91\ 10^{-14}$	$2.19\ 10^{-10}$	Adult	$6.87\ 10^{-15}$	Adult	$1.07\ 10^{13}$
Cm-245	$6.17\ 10^{-11}$	$9.83\ 10^{-11}$	$3.42\ 10^{-10}$	Adult	$7.21\ 10^{-15}$	Adult	$3.05\ 10^{12}$

Radionuclide	Leachate treatment worker ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Reed bed treatment worker ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Farming family ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Limiting age group on farm	Fishing family ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Limiting age group fishing	Scenario radiological capacity (MBq)
Cm-246	$5.11\ 10^{-11}$	$6.32\ 10^{-12}$	$3.38\ 10^{-10}$	Adult	$4.13\ 10^{-15}$	Adult	$5.88\ 10^{12}$
Cm-248	$4.41\ 10^{-10}$	$2.32\ 10^{-9}$	$1.34\ 10^{-9}$	Adult	$9.19\ 10^{-14}$	Adult	$1.30\ 10^{11}$

812. The doses calculated using illustrative inventories are considered further in Appendix D.

Dose from maximum inventory – Leachate Treatment

813. Off-site treatment of leachate is not used to determine radiological capacity of the landfills. The dose from disposal at the maximum inventory is given in Table 99.

Table 99 Dose for exposure from the off-site treatment of leachate for disposal of the maximum inventory at Port Clarence

Radionuclide	Maximum inventory (MBq)	Leachate treatment worker ($\mu Sv\ y^{-1}$)	Reed bed treatment worker ($\mu Sv\ y^{-1}$)	Farming family ($\mu Sv\ y^{-1}$)	Fishing family ($\mu Sv\ y^{-1}$)
H-3	$1.88\ 10^{8}$	$5.60\ 10^{-4}$	$2.66\ 10^{-3}$	$1.55\ 10^{-3}$	$3.33\ 10^{-7}$
C-14	$1.19\ 10^{8}$	$3.97\ 10^{-4}$	$1.75\ 10^{-2}$	$9.59\ 10^{-4}$	$4.32\ 10^{-4}$
Cl-36	$5.08\ 10^{5}$	$3.09\ 10^{-3}$	$1.99\ 10^{-1}$	$8.77\ 10^{-3}$	$2.00\ 10^{-9}$
Ca-41	$1.05\ 10^{9}$	$2.97\ 10^{-3}$	0	$9.18\ 10^{-2}$	$5.09\ 10^{-7}$
Mn-54	$1.10\ 10^{9}$	$3.31\ 10^{-1}$	$1.10\ 10^{-1}$	$5.60\ 10^{-4}$	$1.07\ 10^{-5}$
Fe-55	$1.10\ 10^{9}$	$4.59\ 10^{-5}$	$1.02\ 10^{-10}$	$4.91\ 10^{-4}$	$2.30\ 10^{-8}$
Co-60	$4.39\ 10^{7}$	$3.08\ 10^{-1}$	$3.96\ 10^{-1}$	$1.63\ 10^{-2}$	$4.57\ 10^{-5}$
Ni-59	$1.10\ 10^{9}$	$7.54\ 10^{-5}$	$8.36\ 10^{-4}$	$2.50\ 10^{-3}$	$7.63\ 10^{-7}$
Ni-63	$1.10\ 10^{9}$	$5.29\ 10^{-4}$	$6.15\ 10^{-3}$	$6.19\ 10^{-3}$	$1.82\ 10^{-6}$
Zn-65	$1.10\ 10^{9}$	$2.50\ 10^{-1}$	$6.51\ 10^{-2}$	$4.48\ 10^{-4}$	$1.79\ 10^{-3}$
Se-79	$4.39\ 10^{8}$	$2.79\ 10^{-3}$	$3.61\ 10^{-2}$	$1.44\ 10^{-1}$	$9.58\ 10^{-4}$
Sr-90	$4.39\ 10^{7}$	$1.56\ 10^{-2}$	$5.18\ 10^{-1}$	$1.03\ 10^{-1}$	$2.68\ 10^{-6}$
Mo-93	$5.95\ 10^{7}$	$9.40\ 10^{-5}$	$1.18\ 10^{-3}$	$2.64\ 10^{-9}$	$2.26\ 10^{-8}$
Zr-93	$1.10\ 10^{9}$	$1.37\ 10^{-3}$	$6.11\ 10^{-3}$	$6.86\ 10^{-8}$	$9.59\ 10^{-8}$
Nb-93m	$1.10\ 10^{9}$	$1.58\ 10^{-5}$	$3.61\ 10^{-5}$	$7.20\ 10^{-9}$	$1.67\ 10^{-8}$
Nb-94	$2.19\ 10^{7}$	$2.10\ 10^{-2}$	$3.33\ 10^{-1}$	$1.20\ 10^{-5}$	$7.57\ 10^{-7}$
Tc-99	$1.73\ 10^{7}$	$7.11\ 10^{-3}$	$4.50\ 10^{-1}$	$4.17\ 10^{-1}$	$8.41\ 10^{-5}$
Ru-106	$1.10\ 10^{9}$	$1.58\ 10^{-1}$	$2.55\ 10^{-1}$	$2.71\ 10^{-4}$	$2.01\ 10^{-4}$
Ag-108m	$2.19\ 10^{7}$	$1.43\ 10^{-1}$	$1.24\ 10^{0}$	$8.94\ 10^{-5}$	$1.08\ 10^{-5}$
Ag-110m	$4.39\ 10^{8}$	$2.07\ 10^{0}$	$3.15\ 10^{-1}$	$2.18\ 10^{-3}$	$2.69\ 10^{-4}$
Cd-109	$1.10\ 10^{9}$	$2.18\ 10^{-3}$	$4.01\ 10^{-3}$	$2.48\ 10^{-4}$	$8.78\ 10^{-4}$
Sb-125	$1.10\ 10^{9}$	$7.88\ 10^{0}$	$5.33\ 10^{0}$	$3.81\ 10^{-3}$	$7.72\ 10^{-4}$
Sn-119m	$1.10\ 10^{9}$	$1.15\ 10^{-4}$	$3.29\ 10^{-5}$	$2.28\ 10^{-2}$	$1.44\ 10^{-5}$
Sn-123	$1.10\ 10^{9}$	$4.98\ 10^{-3}$	$6.99\ 10^{-4}$	$1.75\ 10^{-1}$	$1.20\ 10^{-4}$
Sn-126	$1.10\ 10^{7}$	$1.22\ 10^{-2}$	$1.94\ 10^{-1}$	$4.17\ 10^{-2}$	$1.82\ 10^{-5}$
Te-127m	$1.10\ 10^{9}$	$3.63\ 10^{-4}$	$3.44\ 10^{-5}$	$2.32\ 10^{-1}$	$1.85\ 10^{-3}$
I-129	$4.39\ 10^{7}$	$2.74\ 10^{-2}$	$2.30\ 10^{-1}$	$7.83\ 10^{-2}$	$1.82\ 10^{-4}$
Ba-133	$2.12\ 10^{8}$	$2.29\ 10^{1}$	$3.69\ 10^{2}$	$1.14\ 10^{-1}$	$3.33\ 10^{-3}$
Cs-134	$1.10\ 10^{9}$	$5.79\ 10^{-1}$	$7.38\ 10^{-1}$	$3.26\ 10^{-2}$	$1.71\ 10^{-4}$
Cs-135	$1.10\ 10^{9}$	$1.52\ 10^{-3}$	$3.63\ 10^{-2}$	$5.16\ 10^{-4}$	$5.80\ 10^{-6}$
Cs-137	$4.39\ 10^{7}$	$1.14\ 10^{-2}$	$1.57\ 10^{-1}$	$1.83\ 10^{-4}$	$9.73\ 10^{-6}$

Radionuclide	Maximum inventory (MBq)	Leachate treatment worker (µSv y^{-1})	Reed bed treatment worker (µSv y^{-1})	Farming family (µSv y^{-1})	Fishing family (µSv y^{-1})
Ce-144	1.10 10^{9}	5.24 10^{-3}	1.53 10^{-3}	3.50 10^{-5}	6.66 10^{-6}
Pm-147	1.10 10^{9}	2.74 10^{-3}	2.70 10^{-3}	1.86 10^{-5}	4.15 10^{-7}
Sm-147	3.83 10^{7}	1.15 10^{-3}	0	8.70 10^{-6}	6.00 10^{-6}
Sm-151	1.10 10^{9}	2.13 10^{-4}	2.45 10^{-3}	5.74 10^{-7}	3.44 10^{-7}
Eu-152	4.39 10^{8}	1.86 10^{0}	9.19 10^{0}	8.55 10^{-2}	3.78 10^{-3}
Eu-154	1.10 10^{9}	4.92 10^{0}	1.60 10^{1}	1.85 10^{-1}	8.20 10^{-3}
Eu-155	1.10 10^{9}	1.11 10^{-1}	2.02 10^{-1}	4.57 10^{-3}	1.46 10^{-4}
Gd-153	1.10 10^{9}	3.03 10^{-2}	7.79 10^{-3}	1.61 10^{-6}	1.78 10^{-5}
Pb-210	7.84 10^{6}	1.26 10^{-3}	5.68 10^{-4}	9.49 10^{-3}	9.56 10^{-5}
Po-210	4.39 10^{8}	7.94 10^{-2}	5.97 10^{-7}	5.64 10^{-2}	2.14 10^{-5}
Ra-226	1.39 10^{6}	2.61 10^{-3}	3.91 10^{-2}	4.70 10^{-4}	1.49 10^{-5}
Ra-228	4.39 10^{7}	3.94 10^{-2}	7.95 10^{-2}	1.15 10^{-2}	2.68 10^{-4}
Ac-227	1.10 10^{7}	2.07 10^{-2}	1.50 10^{-2}	9.88 10^{-6}	1.51 10^{-6}
Th-228	4.39 10^{7}	4.62 10^{-2}	1.79 10^{-2}	5.13 10^{-3}	1.16 10^{-5}
Th-229	4.27 10^{6}	3.81 10^{-3}	9.38 10^{-3}	1.14 10^{-4}	6.68 10^{-7}
Th-230	2.03 10^{6}	5.10 10^{-4}	3.13 10^{-6}	5.38 10^{-4}	3.86 10^{-7}
Th-232	2.16 10^{6}	5.68 10^{-3}	4.21 10^{-2}	4.06 10^{-4}	1.23 10^{-6}
Pa-231	7.73 10^{5}	2.97 10^{-4}	1.55 10^{-4}	6.32 10^{-6}	1.06 10^{-7}
U-232	1.10 10^{7}	5.27 10^{-2}	2.43 10^{0}	1.83 10^{-3}	4.04 10^{-5}
U-233	2.52 10^{5}	7.65 10^{-6}	2.93 10^{-6}	2.46 10^{-6}	2.27 10^{-8}
U-234	1.55 10^{6}	4.57 10^{-5}	6.87 10^{-6}	1.47 10^{-5}	1.34 10^{-7}
U-235	2.09 10^{5}	3.63 10^{-5}	1.99 10^{-3}	2.17 10^{-6}	3.64 10^{-8}
U-236	4.24 10^{6}	1.16 10^{-4}	9.33 10^{-6}	3.84 10^{-5}	3.52 10^{-7}
U-238	4.17 10^{6}	5.05 10^{-4}	2.58 10^{-2}	3.74 10^{-5}	4.00 10^{-7}
Np-237	7.47 10^{4}	6.53 10^{-4}	5.85 10^{-3}	2.39 10^{-6}	1.06 10^{-6}
Pu-238	4.39 10^{7}	1.73 10^{-2}	1.17 10^{-5}	2.85 10^{-4}	1.09 10^{-4}
Pu-239	3.89 10^{6}	1.69 10^{-3}	3.65 10^{-6}	3.69 10^{-5}	1.06 10^{-5}
Pu-240	5.98 10^{6}	2.59 10^{-3}	2.08 10^{-6}	2.07 10^{-6}	1.63 10^{-5}
Pu-241	1.10 10^{9}	8.68 10^{-3}	1.63 10^{-5}	2.56 10^{-4}	5.34 10^{-5}
Pu-242	3.41 10^{6}	1.36 10^{-3}	6.70 10^{-6}	3.03 10^{-6}	9.26 10^{-6}
Pu-244	1.80 10^{6}	1.57 10^{-3}	1.36 10^{-2}	3.71 10^{-2}	8.56 10^{-6}
Am-241	2.19 10^{7}	3.96 10^{-3}	8.35 10^{-4}	2.05 10^{-4}	4.09 10^{-7}
Am-242m	2.19 10^{7}	4.88 10^{-3}	1.90 10^{-3}	4.30 10^{-4}	7.16 10^{-7}
Am-243	7.73 10^{6}	2.10 10^{-3}	6.68 10^{-3}	1.35 10^{-5}	1.46 10^{-6}
Cm-242	4.39 10^{8}	3.45 10^{-4}	3.81 10^{-8}	1.86 10^{-4}	5.31 10^{-6}
Cm-243	4.39 10^{7}	2.22 10^{-3}	3.34 10^{-3}	1.09 10^{-2}	3.38 10^{-7}
Cm-244	4.39 10^{7}	1.24 10^{-3}	8.40 10^{-7}	9.60 10^{-3}	3.01 10^{-7}
Cm-245	1.45 10^{7}	8.92 10^{-4}	1.42 10^{-3}	4.94 10^{-3}	1.04 10^{-7}
Cm-246	4.39 10^{7}	2.24 10^{-3}	2.77 10^{-4}	1.48 10^{-2}	1.81 10^{-7}
Cm-248	1.25 10^{6}	5.52 10^{-4}	2.90 10^{-3}	1.68 10^{-3}	1.15 10^{-7}

Dose from Processing Leachate at the WRP

814. Under normal circumstances leachate generated in the landfill is treated on-site through the waste stabilisation plant (about 20,000 m^3 y^{-1}). This process binds the leachate in the stabilisation matrix. The stabilised material is then disposed of in the landfill. Use of leachate at the on-site soil treatment facility is covered by the local assessment for the treatment facility in compliance with the Ionising Radiation Regulations (IRR). The dose criterion used for this scenario is the site criterion of 1 mSv y^{-1} for workers.

815. The impact of treatment on-site uses the model described above for a leachate treatment worker using the following assumptions:

- a leachate throughput of 20,157 m^3 y^{-1};
- a stabilisation process throughput of 120,000 tpa; and,
- a worker spending 375 h y^{-1} in close proximity to the process.

816. On-site treatment of leachate is used to determine radiological capacity of the landfills. The scenario radiological capacity and dose from disposal at the maximum inventory is given in T100.

Table 100 Dose for exposure from the on-site processing of leachate at the WRP

Radionuclide	WRP Leachate treatment worker (µSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)	Maximum inventory (MBq)	Dose at maximum inventory (µSv y^{-1})
H-3	$5.61\ 10^{-11}$	$1.78\ 10^{13}$	$1.88\ 10^{8}$	$1.05\ 10^{-2}$
C-14	$1.02\ 10^{-10}$	$9.82\ 10^{12}$	$1.19\ 10^{8}$	$1.21\ 10^{-2}$
Cl-36	$2.65\ 10^{-7}$	$3.78\ 10^{9}$	$5.08\ 10^{5}$	$1.34\ 10^{-1}$
Ca-41	$6.60\ 10^{-12}$	$1.52\ 10^{14}$	$1.05\ 10^{9}$	$6.93\ 10^{-3}$
Mn-54	$3.23\ 10^{-9}$	$3.10\ 10^{11}$	$1.10\ 10^{9}$	$3.54\ 10^{0}$
Fe-55	$8.69\ 10^{-14}$	$1.15\ 10^{16}$	$1.10\ 10^{9}$	$9.53\ 10^{-5}$
Co-60	$4.79\ 10^{-8}$	$2.09\ 10^{10}$	$4.39\ 10^{7}$	$2.10\ 10^{0}$
Ni-59	$5.90\ 10^{-13}$	$1.70\ 10^{15}$	$1.10\ 10^{9}$	$6.47\ 10^{-4}$
Ni-63	$4.80\ 10^{-12}$	$2.08\ 10^{14}$	$1.10\ 10^{9}$	$5.27\ 10^{-3}$
Zn-65	$2.43\ 10^{-9}$	$4.11\ 10^{11}$	$1.10\ 10^{9}$	$2.67\ 10^{0}$
Se-79	$5.98\ 10^{-11}$	$1.67\ 10^{13}$	$4.39\ 10^{8}$	$2.62\ 10^{-2}$
Sr-90	$1.52\ 10^{-8}$	$6.58\ 10^{10}$	$4.39\ 10^{7}$	$6.67\ 10^{-1}$
Mo-93	$3.53\ 10^{-11}$	$2.84\ 10^{13}$	$5.95\ 10^{7}$	$2.10\ 10^{-3}$
Zr-93	$5.06\ 10^{-12}$	$1.98\ 10^{14}$	$1.10\ 10^{9}$	$5.55\ 10^{-3}$
Nb-93m	$9.36\ 10^{-14}$	$1.07\ 10^{16}$	$1.10\ 10^{9}$	$1.03\ 10^{-4}$
Nb-94	$1.02\ 10^{-8}$	$9.78\ 10^{10}$	$2.19\ 10^{7}$	$2.24\ 10^{-1}$
Tc-99	$1.76\ 10^{-8}$	$5.67\ 10^{10}$	$1.73\ 10^{7}$	$3.06\ 10^{-1}$
Ru-106	$6.27\ 10^{-9}$	$1.59\ 10^{11}$	$1.10\ 10^{9}$	$6.88\ 10^{0}$
Ag-108m	$3.98\ 10^{-8}$	$2.51\ 10^{10}$	$2.19\ 10^{7}$	$8.74\ 10^{-1}$
Ag-110m	$2.88\ 10^{-8}$	$3.48\ 10^{10}$	$4.39\ 10^{8}$	$1.26\ 10^{1}$
Cd-109	$8.27\ 10^{-11}$	$1.21\ 10^{13}$	$1.10\ 10^{9}$	$9.07\ 10^{-2}$

Radionuclide	WRP Leachate treatment worker (µSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)	Maximum inventory (MBq)	Dose at maximum inventory (µSv y^{-1})
Sb-125	$4.91\ 10^{-8}$	$2.04\ 10^{10}$	$1.10\ 10^{9}$	$5.38\ 10^{1}$
Sn-119m	$1.06\ 10^{-12}$	$9.45\ 10^{14}$	$1.10\ 10^{9}$	$1.16\ 10^{-3}$
Sn-123	$4.85\ 10^{-11}$	$2.06\ 10^{13}$	$1.10\ 10^{9}$	$5.32\ 10^{-2}$
Sn-126	$1.19\ 10^{-8}$	$8.38\ 10^{10}$	$1.10\ 10^{7}$	$1.31\ 10^{-1}$
Te-127m	$3.11\ 10^{-12}$	$3.22\ 10^{14}$	$1.10\ 10^{9}$	$3.41\ 10^{-3}$
I-129	$7.85\ 10^{-9}$	$1.27\ 10^{11}$	$4.39\ 10^{7}$	$3.44\ 10^{-1}$
Ba-133	$4.72\ 10^{-6}$	$2.12\ 10^{8}$	$2.12\ 10^{8}$	$1.00\ 10^{3}$
Cs-134	$9.06\ 10^{-9}$	$1.10\ 10^{11}$	$1.10\ 10^{9}$	$9.94\ 10^{0}$
Cs-135	$2.28\ 10^{-11}$	$4.38\ 10^{13}$	$1.10\ 10^{9}$	$2.50\ 10^{-2}$
Cs-137	$4.44\ 10^{-9}$	$2.25\ 10^{11}$	$4.39\ 10^{7}$	$1.95\ 10^{-1}$
Ce-144	$4.98\ 10^{-11}$	$2.01\ 10^{13}$	$1.10\ 10^{9}$	$5.47\ 10^{-2}$
Pm-147	$2.64\ 10^{-11}$	$3.79\ 10^{13}$	$1.10\ 10^{9}$	$2.89\ 10^{-2}$
Sm-147	$1.11\ 10^{-10}$	$9.02\ 10^{12}$	$3.83\ 10^{7}$	$4.25\ 10^{-3}$
Sm-151	$1.94\ 10^{-12}$	$5.14\ 10^{14}$	$1.10\ 10^{9}$	$2.13\ 10^{-3}$
Eu-152	$4.54\ 10^{-8}$	$2.20\ 10^{10}$	$4.39\ 10^{8}$	$1.99\ 10^{1}$
Eu-154	$4.80\ 10^{-8}$	$2.08\ 10^{10}$	$1.10\ 10^{9}$	$5.26\ 10^{1}$
Eu-155	$1.08\ 10^{-9}$	$9.23\ 10^{11}$	$1.10\ 10^{9}$	$1.19\ 10^{0}$
Gd-153	$2.96\ 10^{-10}$	$3.38\ 10^{12}$	$1.10\ 10^{9}$	$3.24\ 10^{-1}$
Pb-210	$4.06\ 10^{-10}$	$2.46\ 10^{12}$	$7.84\ 10^{6}$	$3.18\ 10^{-3}$
Po-210	$3.77\ 10^{-10}$	$2.65\ 10^{12}$	$4.39\ 10^{8}$	$1.65\ 10^{-1}$
Ra-226	$1.95\ 10^{-8}$	$5.13\ 10^{10}$	$1.39\ 10^{6}$	$2.71\ 10^{-2}$
Ra-228	$9.09\ 10^{-9}$	$1.10\ 10^{11}$	$4.39\ 10^{7}$	$3.99\ 10^{-1}$
Ac-227	$5.28\ 10^{-9}$	$1.89\ 10^{11}$	$1.10\ 10^{7}$	$5.79\ 10^{-2}$
Th-228	$6.10\ 10^{-9}$	$1.64\ 10^{11}$	$4.39\ 10^{7}$	$2.68\ 10^{-1}$
Th-229	$2.83\ 10^{-9}$	$3.53\ 10^{11}$	$4.27\ 10^{6}$	$1.21\ 10^{-2}$
Th-230	$5.23\ 10^{-10}$	$1.91\ 10^{12}$	$2.03\ 10^{6}$	$1.06\ 10^{-3}$
Th-232	$1.41\ 10^{-8}$	$7.10\ 10^{10}$	$2.16\ 10^{6}$	$3.05\ 10^{-2}$
Pa-231	$8.86\ 10^{-10}$	$1.13\ 10^{12}$	$7.73\ 10^{5}$	$6.86\ 10^{-4}$
U-232	$2.03\ 10^{-7}$	$4.93\ 10^{9}$	$1.10\ 10^{7}$	$2.22\ 10^{0}$
U-233	$5.26\ 10^{-10}$	$1.90\ 10^{12}$	$2.52\ 10^{5}$	$1.33\ 10^{-4}$
U-234	$5.09\ 10^{-10}$	$1.97\ 10^{12}$	$1.55\ 10^{6}$	$7.89\ 10^{-4}$
U-235	$6.87\ 10^{-9}$	$1.46\ 10^{11}$	$2.09\ 10^{5}$	$1.43\ 10^{-3}$
U-236	$4.72\ 10^{-10}$	$2.12\ 10^{12}$	$4.24\ 10^{6}$	$2.00\ 10^{-3}$
U-238	$4.61\ 10^{-9}$	$2.17\ 10^{11}$	$4.17\ 10^{6}$	$1.92\ 10^{-2}$
Np-237	$6.68\ 10^{-8}$	$1.50\ 10^{10}$	$7.47\ 10^{4}$	$4.99\ 10^{-3}$
Pu-238	$1.46\ 10^{-9}$	$6.84\ 10^{11}$	$4.39\ 10^{7}$	$6.41\ 10^{-2}$
Pu-239	$1.61\ 10^{-9}$	$6.22\ 10^{11}$	$3.89\ 10^{6}$	$6.26\ 10^{-3}$
Pu-240	$1.61\ 10^{-9}$	$6.23\ 10^{11}$	$5.98\ 10^{6}$	$9.61\ 10^{-3}$
Pu-241	$2.93\ 10^{-11}$	$3.41\ 10^{13}$	$1.10\ 10^{9}$	$3.22\ 10^{-2}$

Radionuclide	WRP Leachate treatment worker (µSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)	Maximum inventory (MBq)	Dose at maximum inventory (µSv y^{-1})
Pu-242	1.48 10^{-9}	6.77 10^{11}	3.41 10^{6}	5.04 10^{-3}
Pu-244	6.57 10^{-9}	1.52 10^{11}	1.80 10^{6}	1.18 10^{-2}
Am-241	3.92 10^{-10}	2.55 10^{12}	2.19 10^{7}	8.60 10^{-3}
Am-242m	5.06 10^{-10}	1.97 10^{12}	2.19 10^{7}	1.11 10^{-2}
Am-243	9.49 10^{-10}	1.05 10^{12}	7.73 10^{6}	7.34 10^{-3}
Cm-242	1.64 10^{-12}	6.11 10^{14}	4.39 10^{8}	7.19 10^{-4}
Cm-243	1.68 10^{-10}	5.94 10^{12}	4.39 10^{7}	7.39 10^{-3}
Cm-244	5.85 10^{-11}	1.71 10^{13}	4.39 10^{7}	2.57 10^{-3}
Cm-245	1.72 10^{-10}	5.82 10^{12}	1.45 10^{7}	2.48 10^{-3}
Cm-246	1.09 10^{-10}	9.19 10^{12}	4.39 10^{7}	4.78 10^{-3}
Cm-248	1.94 10^{-9}	5.14 10^{11}	1.25 10^{6}	2.43 10^{-3}

E.3.8. Dose resulting from exposure to waste from a dropped container

817. This scenario applies during the pre-closure phase and the exposed groups are workers and the public.

818. This scenario was also addressed for the ENRMF using a radiological risk assessment for occupational exposure completed by the HPA (Annex C, (Augean, 2009a)). Their conclusion was that with appropriate precautions the worker exposure can be kept within the site criterion under the unlikely circumstance of a dropped container which gives rise to a release.

819. This scenario is not used to constrain landfill capacity because it is independent of the tonnage disposed at Port Clarence. However, worker and public exposure under this scenario are two of the scenarios used to determine the proposed radionuclide activity concentration limits for packaged wastes and for loose tipped wastes (see Section 7.4.1.2 for further details).

820. The dose criteria are the legal dose limit to workers of 20 mSv y^{-1}, the site criterion of 1 mSv y^{-1} for workers and the dose constraint for the public of 0.3 mSv y^{-1}.

Potentially exposed group

821. The assessment of doses from waste released to atmosphere following a dropped load during the operational phase is based on that used in the ENRMF assessment (Augean, 2009a) and subsequently (Eden NE, 2023). The exposed groups are workers and the public (adult, child and infant) and are assumed to be exposed as a result of inhalation of contaminated dust.

822. The load is assumed to be a flexible container that spills a proportion of its load, assumed to contain 200 Bq g^{-1}. The distance to the nearest exposed member of the public is cautiously assumed to be 50 m and the event duration is 30 minutes. The worker remains very close to the dropped waste without taking precautions or

retreating for at least 30 minutes. The inhalation rates used for workers and members of the public are presented in Table 101.

E.3.8.1. Scenario assumptions for estimating doses following a dropped load

823. The scenario is not contained within the SNIFFER model and has been separately addressed. Exposure to both workers and the public has been calculated under the following assumptions using the UKAEA dropped load methodology from the safety assessment handbook [reference 22 of (Augean, 2009a)].

824. The assumptions are as follows.

- A one cubic metre flexible container of wastes is dropped and spills 10% of its contents through broken seams.
- The bag is filled with a dry solid and it is assumed that a fraction (0.001) of the spilt material is released to air.
- The bag contains a single nuclide at 200 Bq g^{-1}.
- The bag weighs 1 tonne.
- The distance to the nearest member of the public is 50 m and the event duration is 30 minutes.
- The worker remains very close to the dropped waste without taking precautions or retreating for at least 30 minutes.
- The atmospheric conditions are worst case, still conditions.

E.3.8.2. Assessment calculation involving a dropped load

825. The dose (Sv y^{-1}) arising from the inhalation of contaminated material is given by:

$$Dose_{inh} = \frac{I \cdot RF_1 \cdot RF_2 \cdot C \cdot B \cdot D_{inh}^{Rn}}{DF}$$

where:

- $Dose_{inh}$ is the dose from inhalation of contaminated material (Sv y^{-1});
- I is the inventory of radionuclide *Rn* released (Bq), from a bag containing 1 t at 200 Bq/g that is spilt, representing 10% of the bag content;
- RF_1 is the fraction of spilt material that becomes suspended (0.001);
- RF_2 is the respirable fraction of suspended material (0.1);
- C is the dispersion coefficient (s m^{-3});
- B is the inhalation rate (m^3 s^{-1});
- D_{inh}^{Rn} is the inhalation dose coefficient for radionuclide *Rn* (Sv Bq^{-1}), see Table 225; and,
- DF is the decontamination factor.

826. The parameters used in this calculation are given in Table 101. The Inventory is calculated assuming that a bag containing 1 t of material at 200 Bq/g (2 10^{8} Bq) spills 10% of its contents (2 10^{7} Bq).

827. Additional ALARA precautions are that the waste acceptance criteria at Port Clarence do not permit disposal of powders, hence the dusts that are released will be fine materials associated with larger masses, e.g., associated with rubble, and therefore comprising a very small fraction of the waste mass. It is therefore assumed that only a small fraction of spilt material (0.001) becomes suspended in air.

828. The respirable fraction (0.1) is that proportion of the material suspended in air that could be inhaled (i.e. 10 micron diameter or less). The inhalation dose coefficients are given in Table 225. The decontamination factor (*DF*) provides for some flexibility in the calculation to allow for clean-up practices. It is assumed in this scenario that there is no clean-up and a value of 1 is applied.

Table 101 Dropped container parameters

Parameter	Units	Value	Description	
I	Bq	2 10^{7}	Radionuclide inventory lost from a container	
RF_1		1 10^{-3}	Release fraction to air	
RF_2		0.1	Respirable fraction	
C	s m^{-3}	5	Dispersion coefficient	Worker
		1.7 10^{-2}		Public
B	m^{3} s^{-1}	4.69 10^{-4}	Inhalation rate	Worker (1.69 m^{3}/h)
		3.35 10^{-4}		Adult (1.21 m^{3}/h)
		2.43 10^{-4}		Child (0.87 m^{3}/h)
		8.52 10^{-5}		Infant (0.31 m^{3}/h)
DF		1	Decontamination factor	

Note: Inhalation rates based on ICRP 66 (ICRP, 1994), see Table 73 for derivation.

E.3.8.3. Dose from a dropped load

829. The effective doses arising from a dropped container are given in Table 102. The results for Ra-226 are independent of the Ra-226 placement depth in the site.

Table 102 Doses from a dropped container containing waste with 200 Bq g^{-1} of the radionuclide

Radionuclide	Dropped load dose assuming 200 Bq g^{-1} in the waste			
	Worker (mSv)	Public Adult (mSv)	Public Child (mSv)	Public Infant (mSv)
H-3	1.22 10^{-6}	2.97 10^{-9}	3.13 10^{-9}	2.90 10^{-9}
C-14	2.72 10^{-5}	6.61 10^{-8}	6.10 10^{-8}	4.92 10^{-8}
Cl-36	3.42 10^{-5}	8.33 10^{-8}	8.25 10^{-8}	7.53 10^{-8}
Ca-41	8.44 10^{-7}	2.05 10^{-9}	2.72 10^{-9}	1.74 10^{-9}
Mn-54	7.03 10^{-6}	1.71 10^{-8}	1.98 10^{-8}	1.80 10^{-8}
Fe-55	3.61 10^{-6}	8.78 10^{-9}	1.15 10^{-8}	9.27 10^{-9}
Co-60	1.45 10^{-4}	3.54 10^{-7}	3.30 10^{-7}	2.49 10^{-7}

Radionuclide	Dropped load dose assuming 200 Bq g^{-1} in the waste			
	Worker (mSv)	Public Adult (mSv)	Public Child (mSv)	Public Infant (mSv)
Ni-59	$2.06\ 10^{-6}$	$5.02\ 10^{-9}$	$4.87\ 10^{-9}$	$4.34\ 10^{-9}$
Ni-63	$6.09\ 10^{-6}$	$1.48\ 10^{-8}$	$1.40\ 10^{-8}$	$1.25\ 10^{-8}$
Zn-65	$1.03\ 10^{-5}$	$2.51\ 10^{-8}$	$3.13\ 10^{-8}$	$2.90\ 10^{-8}$
Se-79	$3.19\ 10^{-5}$	$7.75\ 10^{-8}$	$7.18\ 10^{-8}$	$5.79\ 10^{-8}$
Sr-90	$7.57\ 10^{-4}$	$1.84\ 10^{-6}$	$1.51\ 10^{-6}$	$1.18\ 10^{-6}$
Mo-93	$1.08\ 10^{-5}$	$2.62\ 10^{-8}$	$2.31\ 10^{-8}$	$1.68\ 10^{-8}$
Zr-93	$1.17\ 10^{-4}$	$2.85\ 10^{-7}$	$8.00\ 10^{-8}$	$1.85\ 10^{-8}$
Nb-93m	$8.44\ 10^{-6}$	$2.05\ 10^{-8}$	$2.06\ 10^{-8}$	$1.88\ 10^{-8}$
Nb-94	$2.30\ 10^{-4}$	$5.59\ 10^{-7}$	$4.78\ 10^{-7}$	$3.48\ 10^{-7}$
Tc-99	$6.09\ 10^{-5}$	$1.48\ 10^{-7}$	$1.40\ 10^{-7}$	$1.07\ 10^{-7}$
Ru-106	$3.09\ 10^{-4}$	$7.53\ 10^{-7}$	$7.51\ 10^{-7}$	$6.66\ 10^{-7}$
Ag-108m	$1.73\ 10^{-4}$	$4.22\ 10^{-7}$	$3.63\ 10^{-7}$	$2.52\ 10^{-7}$
Ag-110m	$5.63\ 10^{-5}$	$1.37\ 10^{-7}$	$1.48\ 10^{-7}$	$1.19\ 10^{-7}$
Cd-109	$3.80\ 10^{-5}$	$9.24\ 10^{-8}$	$1.15\ 10^{-7}$	$1.07\ 10^{-7}$
Sb-125	$6.07\ 10^{-5}$	$1.48\ 10^{-7}$	$1.43\ 10^{-7}$	$1.19\ 10^{-7}$
Sn-119m	$1.03\ 10^{-5}$	$2.51\ 10^{-8}$	$2.56\ 10^{-8}$	$2.29\ 10^{-8}$
Sn-123	$3.80\ 10^{-5}$	$9.24\ 10^{-8}$	$9.90\ 10^{-8}$	$8.98\ 10^{-8}$
Sn-126	$1.33\ 10^{-4}$	$3.25\ 10^{-7}$	$3.44\ 10^{-7}$	$2.96\ 10^{-7}$
Te-127m	$4.59\ 10^{-5}$	$1.12\ 10^{-7}$	$1.15\ 10^{-7}$	$9.56\ 10^{-8}$
I-129	$1.69\ 10^{-4}$	$4.11\ 10^{-7}$	$5.53\ 10^{-7}$	$2.49\ 10^{-7}$
Ba-133	$4.69\ 10^{-5}$	$1.14\ 10^{-7}$	$1.07\ 10^{-7}$	$8.40\ 10^{-8}$
Cs-134	$9.38\ 10^{-5}$	$2.28\ 10^{-7}$	$2.31\ 10^{-7}$	$1.82\ 10^{-7}$
Cs-135	$4.03\ 10^{-5}$	$9.81\ 10^{-8}$	$9.07\ 10^{-8}$	$6.95\ 10^{-8}$
Cs-137	$1.83\ 10^{-4}$	$4.45\ 10^{-7}$	$3.96\ 10^{-7}$	$2.90\ 10^{-7}$
Ce-144	$2.48\ 10^{-4}$	$6.04\ 10^{-7}$	$6.43\ 10^{-7}$	$7.82\ 10^{-7}$
Pm-147	$2.34\ 10^{-5}$	$5.70\ 10^{-8}$	$5.77\ 10^{-8}$	$5.21\ 10^{-8}$
Sm-147	$4.50\ 10^{-2}$	$1.09\ 10^{-4}$	$9.07\ 10^{-5}$	$6.66\ 10^{-5}$
Sm-151	$1.88\ 10^{-5}$	$4.56\ 10^{-8}$	$3.71\ 10^{-8}$	$2.90\ 10^{-8}$
Eu-152	$1.97\ 10^{-4}$	$4.79\ 10^{-7}$	$4.04\ 10^{-7}$	$2.90\ 10^{-7}$
Eu-154	$2.48\ 10^{-4}$	$6.04\ 10^{-7}$	$5.36\ 10^{-7}$	$4.34\ 10^{-7}$
Eu-155	$3.23\ 10^{-5}$	$7.87\ 10^{-8}$	$7.59\ 10^{-8}$	$6.66\ 10^{-8}$
Gd-153	$9.84\ 10^{-6}$	$2.39\ 10^{-8}$	$3.22\ 10^{-8}$	$3.48\ 10^{-8}$
Pb-210	$4.68\ 10^{-2}$	$1.14\ 10^{-4}$	$1.09\ 10^{-4}$	$9.36\ 10^{-5}$
Po-210	$2.02\ 10^{-2}$	$4.90\ 10^{-5}$	$4.87\ 10^{-5}$	$4.05\ 10^{-5}$
Ra-226	$9.15\ 10^{-2}$	$2.23\ 10^{-4}$	$2.08\ 10^{-4}$	$1.78\ 10^{-4}$
Ra-228	$2.80\ 10^{-1}$	$6.80\ 10^{-4}$	$6.58\ 10^{-4}$	$6.02\ 10^{-4}$
Ac-227	$2.67\ 10^{0}$	$6.48\ 10^{-3}$	$6.14\ 10^{-3}$	$4.79\ 10^{-3}$
Th-228	$2.04\ 10^{-1}$	$4.97\ 10^{-4}$	$4.92\ 10^{-4}$	$4.63\ 10^{-4}$
Th-229	$1.20\ 10^{0}$	$2.92\ 10^{-3}$	$2.57\ 10^{-3}$	$1.61\ 10^{-3}$

Radionuclide	Dropped load dose assuming 200 Bq g^{-1} in the waste			
	Worker (mSv)	Public Adult (mSv)	Public Child (mSv)	Public Infant (mSv)
Th-230	4.69 10^{-1}	1.14 10^{-3}	9.07 10^{-4}	5.79 10^{-4}
Th-232	7.95 10^{-1}	1.93 10^{-3}	1.73 10^{-3}	1.24 10^{-3}
Pa-231	6.56 10^{-1}	1.60 10^{-3}	1.24 10^{-3}	6.66 10^{-4}
U-232	3.78 10^{-1}	9.19 10^{-4}	8.47 10^{-4}	7.44 10^{-4}
U-233	4.50 10^{-2}	1.09 10^{-4}	9.90 10^{-5}	8.69 10^{-5}
U-234	4.41 10^{-2}	1.07 10^{-4}	9.90 10^{-5}	8.40 10^{-5}
U-235	3.98 10^{-2}	9.69 10^{-5}	9.07 10^{-5}	7.53 10^{-5}
U-236	4.08 10^{-2}	9.92 10^{-5}	9.07 10^{-5}	7.82 10^{-5}
U-238	3.75 10^{-2}	9.13 10^{-5}	8.26 10^{-5}	7.25 10^{-5}
Np-237	2.34 10^{-1}	5.70 10^{-4}	4.12 10^{-4}	2.69 10^{-4}
Pu-238	5.16 10^{-1}	1.25 10^{-3}	9.07 10^{-4}	5.50 10^{-4}
Pu-239	5.63 10^{-1}	1.37 10^{-3}	9.90 10^{-4}	5.79 10^{-4}
Pu-240	5.63 10^{-1}	1.37 10^{-3}	9.90 10^{-4}	5.79 10^{-4}
Pu-241	1.08 10^{-2}	2.62 10^{-5}	1.98 10^{-5}	8.40 10^{-6}
Pu-242	5.16 10^{-1}	1.25 10^{-3}	9.90 10^{-4}	5.50 10^{-4}
Pu-244	5.16 10^{-1}	1.25 10^{-3}	9.90 10^{-4}	5.50 10^{-4}
Am-241	4.50 10^{-1}	1.09 10^{-3}	8.25 10^{-4}	5.21 10^{-4}
Am-242m	5.43 10^{-1}	1.32 10^{-3}	1.00 10^{-3}	5.79 10^{-4}
Am-243	4.50 10^{-1}	1.09 10^{-3}	8.25 10^{-4}	4.92 10^{-4}
Cm-242	2.77 10^{-2}	6.73 10^{-5}	6.76 10^{-5}	6.08 10^{-5}
Cm-243	3.25 10^{-1}	7.90 10^{-4}	6.05 10^{-4}	4.36 10^{-4}
Cm-244	2.67 10^{-1}	6.50 10^{-4}	5.03 10^{-4}	3.77 10^{-4}
Cm-245	4.64 10^{-1}	1.13 10^{-3}	8.25 10^{-4}	5.21 10^{-4}
Cm-246	4.59 10^{-1}	1.12 10^{-3}	8.25 10^{-4}	5.21 10^{-4}
Cm-248	1.69 10^{0}	4.11 10^{-3}	3.05 10^{-3}	1.88 10^{-3}

830. The dropped load assessment is one of the exposure scenarios used to determine the limiting activity concentrations in waste consignments. The potential impact from specific radionuclide concentrations in the waste is calculated by scaling the doses given in Table 102 by the proposed activity concentration limit (see Section 7.4.1.2). The limiting activity concentrations proposed for the Port Clarence waste acceptance criteria are lower than those that can be calculated using this scenario based on public exposure. All doses to the public are below 0.01 mSv at the proposed limiting activity concentrations. We also test that the maximum activity concentration per package that is part of a consignment (a factor of 1 to 5 above the consignment activity limit), remains appropriate. For members of the public, this demonstrates that the maximum consignment average and peak activity concentrations are appropriate and that the dose constraint for members of the public is not exceeded.

831. The doses from a bag containing 200 Bq/g meet the site criterion for workers for all radionuclides except Ac-227, Th-229 and Cm-248. Although emergency plans applied in the event of a spill would reduce the potential exposure of workers, this scenario is now used to limit activity concentrations in waste consignments. The doses from a bag

containing waste at the consignment average limit and the package limit are presented in Table 103.

Table 103 Doses from a dropped container containing waste at the consignment average and package limits

Radionuclide	Consignment average limit (Bq g^{-1})	Waste at consignment average limit		Waste at package limit	
		Worker (mSv)	Public maximum (mSv)	Worker (mSv)	Public maximum (mSv)
H-3	5000	3.05 10^{-5}	7.84 10^{-8}	3.05 10^{-5}	7.84 10^{-8}
C-14	5000	6.80 10^{-4}	1.65 10^{-6}	6.80 10^{-4}	1.65 10^{-6}
Cl-36	5000	8.55 10^{-4}	2.08 10^{-6}	8.55 10^{-4}	2.08 10^{-6}
Ca-41	5000	2.11 10^{-5}	6.80 10^{-8}	2.11 10^{-5}	6.80 10^{-8}
Mn-54	5000	1.76 10^{-4}	4.95 10^{-7}	1.76 10^{-4}	4.95 10^{-7}
Fe-55	5000	9.02 10^{-5}	2.89 10^{-7}	9.02 10^{-5}	2.89 10^{-7}
Co-60	200	1.45 10^{-4}	3.54 10^{-7}	7.27 10^{-4}	1.77 10^{-6}
Ni-59	5000	5.16 10^{-5}	1.25 10^{-7}	5.16 10^{-5}	1.25 10^{-7}
Ni-63	5000	1.52 10^{-4}	3.71 10^{-7}	1.52 10^{-4}	3.71 10^{-7}
Zn-65	5000	2.58 10^{-4}	7.84 10^{-7}	2.58 10^{-4}	7.84 10^{-7}
Se-79	2000	3.19 10^{-4}	7.75 10^{-7}	4.78 10^{-4}	1.16 10^{-6}
Sr-90	200	7.57 10^{-4}	1.84 10^{-6}	3.79 10^{-3}	9.21 10^{-6}
Mo-93	5000	2.70 10^{-4}	6.56 10^{-7}	2.70 10^{-4}	6.56 10^{-7}
Zr-93	5000	2.93 10^{-3}	7.13 10^{-6}	2.93 10^{-3}	7.13 10^{-6}
Nb-93m	5000	2.11 10^{-4}	5.16 10^{-7}	2.11 10^{-4}	5.16 10^{-7}
Nb-94	100	1.15 10^{-4}	2.79 10^{-7}	5.74 10^{-4}	1.40 10^{-6}
Tc-99	200	6.09 10^{-5}	1.48 10^{-7}	3.05 10^{-4}	7.41 10^{-7}
Ru-106	5000	7.73 10^{-3}	1.88 10^{-5}	7.73 10^{-3}	1.88 10^{-5}
Ag-108m	100	8.67 10^{-5}	2.11 10^{-7}	4.34 10^{-4}	1.05 10^{-6}
Ag-110m	2000	5.63 10^{-4}	1.48 10^{-6}	8.44 10^{-4}	2.23 10^{-6}
Cd-109	5000	9.49 10^{-4}	2.89 10^{-6}	9.49 10^{-4}	2.89 10^{-6}
Sb-125	5000	1.52 10^{-3}	3.69 10^{-6}	1.52 10^{-3}	3.69 10^{-6}
Sn-119m	5000	2.58 10^{-4}	6.39 10^{-7}	2.58 10^{-4}	6.39 10^{-7}
Sn-123	5000	9.49 10^{-4}	2.47 10^{-6}	9.49 10^{-4}	2.47 10^{-6}
Sn-126	50	3.34 10^{-5}	8.61 10^{-8}	1.67 10^{-4}	4.30 10^{-7}
Te-127m	5000	1.15 10^{-3}	2.89 10^{-6}	1.15 10^{-3}	2.89 10^{-6}
I-129	200	1.69 10^{-4}	5.53 10^{-7}	8.44 10^{-4}	2.76 10^{-6}
Ba-133	5000	1.17 10^{-3}	2.85 10^{-6}	1.17 10^{-3}	2.85 10^{-6}
Cs-134	5000	2.34 10^{-3}	5.77 10^{-6}	2.34 10^{-3}	5.77 10^{-6}
Cs-135	5000	1.01 10^{-3}	2.45 10^{-6}	1.01 10^{-3}	2.45 10^{-6}
Cs-137	200	1.83 10^{-4}	4.45 10^{-7}	9.14 10^{-4}	2.22 10^{-6}
Ce-144	5000	6.21 10^{-3}	1.96 10^{-5}	6.21 10^{-3}	1.96 10^{-5}
Pm-147	5000	5.86 10^{-4}	1.44 10^{-6}	5.86 10^{-4}	1.44 10^{-6}
Sm-147	200	4.50 10^{-2}	1.09 10^{-4}	2.25 10^{-1}	5.47 10^{-4}

Radionuclide	Consignment average limit (Bq g^{-1})	Waste at consignment average limit		Waste at package limit	
		Worker (mSv)	Public maximum (mSv)	Worker (mSv)	Public maximum (mSv)
Sm-151	5000	4.69 10^{-4}	1.14 10^{-6}	4.69 10^{-4}	1.14 10^{-6}
Eu-152	2000	1.97 10^{-3}	4.79 10^{-6}	2.95 10^{-3}	7.18 10^{-6}
Eu-154	5000	6.21 10^{-3}	1.51 10^{-5}	6.21 10^{-3}	1.51 10^{-5}
Eu-155	5000	8.09 10^{-4}	1.97 10^{-6}	8.09 10^{-4}	1.97 10^{-6}
Gd-153	5000	2.46 10^{-4}	8.69 10^{-7}	2.46 10^{-4}	8.69 10^{-7}
Pb-210	50	1.17 10^{-2}	2.85 10^{-5}	5.86 10^{-2}	1.42 10^{-4}
Po-210	2000	2.02 10^{-1}	4.90 10^{-4}	3.02 10^{-1}	7.36 10^{-4}
Ra-226	10	4.58 10^{-3}	1.11 10^{-5}	2.29 10^{-2}	5.57 10^{-5}
Ra-228	200	2.80 10^{-1}	6.80 10^{-4}	1.40 10^{0}	3.40 10^{-3}
Ac-227	50	6.66 10^{-1}	1.62 10^{-3}	3.33 10^{0}	8.11 10^{-3}
Th-228	200	2.04 10^{-1}	4.97 10^{-4}	1.02 10^{0}	2.49 10^{-3}
Th-229	20	1.20 10^{-1}	2.92 10^{-4}	6.01 10^{-1}	1.46 10^{-3}
Th-230	100	2.34 10^{-1}	5.70 10^{-4}	1.17 10^{0}	2.85 10^{-3}
Th-232	10	3.98 10^{-2}	9.67 10^{-5}	1.99 10^{-1}	4.84 10^{-4}
Pa-231	10	3.28 10^{-2}	7.98 10^{-5}	1.64 10^{-1}	3.99 10^{-4}
U-232	50	9.45 10^{-2}	2.30 10^{-4}	4.72 10^{-1}	1.15 10^{-3}
U-233	200	4.50 10^{-2}	1.09 10^{-4}	2.25 10^{-1}	5.47 10^{-4}
U-234	200	4.41 10^{-2}	1.07 10^{-4}	2.20 10^{-1}	5.36 10^{-4}
U-235	200	3.98 10^{-2}	9.69 10^{-5}	1.99 10^{-1}	4.85 10^{-4}
U-236	200	4.08 10^{-2}	9.92 10^{-5}	2.04 10^{-1}	4.96 10^{-4}
U-238	200	3.75 10^{-2}	9.13 10^{-5}	1.88 10^{-1}	4.57 10^{-4}
Np-237	200	2.34 10^{-1}	5.70 10^{-4}	1.17 10^{0}	2.85 10^{-3}
Pu-238	200	5.16 10^{-1}	1.25 10^{-3}	2.58 10^{0}	6.27 10^{-3}
Pu-239	100	2.81 10^{-1}	6.84 10^{-4}	1.41 10^{0}	3.42 10^{-3}
Pu-240	200	5.63 10^{-1}	1.37 10^{-3}	2.81 10^{0}	6.84 10^{-3}
Pu-241	5000	2.70 10^{-1}	6.56 10^{-4}	2.70 10^{-1}	6.56 10^{-4}
Pu-242	200	5.16 10^{-1}	1.25 10^{-3}	2.58 10^{0}	6.27 10^{-3}
Pu-244	200	5.16 10^{-1}	1.25 10^{-3}	2.58 10^{0}	6.27 10^{-3}
Am-241	100	2.25 10^{-1}	5.47 10^{-4}	1.13 10^{0}	2.74 10^{-3}
Am-242m	100	2.71 10^{-1}	6.60 10^{-4}	1.36 10^{0}	3.30 10^{-3}
Am-243	200	4.50 10^{-1}	1.09 10^{-3}	2.25 10^{0}	5.47 10^{-3}
Cm-242	2000	2.77 10^{-1}	6.76 10^{-4}	4.15 10^{-1}	1.01 10^{-3}
Cm-243	200	3.25 10^{-1}	7.90 10^{-4}	1.62 10^{0}	3.95 10^{-3}
Cm-244	200	2.67 10^{-1}	6.50 10^{-4}	1.34 10^{0}	3.25 10^{-3}
Cm-245	200	4.64 10^{-1}	1.13 10^{-3}	2.32 10^{0}	5.65 10^{-3}
Cm-246	200	4.59 10^{-1}	1.12 10^{-3}	2.30 10^{0}	5.59 10^{-3}
Cm-248	50	4.22 10^{-1}	1.03 10^{-3}	2.11 10^{0}	5.13 10^{-3}

832. With the proposed activity concentrations in a consignment the maximum dose to a worker is then 0.67 mSv. We also test that the activity concentration per package, that is part of a consignment (a factor of 1 to 5 above the consignment activity limit), to determine if this remains appropriate. In a number of cases (Ra-228, Ac-227, Th-228, Th-230, Np-237, Pu-238, Pu-239, Pu-240, Pu-242, Pu-244, Am-241, Am-242m, Am-243, Cm-243, Cm-244, Cm-245, Cm-246 and Cm-248), the worker dose from exposure to a release from a package containing the maximum activity concentration proposed for a package in a consignment could exceed the site worker criterion. An assessment based on the maximum recorded activity concentrations of LLW disposed of at the ENRMF shows that none of these radionuclides would lead to a dose that exceeds the site worker criterion. We also note that local rules for dealing with a spillage will ensure that workers are protected and that the estimated doses are less than the criterion of 6 mSv for classifying workers as radiation workers.

833. The Port Clarence emergency plans are found in the local rules for handling LLW. These rules detail the mitigation measures that would be taken, in the event that LLW is found to have escaped from a container, as follows:

- If a person is suspected of being contaminated, they should change and wash exposed skin, and then be checked with a contamination monitor to confirm that they are clean;
- Where possible, steps to avoid spreading contamination should be taken. The aim should be to:
  - avoid disturbing any loose contamination;
  - designate the immediate area as a Controlled Area;
  - plan the clean-up operation under the supervision of an RPS;
  - a Controlled Area entry/exit point should be set up, and ensure that persons and equipment leaving the area are checked for contamination;
  - as a precaution, persons involved in cleaning up spills should wear Respiratory Protective Equipment RPE with a minimum protection factor of 5;
  - steps to minimise airborne dust during the clean-up should be taken, for example damping down; and,
  - all spilled LLW should be placed into a suitable disposal container, and then disposed of in accordance with normal procedures.
- The area of the spill should be monitored after cleaning to ensure that no residual contamination exists. If the area remains contaminated, the Controlled Area should remain and the RPA should be consulted. If the area is clean, the Controlled Area should be de-designated.

834. A key measure to mitigate dropped load dispersion events will be to use waste containers that are engineered to withstand or substantially withstand accidental drops during handling. Where drums are used these will be rated under existing dangerous good transport regulations for radioactive material to withstand a drop test. Flexible containers may only be used where this is acceptable under dangerous goods

transport regulations (i.e. they are rated to withstand a drop test). In addition, the above assessment calculations assume that the bag contains loose dry material that disperses readily, that the packaging fails and that the worker does not respond correctly. These are highly conservative assumptions. Hence, studies for the ENRMF (Eden NE, 2023) concluded that an activity concentration of 200 Bq g^{-1} could be applied to all radionuclides in the wastes disposed of at the site. The same conclusion is also valid for Port Clarence.

835. This scenario has not been used to constrain the radiological capacity because it has a low probability of occurrence and is independent of the total tonnage and total activity received at Port Clarence.

836. The exposure of the public and workers in this scenario are considered when determining the proposed radionuclide activity concentration limits for packaged wastes (see Section 7.4.1.2 for further details).

E.3.8.4. Dose from spillage from a tipper

837. The model for a dropped load has been adapted to consider a greater spillage (20% of the consignment is released) from a tipper truck load (of 20 t) to assess the potential impact of a load destined for loose tipping. The greater load (x20) and increased fraction spilt (x2) increases potential doses by a factor of 40. The potential impact from a different specific activity concentration in the waste is calculated by scaling the doses given in Table 104 by the activity concentration (see Section 7.4.1.2). The exposure of the public and workers in this scenario are considered when determining the proposed radionuclide activity concentration limits for loose tipped wastes (see Section 7.4.1.2 for further details).

Table 104 Doses from a tipper truck load spillage assuming 200 Bq g^{-1} in the load

Radionuclide	Tipper truck load spillage			
	Worker (mSv)	Public Adult (mSv)	Public Child (mSv)	Public Infant (mSv)
H-3	$4.88\ 10^{-5}$	$1.19\ 10^{-7}$	$1.25\ 10^{-7}$	$1.16\ 10^{-7}$
C-14	$1.09\ 10^{-3}$	$2.65\ 10^{-6}$	$2.44\ 10^{-6}$	$1.97\ 10^{-6}$
Cl-36	$1.37\ 10^{-3}$	$3.33\ 10^{-6}$	$3.30\ 10^{-6}$	$3.01\ 10^{-6}$
Ca-41	$3.38\ 10^{-5}$	$8.21\ 10^{-8}$	$1.09\ 10^{-7}$	$6.95\ 10^{-8}$
Mn-54	$2.81\ 10^{-4}$	$6.84\ 10^{-7}$	$7.92\ 10^{-7}$	$7.18\ 10^{-7}$
Fe-55	$1.44\ 10^{-4}$	$3.51\ 10^{-7}$	$4.62\ 10^{-7}$	$3.71\ 10^{-7}$
Co-60	$5.81\ 10^{-3}$	$1.41\ 10^{-5}$	$1.32\ 10^{-5}$	$9.96\ 10^{-6}$
Ni-59	$8.25\ 10^{-5}$	$2.01\ 10^{-7}$	$1.95\ 10^{-7}$	$1.74\ 10^{-7}$
Ni-63	$2.44\ 10^{-4}$	$5.93\ 10^{-7}$	$5.61\ 10^{-7}$	$4.98\ 10^{-7}$
Zn-65	$4.13\ 10^{-4}$	$1.00\ 10^{-6}$	$1.25\ 10^{-6}$	$1.16\ 10^{-6}$
Se-79	$1.28\ 10^{-3}$	$3.10\ 10^{-6}$	$2.87\ 10^{-6}$	$2.32\ 10^{-6}$
Sr-90	$3.03\ 10^{-2}$	$7.37\ 10^{-5}$	$6.03\ 10^{-5}$	$4.74\ 10^{-5}$
Mo-93	$4.31\ 10^{-4}$	$1.05\ 10^{-6}$	$9.24\ 10^{-7}$	$6.72\ 10^{-7}$
Zr-93	$4.69\ 10^{-3}$	$1.14\ 10^{-5}$	$3.20\ 10^{-6}$	$7.41\ 10^{-7}$
Nb-93m	$3.38\ 10^{-4}$	$8.21\ 10^{-7}$	$8.25\ 10^{-7}$	$7.53\ 10^{-7}$

Radionuclide	Tipper truck load spillage			
	Worker (mSv)	Public Adult (mSv)	Public Child (mSv)	Public Infant (mSv)
Nb-94	$9.19\ 10^{-3}$	$2.24\ 10^{-5}$	$1.91\ 10^{-5}$	$1.39\ 10^{-5}$
Tc-99	$2.44\ 10^{-3}$	$5.93\ 10^{-6}$	$5.61\ 10^{-6}$	$4.29\ 10^{-6}$
Ru-106	$1.24\ 10^{-2}$	$3.01\ 10^{-5}$	$3.00\ 10^{-5}$	$2.66\ 10^{-5}$
Ag-108m	$6.94\ 10^{-3}$	$1.69\ 10^{-5}$	$1.45\ 10^{-5}$	$1.01\ 10^{-5}$
Ag-110m	$2.25\ 10^{-3}$	$5.47\ 10^{-6}$	$5.94\ 10^{-6}$	$4.75\ 10^{-6}$
Cd-109	$1.52\ 10^{-3}$	$3.69\ 10^{-6}$	$4.62\ 10^{-6}$	$4.29\ 10^{-6}$
Sb-125	$2.43\ 10^{-3}$	$5.91\ 10^{-6}$	$5.72\ 10^{-6}$	$4.75\ 10^{-6}$
Sn-119m	$4.13\ 10^{-4}$	$1.00\ 10^{-6}$	$1.02\ 10^{-6}$	$9.15\ 10^{-7}$
Sn-123	$1.52\ 10^{-3}$	$3.69\ 10^{-6}$	$3.96\ 10^{-6}$	$3.59\ 10^{-6}$
Sn-126	$5.34\ 10^{-3}$	$1.30\ 10^{-5}$	$1.38\ 10^{-5}$	$1.18\ 10^{-5}$
Te-127m	$1.84\ 10^{-3}$	$4.47\ 10^{-6}$	$4.62\ 10^{-6}$	$3.82\ 10^{-6}$
I-129	$6.75\ 10^{-3}$	$1.64\ 10^{-5}$	$2.21\ 10^{-5}$	$9.96\ 10^{-6}$
Ba-133	$1.88\ 10^{-3}$	$4.56\ 10^{-6}$	$4.29\ 10^{-6}$	$3.36\ 10^{-6}$
Cs-134	$3.75\ 10^{-3}$	$9.12\ 10^{-6}$	$9.24\ 10^{-6}$	$7.30\ 10^{-6}$
Cs-135	$1.61\ 10^{-3}$	$3.92\ 10^{-6}$	$3.63\ 10^{-6}$	$2.78\ 10^{-6}$
Cs-137	$7.31\ 10^{-3}$	$1.78\ 10^{-5}$	$1.58\ 10^{-5}$	$1.16\ 10^{-5}$
Ce-144	$9.94\ 10^{-3}$	$2.42\ 10^{-5}$	$2.57\ 10^{-5}$	$3.13\ 10^{-5}$
Pm-147	$9.38\ 10^{-4}$	$2.28\ 10^{-6}$	$2.31\ 10^{-6}$	$2.09\ 10^{-6}$
Sm-147	$1.80\ 10^{0}$	$4.38\ 10^{-3}$	$3.63\ 10^{-3}$	$2.66\ 10^{-3}$
Sm-151	$7.50\ 10^{-4}$	$1.82\ 10^{-6}$	$1.48\ 10^{-6}$	$1.16\ 10^{-6}$
Eu-152	$7.88\ 10^{-3}$	$1.92\ 10^{-5}$	$1.62\ 10^{-5}$	$1.16\ 10^{-5}$
Eu-154	$9.94\ 10^{-3}$	$2.42\ 10^{-5}$	$2.14\ 10^{-5}$	$1.74\ 10^{-5}$
Eu-155	$1.29\ 10^{-3}$	$3.15\ 10^{-6}$	$3.04\ 10^{-6}$	$2.66\ 10^{-6}$
Gd-153	$3.94\ 10^{-4}$	$9.58\ 10^{-7}$	$1.29\ 10^{-6}$	$1.39\ 10^{-6}$
Pb-210	$1.87\ 10^{0}$	$4.56\ 10^{-3}$	$4.36\ 10^{-3}$	$3.74\ 10^{-3}$
Po-210	$8.06\ 10^{-1}$	$1.96\ 10^{-3}$	$1.95\ 10^{-3}$	$1.62\ 10^{-3}$
Ra-226	$3.66\ 10^{0}$	$8.91\ 10^{-3}$	$8.34\ 10^{-3}$	$7.11\ 10^{-3}$
Ra-228	$1.12\ 10^{1}$	$2.72\ 10^{-2}$	$2.63\ 10^{-2}$	$2.41\ 10^{-2}$
Ac-227	$1.07\ 10^{2}$	$2.59\ 10^{-1}$	$2.46\ 10^{-1}$	$1.92\ 10^{-1}$
Th-228	$8.18\ 10^{0}$	$1.99\ 10^{-2}$	$1.97\ 10^{-2}$	$1.85\ 10^{-2}$
Th-229	$4.80\ 10^{1}$	$1.17\ 10^{-1}$	$1.03\ 10^{-1}$	$6.43\ 10^{-2}$
Th-230	$1.88\ 10^{1}$	$4.56\ 10^{-2}$	$3.63\ 10^{-2}$	$2.32\ 10^{-2}$
Th-232	$3.18\ 10^{1}$	$7.74\ 10^{-2}$	$6.92\ 10^{-2}$	$4.96\ 10^{-2}$
Pa-231	$2.63\ 10^{1}$	$6.39\ 10^{-2}$	$4.95\ 10^{-2}$	$2.66\ 10^{-2}$
U-232	$1.51\ 10^{1}$	$3.68\ 10^{-2}$	$3.39\ 10^{-2}$	$2.98\ 10^{-2}$
U-233	$1.80\ 10^{0}$	$4.38\ 10^{-3}$	$3.96\ 10^{-3}$	$3.48\ 10^{-3}$
U-234	$1.76\ 10^{0}$	$4.29\ 10^{-3}$	$3.96\ 10^{-3}$	$3.36\ 10^{-3}$
U-235	$1.59\ 10^{0}$	$3.88\ 10^{-3}$	$3.63\ 10^{-3}$	$3.01\ 10^{-3}$
U-236	$1.63\ 10^{0}$	$3.97\ 10^{-3}$	$3.63\ 10^{-3}$	$3.13\ 10^{-3}$

Radionuclide	Tipper truck load spillage			
	Worker (mSv)	Public Adult (mSv)	Public Child (mSv)	Public Infant (mSv)
U-238	$1.50\ 10^{0}$	$3.65\ 10^{-3}$	$3.30\ 10^{-3}$	$2.90\ 10^{-3}$
Np-237	$9.38\ 10^{0}$	$2.28\ 10^{-2}$	$1.65\ 10^{-2}$	$1.08\ 10^{-2}$
Pu-238	$2.06\ 10^{1}$	$5.02\ 10^{-2}$	$3.63\ 10^{-2}$	$2.20\ 10^{-2}$
Pu-239	$2.25\ 10^{1}$	$5.47\ 10^{-2}$	$3.96\ 10^{-2}$	$2.32\ 10^{-2}$
Pu-240	$2.25\ 10^{1}$	$5.47\ 10^{-2}$	$3.96\ 10^{-2}$	$2.32\ 10^{-2}$
Pu-241	$4.31\ 10^{-1}$	$1.05\ 10^{-3}$	$7.92\ 10^{-4}$	$3.36\ 10^{-4}$
Pu-242	$2.06\ 10^{1}$	$5.02\ 10^{-2}$	$3.96\ 10^{-2}$	$2.20\ 10^{-2}$
Pu-244	$2.06\ 10^{1}$	$5.02\ 10^{-2}$	$3.96\ 10^{-2}$	$2.20\ 10^{-2}$
Am-241	$1.80\ 10^{1}$	$4.38\ 10^{-2}$	$3.30\ 10^{-2}$	$2.09\ 10^{-2}$
Am-242m	$2.17\ 10^{1}$	$5.28\ 10^{-2}$	$4.01\ 10^{-2}$	$2.32\ 10^{-2}$
Am-243	$1.80\ 10^{1}$	$4.38\ 10^{-2}$	$3.30\ 10^{-2}$	$1.97\ 10^{-2}$
Cm-242	$1.11\ 10^{0}$	$2.69\ 10^{-3}$	$2.71\ 10^{-3}$	$2.43\ 10^{-3}$
Cm-243	$1.30\ 10^{1}$	$3.16\ 10^{-2}$	$2.42\ 10^{-2}$	$1.74\ 10^{-2}$
Cm-244	$1.07\ 10^{1}$	$2.60\ 10^{-2}$	$2.01\ 10^{-2}$	$1.51\ 10^{-2}$
Cm-245	$1.86\ 10^{1}$	$4.52\ 10^{-2}$	$3.30\ 10^{-2}$	$2.09\ 10^{-2}$
Cm-246	$1.84\ 10^{1}$	$4.47\ 10^{-2}$	$3.30\ 10^{-2}$	$2.09\ 10^{-2}$
Cm-248	$6.75\ 10^{1}$	$1.64\ 10^{-1}$	$1.22\ 10^{-1}$	$7.53\ 10^{-2}$

E.3.9. Wound exposure

838. Radionuclides can enter the body via wounds and absorption through intact skin. This is not a reasonably foreseeable scenario under normal circumstances. However, it is a possible accident scenario. Management of the health and safety aspects of working with radioactive substances falls under the remit of the Ionising Radiation Regulations 2017 and is enforced by the Health and Safety Executive. This information is provided in the ESC for information and as evidence of the Environmental Safety Culture and Management Systems in place within the company.

839. Exposure due to radionuclides embedded in a wound is relevant to landfill site workers during the pre-closure phase. The scenario is not considered in the SNIFFER landfill assessment model.

840. While much of the material may be retained at the wound site, soluble material can be transferred to the blood and hence to other parts of the body. Insoluble material will be slowly translocated to regional lymphatic tissue, where it will gradually dissolve and eventually enter the blood (IAEA, 2004). A variable fraction of insoluble material can be retained at the wound site or in lymphatic tissue for the life of the individual. If the materials deposited in a wound are soluble, then they may translocate to the blood with a time course that depends on their dissolution rate in vivo. The distribution of this soluble component will, in most instances, be similar to that entering the blood from the lungs or GI tract. The biokinetic models developed by the ICRP can be used for the calculation of the effective dose arising from the soluble component once the systemic uptake has been determined. As a first approximation, data for direct uptake to blood (injection) can be used.

841. The National Council on Radiation Protection and Measurements Report No. 156 (NCRP, 2007), presents a biokinetic model for intakes of radionuclides via contaminated wounds. The model comprises seven categories that describe the behaviour of the injected radioactive material as a function of its physical and chemical form. Materials injected in soluble form are described by their retention at the wound site as either weakly retained, moderately retained, strongly retained or avidly retained, in order of increasing retention half-time, as determined primarily in rats. Three additional categories: Colloid, Particle, and Fragment, complete the classification. The first four categories reflect the compound's solubility in water, whereas the Colloid and Particle categories are based on the behaviour of injected plutonium compounds in animal models, and the Fragment category is based on the behaviour of uranium metal implants in animal models. A further distinction is made between particles and fragments in that fragments are too large to be ingested by connective tissue macrophages, i.e., fragments are greater than 100 µm in any dimension.

842. In order to assess the dose arising from contamination entering a wound it is necessary to estimate the quantity of material in the wound and the category of the contamination. A person would clean the wound, so removing some of the contamination. In one case (Schadilov, et al., 2010), the residual contamination within the wound after cleaning amounted to 0.05% of the initial contamination; in another case about 70% of the initial wound activity was removed by physical (surgical) means (Bailey, et al., 2003). It was also noted (Toohey, et al., 2014) that the activity in the body cleared more quickly than was assumed in the NCRP model. It has been remarked that more than 80% of contaminated puncture wounds exceed 1 mm in depth (Ilyn, 2001).

843. Two situations are considered here: a minor cut that is ignored and a more significant gash that is cleaned promptly.

844. A minor cut 10 mm long and 1mm wide is considered. The top layer of skin is the keratinised 'dead' layer so no transfer into the blood stream is assumed to take place in this layer. On the palm of the hand this depth is about 400 microns, and the average over the body is 70 microns. It is assumed that the wound extends 0.5 mm into the 'active' layer below this keratinised layer, causing a small amount of bleeding which soon stops. The wound is then left to 'heal itself' with the contaminated material (dust) still in place. The quantity of dust in the wound is 10 x 1 x 0.5 mm^3 i.e. 5 mm^3, corresponding to 0.0078 g using a density of 1.53 g cm^{-3}.

845. A gash 4 cm long is assumed to be contaminated to a depth of 2 mm and to be 1 mm wide. If full of contaminated dust this would contain 80 mm^3 (0.08 cm^3), corresponding to 0.2 g of dust. This would be attended to promptly as it would bleed and be painful. Assuming that the wound is cleaned up within a few hours and that 95% is removed, this leaves 0.0061 g of contaminated concrete in the wound.

846. The two different scenarios result in similar estimates of the quantity remaining in the wound. Hence, a reasonable assumption to use for this scenario would be to assume that 0.01 g of material is in the wound.

847. The effective dose coefficients using the NCRP model are presented in (Toohey, et al., 2014) and dose coefficients for injection are presented in (IAEA, 2004). Doses were calculated from the injection dose coefficients and from each NCRP category dose coefficient (results for the worst dose coefficient are presented below).

848. In practice, material likely to be entering a wound would be dust or grit, which are not soluble. As such, using the 'fragment' category dose coefficient is the most realistic.

The maximum dose from all NCRP categories and the dose using the fragment dose coefficient for a waste activity concentration of 1 Bq g^{-1} are presented in Table 106. The ratio of the fragment dose coefficient and the dose coefficient resulting in the highest dose is also presented. The fragment dose coefficients are two to three orders of magnitude smaller than the coefficients resulting in the highest dose.

849. The doses associated with the consignment average limit (Table 105) and less likely event involving package limit (Table 106) are presented below.

Table 105 Wound doses using consignment average limit

Radionuclide	Fragment dose coefficient (Sv/Bq)	Worst dose coefficient (Sv/Bq)	Ratio fragment dose to worst dose	Fragment dose from consignment average limit (mSv)	Maximum dose from consignment average limit (mSv)
H-3	$4.07\ 10^{-13}$	$1.84\ 10^{-11}$	$2.21\ 10^{-2}$	$2.04\ 10^{-8}$	$9.20\ 10^{-7}$
C-14	$3.19\ 10^{-11}$	$5.77\ 10^{-10}$	$5.53\ 10^{-2}$	$1.60\ 10^{-6}$	$2.89\ 10^{-5}$
Fe-55	nd	$3.00\ 10^{-9}$	n/a	n/a	$1.50\ 10^{-4}$
Co-60	$2.47\ 10^{-10}$	$1.94\ 10^{-8}$	$1.27\ 10^{-2}$	$4.94\ 10^{-7}$	$3.88\ 10^{-5}$
Sr-90	$2.87\ 10^{-9}$	$8.81\ 10^{-8}$	$3.26\ 10^{-2}$	$5.74\ 10^{-6}$	$1.76\ 10^{-4}$
Tc-99	nd	$8.70\ 10^{-10}$	n/a	n/a	$1.74\ 10^{-6}$
Ru-106	$1.65\ 10^{-10}$	$3.02\ 10^{-8}$	$5.46\ 10^{-3}$	$8.25\ 10^{-6}$	$1.51\ 10^{-3}$
Sb-125	nd	$5.40\ 10^{-9}$	n/a	n/a	$2.70\ 10^{-4}$
I-129	$5.87\ 10^{-9}$	$1.07\ 10^{-7}$	$5.49\ 10^{-2}$	$1.17\ 10^{-5}$	$2.14\ 10^{-4}$
Cs-134	$1.48\ 10^{-10}$	$1.94\ 10^{-8}$	$7.63\ 10^{-3}$	$7.40\ 10^{-6}$	$9.70\ 10^{-4}$
Cs-137	$4.77\ 10^{-10}$	$1.40\ 10^{-8}$	$3.41\ 10^{-2}$	$9.54\ 10^{-7}$	$2.80\ 10^{-5}$
Ce-144	nd	$1.70\ 10^{-7}$	n/a	n/a	$8.50\ 10^{-3}$
Gd-153	nd	$8.60\ 10^{-9}$	n/a	n/a	$4.30\ 10^{-4}$
Pb-210	nd	$3.50\ 10^{-6}$	n/a	n/a	$1.75\ 10^{-3}$
Po-210	$7.72\ 10^{-9}$	$2.40\ 10^{-6}$	$3.22\ 10^{-3}$	$1.54\ 10^{-4}$	$4.80\ 10^{-2}$
Ra-226	$1.65\ 10^{-7}$	$2.64\ 10^{-6}$	$6.25\ 10^{-2}$	$1.65\ 10^{-5}$	$2.64\ 10^{-4}$
Ra-228	$1.13\ 10^{-6}$	$4.56\ 10^{-5}$	$2.48\ 10^{-2}$	$2.26\ 10^{-3}$	$9.12\ 10^{-2}$
Th-228	$8.64\ 10^{-7}$	$1.20\ 10^{-4}$	$7.20\ 10^{-3}$	$1.73\ 10^{-3}$	$2.40\ 10^{-1}$
Th-230	$1.44\ 10^{-5}$	$4.19\ 10^{-4}$	$3.44\ 10^{-2}$	$1.44\ 10^{-2}$	$4.19\ 10^{-1}$
Th-232	$1.92\ 10^{-5}$	$4.52\ 10^{-4}$	$4.25\ 10^{-2}$	$1.92\ 10^{-3}$	$4.52\ 10^{-2}$
U-234	$8.75\ 10^{-8}$	$2.30\ 10^{-6}$	$3.80\ 10^{-2}$	$1.75\ 10^{-4}$	$4.60\ 10^{-3}$
U-235	$8.13\ 10^{-8}$	$2.11\ 10^{-6}$	$3.85\ 10^{-2}$	$1.63\ 10^{-4}$	$4.22\ 10^{-3}$
U-238	$7.89\ 10^{-8}$	$2.10\ 10^{-6}$	$3.76\ 10^{-2}$	$1.58\ 10^{-4}$	$4.20\ 10^{-3}$
Np-237	$7.91\ 10^{-6}$	$2.10\ 10^{-4}$	$3.77\ 10^{-2}$	$1.58\ 10^{-2}$	$4.20\ 10^{-1}$
Pu-238	$1.41\ 10^{-5}$	$4.50\ 10^{-4}$	$3.13\ 10^{-2}$	$2.82\ 10^{-2}$	$9.00\ 10^{-1}$
Pu-239	$1.67\ 10^{-5}$	$4.90\ 10^{-4}$	$3.41\ 10^{-2}$	$1.67\ 10^{-2}$	$4.90\ 10^{-1}$
Pu-240	$1.67\ 10^{-5}$	$4.90\ 10^{-4}$	$3.41\ 10^{-2}$	$3.34\ 10^{-2}$	$9.80\ 10^{-1}$
Pu-241	$4.10\ 10^{-7}$	$9.68\ 10^{-6}$	$4.24\ 10^{-2}$	$2.05\ 10^{-2}$	$4.84\ 10^{-1}$
Am-241	$1.41\ 10^{-5}$	$4.00\ 10^{-4}$	$3.53\ 10^{-2}$	$1.41\ 10^{-2}$	$4.00\ 10^{-1}$
Cm-242	$1.02\ 10^{-7}$	$1.40\ 10^{-5}$	$7.29\ 10^{-3}$	$2.04\ 10^{-3}$	$2.80\ 10^{-1}$
Cm-244	$5.72\ 10^{-6}$	$2.40\ 10^{-4}$	$2.38\ 10^{-2}$	$1.14\ 10^{-2}$	$4.80\ 10^{-1}$

Table 106 Wound doses using package limit

Radionuclide	Fragment dose coefficient (Sv/Bq)	Worst dose coefficient (Sv/Bq)	Ratio fragment dose to worst dose	Fragment dose from package limit in a consignment (mSv)	Maximum dose from package limit in a consignment (mSv)
H-3	$4.07\ 10^{-13}$	$1.84\ 10^{-11}$	$2.21\ 10^{-2}$	$2.04\ 10^{-8}$	$9.20\ 10^{-7}$
C-14	$3.19\ 10^{-11}$	$5.77\ 10^{-10}$	$5.53\ 10^{-2}$	$1.60\ 10^{-6}$	$2.89\ 10^{-5}$
Fe-55	nd	$3.00\ 10^{-9}$	n/a	n/a	$1.50\ 10^{-4}$
Co-60	$2.47\ 10^{-10}$	$1.94\ 10^{-8}$	$1.27\ 10^{-2}$	$2.47\ 10^{-6}$	$1.94\ 10^{-4}$
Sr-90	$2.87\ 10^{-9}$	$8.81\ 10^{-8}$	$3.26\ 10^{-2}$	$2.87\ 10^{-5}$	$8.81\ 10^{-4}$
Tc-99	nd	$8.70\ 10^{-10}$	n/a	n/a	$8.70\ 10^{-6}$
Ru-106	$1.65\ 10^{-10}$	$3.02\ 10^{-8}$	$5.46\ 10^{-3}$	$8.25\ 10^{-6}$	$1.51\ 10^{-3}$
Sb-125	nd	$5.40\ 10^{-9}$	n/a	n/a	$2.70\ 10^{-4}$
I-129	$5.87\ 10^{-9}$	$1.07\ 10^{-7}$	$5.49\ 10^{-2}$	$5.87\ 10^{-5}$	$1.07\ 10^{-3}$
Cs-134	$1.48\ 10^{-10}$	$1.94\ 10^{-8}$	$7.63\ 10^{-3}$	$7.40\ 10^{-6}$	$9.70\ 10^{-4}$
Cs-137	$4.77\ 10^{-10}$	$1.40\ 10^{-8}$	$3.41\ 10^{-2}$	$4.77\ 10^{-6}$	$1.40\ 10^{-4}$
Ce-144	nd	$1.70\ 10^{-7}$	n/a	n/a	$8.50\ 10^{-3}$
Gd-153	nd	$8.60\ 10^{-9}$	n/a	n/a	$4.30\ 10^{-4}$
Pb-210	nd	$3.50\ 10^{-6}$	n/a	n/a	$8.75\ 10^{-3}$
Po-210	$7.72\ 10^{-9}$	$2.40\ 10^{-6}$	$3.22\ 10^{-3}$	$2.32\ 10^{-4}$	$7.20\ 10^{-2}$
Ra-226	$1.65\ 10^{-7}$	$2.64\ 10^{-6}$	$6.25\ 10^{-2}$	$8.25\ 10^{-5}$	$1.32\ 10^{-3}$
Ra-228	$1.13\ 10^{-6}$	$4.56\ 10^{-5}$	$2.48\ 10^{-2}$	$1.13\ 10^{-2}$	$4.56\ 10^{-1}$
Th-228	$8.64\ 10^{-7}$	$1.20\ 10^{-4}$	$7.20\ 10^{-3}$	$8.64\ 10^{-3}$	$1.20\ 10^{0}$
Th-230	$1.44\ 10^{-5}$	$4.19\ 10^{-4}$	$3.44\ 10^{-2}$	$7.20\ 10^{-2}$	$2.10\ 10^{0}$
Th-232	$1.92\ 10^{-5}$	$4.52\ 10^{-4}$	$4.25\ 10^{-2}$	$9.60\ 10^{-3}$	$2.26\ 10^{-1}$
U-234	$8.75\ 10^{-8}$	$2.30\ 10^{-6}$	$3.80\ 10^{-2}$	$8.75\ 10^{-4}$	$2.30\ 10^{-2}$
U-235	$8.13\ 10^{-8}$	$2.11\ 10^{-6}$	$3.85\ 10^{-2}$	$8.13\ 10^{-4}$	$2.11\ 10^{-2}$
U-238	$7.89\ 10^{-8}$	$2.10\ 10^{-6}$	$3.76\ 10^{-2}$	$7.89\ 10^{-4}$	$2.10\ 10^{-2}$
Np-237	$7.91\ 10^{-6}$	$2.10\ 10^{-4}$	$3.77\ 10^{-2}$	$7.91\ 10^{-2}$	$2.10\ 10^{0}$
Pu-238	$1.41\ 10^{-5}$	$4.50\ 10^{-4}$	$3.13\ 10^{-2}$	$1.41\ 10^{-1}$	$4.50\ 10^{0}$
Pu-239	$1.67\ 10^{-5}$	$4.90\ 10^{-4}$	$3.41\ 10^{-2}$	$8.35\ 10^{-2}$	$2.45\ 10^{0}$
Pu-240	$1.67\ 10^{-5}$	$4.90\ 10^{-4}$	$3.41\ 10^{-2}$	$1.67\ 10^{-1}$	$4.90\ 10^{0}$
Pu-241	$4.10\ 10^{-7}$	$9.68\ 10^{-6}$	$4.24\ 10^{-2}$	$2.05\ 10^{-2}$	$4.84\ 10^{-1}$
Am-241	$1.41\ 10^{-5}$	$4.00\ 10^{-4}$	$3.53\ 10^{-2}$	$7.05\ 10^{-2}$	$2.00\ 10^{0}$
Cm-242	$1.02\ 10^{-7}$	$1.40\ 10^{-5}$	$7.29\ 10^{-3}$	$3.06\ 10^{-3}$	$4.20\ 10^{-1}$
Cm-244	$5.72\ 10^{-6}$	$2.40\ 10^{-4}$	$2.38\ 10^{-2}$	$5.72\ 10^{-2}$	$2.40\ 10^{0}$

850. For all radionuclides for which data is available, doses when using the fragment coefficient are less than 1 mSv even if the activity concentration in the waste is increased to the package maximum in a consignment. Using the worst dose coefficients, the doses do not exceed 1 mSv using the consignment average concentrations. Doses above 1 mSv, but below 6 mSv are estimated for thorium, plutonium, neptunium, curium and americium isotopes based on the worst dose coefficients and the maximum package concentration in a consignment. This is a very conservative estimate.

E.3.10. Exposure from leachate spillage

851. If leachate is accidentally spilled, for example during leachate transport, then land or a surface water body could become contaminated. Irrespective of the presence of radioactivity, landfill leachate poses a hazard to the environment if spilt and hence any accident involving loss of an entire load would be subject to mitigation measures. It is assumed that if the leachate is accidentally spilled onto land then the land will be

remediated appropriately due to the radiological and non-radiological properties of leachate. The remediation process will also involve a dose assessment, hence this situation is not assessed in the ESC.

852. If the leachate spillage results in contamination of nearby surface water then this is more difficult to remediate. The radiological impact on the public is therefore assessed. It is assumed that farmland adjacent to a water body that becomes contaminated by the spillage also becomes contaminated. Members of the exposed group are assumed to be a farming family who also use the water body for fishing. The leachate spillage pathway is highly uncertain, both in terms of the possibility of occurring and duration. The specific doses presented are illustrative, and might be considered in establishing mitigation measures, but should not be used to determine overall radiological capacities for the landfill site.

853. The dose criterion used for this scenario is the dose constraint for the public, 0.3 mSv y^{-1}.

Potentially exposed group

854. The assessment of doses from a leachate spillage to a water body, e.g. during leachate management work is based on the SNIFFER assessment methodology (SNIFFER, 2006). Members of the exposed group are assumed to be adults, children and infants and it is assumed that farmland adjacent to the contaminated water body subsequently becomes contaminated through irrigation. The exposure pathways considered are:

- consumption of food produced on land contaminated by a contaminated water body, including fish, milk, green vegetables, root vegetables and meat products;
- external irradiation from radionuclides incorporated in contaminated soil;
- inadvertent inhalation of contaminated dust; and,
- inadvertent ingestion of contaminated soil.

855. Table 90 details the habit data assumed for the farming family, assumptions concerning drinking water and fish consumption are in Table 107.

Table 107 Habit data for the leachate spillage: applicable during the Period of Authorisation

Pathway*	Age group	Mean	97.5^{th}	Comment
Fish consumption (kg y^{-1})	Adult	15	40	From (Smith & Jones, 2003).
	Child	6	20	
	Infant	3.5	15	
Drinking water consumption (m^3 y^{-1})	Adult	0.6	n/a	
	Child	0.35		
	Infant	0.26		

*Other data are the same as presented in Table 127.

E.3.10.1. Estimating activity concentrations after a leachate spillage

856. For this assessment, it is assumed that a tanker load of leachate (28 m^3 of leachate) enters a small reservoir (2 10^6 m^3) that is used for drinking water, irrigation and fishing. The dissolved radionuclide activity concentration, C_{Rn},leachate (Bq m^{-3}) in the leachate is based on the peak leachate activity concentrations (per MBq input to the landfill)

from the GoldSim groundwater model during the site management period (Table 85). This is a very conservative set of assumptions.

857. Contamination is assumed to relate to a one-off event with the resulting radioactive contamination in the water body remaining constant for one year. The activity concentration ($C_{Rn,water,spill}$; Bq m^{-3}) in the water body is determined as follows:

$$C_{Rn,water,spill} = \frac{C_{Rn,leachate}(t) \cdot V_{spill}}{V_{water}}$$

where:

- $C_{Rn,water,spill}$ is the activity concentration (Bq m^{-3}) in the water body;
- $C_{Rn,leachate}(t)$ is the activity concentration of radionuclide in the leachate at the time of the spill (Bq m^{-3});
- V_{spill} is the volume of leachate in the spill (m^3); and,
- V_{water} is the volume of the water body (m^3).

858. The resulting doses to the public then arise from water and fish consumption. If the water body is used for irrigation, then a one-off soil activity concentration, $C_{Rn,soil,spill}$ (Bq kg^{-1}), is calculated from:

$$C_{Rn,soil,spill} = C_{Rn,water,spill} \cdot \left\{\frac{Irrig_{rate}}{\rho_{soil} \cdot d_{soil}}\right\}$$

where:

- $C_{Rn,soil,spill}$ is the soil activity concentration (Bq kg^{-1});
- $Irrig_{rate}$ is the amount of irrigation in 1 year (m);
- ρ_{soil} is the density of the soil (kg m^{-3}); and,
- d_{soil} is the depth of the soil layer (m).

Table 108 Properties for soil irrigation

Parameter	Units	Value
Irrigation in 1 year	m y^{-1}	0.108
Density of soil	kg m^{-3}	1300
Depth of soil layer irrigated	m	0.25

Note: For soil parameters (IAEA, 2003)

E.3.10.2. Assessment calculations for a farming family after a leachate spillage

Irrigation and Drinking Water

859. The exposure pathways for irrigation are the same as those detailed for groundwater contamination, see Section E.4.4.8. There is however no allowance for daughter radionuclide ingrowth.

860. Consumption of contaminated water by livestock direct from the water body is included at a rate of 0.06 m^3 d^{-1} (SNIFFER, 2006).

Fish Contamination

861. The dose (Sv y^{-1}) from eating fish taken from the contaminated water body is given by:

$$Dose_{ing,fish} = Q_{fish} \cdot C_{Rn,water,spill} \cdot UF_{Rn,fish} \cdot D_{Rn,ing}$$

where:

- $Dose_{ing,fish}$ is the dose from eating fish (Sv y^{-1});
- $C_{Rn,water,spill}$ is the activity concentration (Bq m^{-3}) in the water body;
- Q_{fish} is the consumption rate of fish (kg y^{-1});
- UF_{fish} is the water to fish transfer factor (m^3 kg^{-1}); and,
- D_{ing} is the dose coefficient for ingestion of radionuclide *Rn* (Sv Bq^{-1}), see Table 225.

862. The transfer factors for freshwater fish are listed in Table 231. These are from (SNIFFER, 2006) updated with revised values from (IAEA, 2010). For Pu isotopes, the SNIFFER value was retained due to low confidence in the IAEA value of 21 m^3 kg^{-1} (n=3).

863. The two pathways resulting in greatest dose from the irrigation and fish pathways are used at critical group consumption rates. The remaining pathways use mean consumptions rates.

E.3.10.3. Doses from Leachate spillage

864. It is expected that a spillage of landfill leachate will be subject to mitigation measures with an assessment of any ground contamination at the site. Leachate that enters water resources would become diluted and effective mitigation measures would be less likely. The doses (µSv per MBq) to a farming family are shown in Table 109. The public dose constraint is 300 µSv.

865. The spillage event has a low probability of occurring and clean-up actions would be taken to largely mitigate the event altogether. Without mitigation measures the scenario constrains the radiological capacity for 11 radionuclides. The results for Ra-226 are independent of the Ra-226 placement depth in the site.

Table 109 Dose to farming family from leachate spillage

Radionuclide	Dose to Farming family – adult (µSv MBq^{-1})	Dose to Farming family – child (µSv MBq^{-1})	Dose to Farming family – infant (µSv MBq^{-1})	Scenario radiological capacity (MBq)
H-3	$3.95\ 10^{-10}$	$3.60\ 10^{-10}$	$4.95\ 10^{-10}$	$6.06\ 10^{11}$
C-14	$5.31\ 10^{-9}$	$3.67\ 10^{-9}$	$5.49\ 10^{-9}$	$5.46\ 10^{10}$
Cl-36	$2.98\ 10^{-8}$	$3.63\ 10^{-8}$	$8.56\ 10^{-8}$	$3.50\ 10^{9}$
Ca-41	$2.47\ 10^{-9}$	$3.18\ 10^{-9}$	$2.54\ 10^{-9}$	$9.43\ 10^{10}$

Radionuclide	Dose to Farming family – adult (µSv MBq^{-1})	Dose to Farming family – child (µSv MBq^{-1})	Dose to Farming family – infant (µSv MBq^{-1})	Scenario radiological capacity (MBq)
Mn-54	$1.45\ 10^{-11}$	$1.37\ 10^{-11}$	$2.35\ 10^{-11}$	$1.28\ 10^{13}$
Fe-55	$5.69\ 10^{-12}$	$1.04\ 10^{-11}$	$1.53\ 10^{-11}$	$1.96\ 10^{13}$
Co-60	$2.86\ 10^{-10}$	$4.79\ 10^{-10}$	$8.44\ 10^{-10}$	$3.55\ 10^{11}$
Ni-59	$2.79\ 10^{-12}$	$2.79\ 10^{-12}$	$5.57\ 10^{-12}$	$5.39\ 10^{13}$
Ni-63	$6.60\ 10^{-12}$	$7.05\ 10^{-12}$	$1.37\ 10^{-11}$	$2.20\ 10^{13}$
Zn-65	$7.86\ 10^{-10}$	$6.48\ 10^{-10}$	$1.21\ 10^{-9}$	$2.48\ 10^{11}$
Se-79	$1.02\ 10^{-8}$	$2.47\ 10^{-8}$	$3.69\ 10^{-8}$	$8.12\ 10^{9}$
Sr-90	$1.41\ 10^{-8}$	$1.62\ 10^{-8}$	$1.59\ 10^{-8}$	$1.85\ 10^{10}$
Mo-93	$6.15\ 10^{-10}$	$4.88\ 10^{-10}$	$5.08\ 10^{-10}$	$4.88\ 10^{11}$
Zr-93	$3.97\ 10^{-11}$	$1.17\ 10^{-11}$	$1.01\ 10^{-11}$	$7.55\ 10^{12}$
Nb-93m	$2.73\ 10^{-12}$	$3.22\ 10^{-12}$	$7.71\ 10^{-12}$	$3.89\ 10^{13}$
Nb-94	$4.08\ 10^{-11}$	$4.27\ 10^{-11}$	$8.60\ 10^{-11}$	$3.49\ 10^{12}$
Tc-99	$3.00\ 10^{-9}$	$3.83\ 10^{-9}$	$7.96\ 10^{-9}$	$3.77\ 10^{10}$
Ru-106	$8.63\ 10^{-11}$	$1.19\ 10^{-10}$	$2.18\ 10^{-10}$	$1.38\ 10^{12}$
Ag-108m	$1.00\ 10^{-10}$	$1.04\ 10^{-10}$	$1.76\ 10^{-10}$	$1.71\ 10^{12}$
Ag-110m	$5.00\ 10^{-11}$	$5.12\ 10^{-11}$	$9.11\ 10^{-11}$	$3.29\ 10^{12}$
Cd-109	$1.23\ 10^{-10}$	$1.20\ 10^{-10}$	$2.16\ 10^{-10}$	$1.39\ 10^{12}$
Sb-125	$2.05\ 10^{-10}$	$2.27\ 10^{-10}$	$4.35\ 10^{-10}$	$6.90\ 10^{11}$
Sn-119m	$1.03\ 10^{-11}$	$1.16\ 10^{-11}$	$2.85\ 10^{-11}$	$1.05\ 10^{13}$
Sn-123	$2.84\ 10^{-11}$	$3.16\ 10^{-11}$	$8.09\ 10^{-11}$	$3.71\ 10^{12}$
Sn-126	$3.38\ 10^{-10}$	$3.57\ 10^{-10}$	$8.02\ 10^{-10}$	$3.74\ 10^{11}$
Te-127m	$3.66\ 10^{-11}$	$4.30\ 10^{-11}$	$1.07\ 10^{-10}$	$2.80\ 10^{12}$
I-129	$1.10\ 10^{-6}$	$9.76\ 10^{-7}$	$8.26\ 10^{-7}$	$2.73\ 10^{8}$
Ba-133	$2.32\ 10^{-8}$	$4.17\ 10^{-8}$	$3.51\ 10^{-8}$	$7.19\ 10^{9}$
Cs-134	$3.55\ 10^{-9}$	$1.31\ 10^{-9}$	$1.12\ 10^{-9}$	$8.46\ 10^{10}$
Cs-135	$5.15\ 10^{-10}$	$2.20\ 10^{-10}$	$2.22\ 10^{-10}$	$5.82\ 10^{11}$
Cs-137	$3.27\ 10^{-9}$	$1.27\ 10^{-9}$	$1.13\ 10^{-9}$	$9.17\ 10^{10}$
Ce-144	$1.24\ 10^{-11}$	$1.67\ 10^{-11}$	$3.37\ 10^{-11}$	$8.89\ 10^{12}$
Pm-147	$3.69\ 10^{-12}$	$4.91\ 10^{-12}$	$9.83\ 10^{-12}$	$3.05\ 10^{13}$
Sm-147	$4.33\ 10^{-10}$	$3.43\ 10^{-10}$	$4.52\ 10^{-10}$	$6.64\ 10^{11}$
Sm-151	$8.60\ 10^{-13}$	$1.07\ 10^{-12}$	$2.05\ 10^{-12}$	$1.46\ 10^{14}$
Eu-152	$1.15\ 10^{-10}$	$1.16\ 10^{-10}$	$2.23\ 10^{-10}$	$1.35\ 10^{12}$
Eu-154	$1.59\ 10^{-10}$	$1.76\ 10^{-10}$	$3.50\ 10^{-10}$	$8.57\ 10^{11}$
Eu-155	$2.36\ 10^{-11}$	$2.72\ 10^{-11}$	$6.01\ 10^{-11}$	$4.99\ 10^{12}$
Gd-153	$1.80\ 10^{-12}$	$2.34\ 10^{-12}$	$4.37\ 10^{-12}$	$6.87\ 10^{13}$
Pb-210	$3.91\ 10^{-8}$	$4.85\ 10^{-8}$	$9.58\ 10^{-8}$	$3.13\ 10^{9}$
Po-210	$1.30\ 10^{-8}$	$1.65\ 10^{-8}$	$3.50\ 10^{-8}$	$8.57\ 10^{9}$
Ra-226	$2.30\ 10^{-8}$	$2.99\ 10^{-8}$	$5.27\ 10^{-8}$	$5.70\ 10^{9}$
Ra-228	$7.84\ 10^{-9}$	$2.17\ 10^{-8}$	$2.38\ 10^{-8}$	$1.26\ 10^{10}$
Ac-227	$5.68\ 10^{-9}$	$5.63\ 10^{-9}$	$7.34\ 10^{-9}$	$4.09\ 10^{10}$

Radionuclide	Dose to Farming family – adult (µSv MBq^{-1})	Dose to Farming family – child (µSv MBq^{-1})	Dose to Farming family – infant (µSv MBq^{-1})	Scenario radiological capacity (MBq)
Th-228	1.30 10^{-9}	2.05 10^{-9}	3.70 10^{-9}	8.11 10^{10}
Th-229	7.88 10^{-9}	8.09 10^{-9}	1.14 10^{-8}	2.64 10^{10}
Th-230	2.70 10^{-9}	1.65 10^{-9}	1.96 10^{-9}	1.11 10^{11}
Th-232	1.37 10^{-8}	3.18 10^{-8}	3.46 10^{-8}	8.66 10^{9}
Pa-231	2.20 10^{-9}	1.83 10^{-9}	1.46 10^{-9}	1.36 10^{11}
U-232	1.33 10^{-8}	1.81 10^{-8}	1.88 10^{-8}	1.60 10^{10}
U-233	1.45 10^{-9}	1.44 10^{-9}	1.38 10^{-9}	2.07 10^{11}
U-234	1.39 10^{-9}	1.37 10^{-9}	1.29 10^{-9}	2.15 10^{11}
U-235	1.35 10^{-9}	1.32 10^{-9}	1.31 10^{-9}	2.23 10^{11}
U-236	1.34 10^{-9}	1.29 10^{-9}	1.29 10^{-9}	2.25 10^{11}
U-238	1.38 10^{-9}	1.39 10^{-9}	1.43 10^{-9}	2.09 10^{11}
Np-237	1.95 10^{-8}	1.27 10^{-8}	1.38 10^{-8}	1.54 10^{10}
Pu-238	1.77 10^{-9}	1.19 10^{-9}	1.08 10^{-9}	1.69 10^{11}
Pu-239	1.94 10^{-9}	1.35 10^{-9}	1.14 10^{-9}	1.55 10^{11}
Pu-240	1.94 10^{-9}	1.35 10^{-9}	1.14 10^{-9}	1.55 10^{11}
Pu-241	3.55 10^{-11}	2.44 10^{-11}	1.48 10^{-11}	8.45 10^{12}
Pu-242	1.86 10^{-9}	1.30 10^{-9}	1.09 10^{-9}	1.61 10^{11}
Pu-244	1.87 10^{-9}	1.32 10^{-9}	1.14 10^{-9}	1.60 10^{11}
Am-241	6.32 10^{-10}	4.22 10^{-10}	4.27 10^{-10}	4.75 10^{11}
Am-242m	7.61 10^{-10}	5.07 10^{-10}	4.99 10^{-10}	3.94 10^{11}
Am-243	6.35 10^{-10}	4.26 10^{-10}	4.34 10^{-10}	4.72 10^{11}
Cm-242	2.99 10^{-11}	3.05 10^{-11}	7.08 10^{-11}	4.23 10^{12}
Cm-243	1.36 10^{-9}	7.42 10^{-10}	1.12 10^{-9}	2.20 10^{11}
Cm-244	1.07 10^{-9}	6.37 10^{-10}	9.68 10^{-10}	2.80 10^{11}
Cm-245	1.95 10^{-9}	1.09 10^{-9}	1.28 10^{-9}	1.54 10^{11}
Cm-246	1.95 10^{-9}	1.04 10^{-9}	1.28 10^{-9}	1.54 10^{11}
Cm-248	7.14 10^{-9}	3.97 10^{-9}	4.85 10^{-9}	4.20 10^{10}

E.4. Radiological impacts after the period of authorisation {R6}

866. As described in Section E.2, the ESC considers the exposure of adults, children and infants occurring after the period of authorisation. Hence the ESC calculates the radiological capacity of Port Clarence based on the greatest radiological impact to one of these three age groups.

867. During the post closure period the site will be actively managed and monitored whilst the Permit is in force. The active management phase ends when the site has stabilised to the extent that active management is no longer necessary and a Permit is no longer relevant (the end of the period of authorisation). The process leading to the end of the period of authorisation will be gradual with a progressive decrease in monitoring and controls as appropriate and where agreed with the Environment Agency.

868. Under requirements in the planning permission for Port Clarence the site must be restored to areas of grassland, scrub and woodland and the surrounding areas will be restored to areas of open water, aquatic marginal vegetation, scrub, wet meadow and ruderal grassland with small hollows, banks and ridges suitable for nature conservation use. The restoration is carried out progressively during the life of the site and will be completed by 2075 CE or earlier. The aftercare of the restored site also continues under the planning requirements for at least 10 years after closure to ensure that the land use and vegetation is properly established.

869. At some point in time after site restoration is complete members of the public will have access to this land for its intended recreational use. This may or may not occur before the end of the period of authorisation. The principal risk to site users could arise from direct radiation from the disposed waste and gas migration. The exposed groups considered for this scenario are recreational site users.

870. During the post closure period gradual degradation of the non-mineral components of the site cap and liner may occur, eventually leading to infiltration of rainwater into the landfill site, leaching of the waste and migration of radionuclides in the groundwater below the site. The characteristics of the site cap and engineered barriers mean that contamination of the groundwater is not expected to occur before the end of the period of authorisation, and probably not until sometime afterwards.

871. The groundwater downstream of the site is subject to saline intrusion, is not potable and will not be used for drinking, irrigation or livestock. Nevertheless, a what-if calculation is performed that considers members of the public drinking groundwater abstracted from a well and using it for irrigation of land. This assessment is not used to calculate the radiological capacity of the site.

872. Contaminated groundwater will migrate downstream of the site, along the aquifer, and enter the estuary. The exposure of a member of the public through ingestion of seafood, external irradiation on the bank and inhalation of sea spray is considered.

873. Leachate level monitoring will continue following the completion of filling, capping and placement of the restoration materials. The control of leachate levels at the site will continue until it is considered by the Environment Agency that the landfill is unlikely to present a significant risk to the environment if leachate management ceases. The potential for overtopping of leachate at a stage when the leachate could have an unacceptable impact on the environment is very unlikely to occur. Nevertheless, the impact of bathtubbing is considered.

874. The future possible erosion of the site is considered. Two assessments are performed: one to a person walking close to the eroded material and one to a member of the public exposed to contamination leached from eroded waste.

875. The last scenario considered is the potential for the site to be inundated as a result of coastal flooding. It is assumed that floodwater enters the base of the landfills and this water then drains out to the surrounding area. It is assumed that this leads to contamination of the land surrounding the site and that a resident living adjacent to the site grows foodstuffs on this land. The model also considered potential movement of this contaminated floodwater to a local non-tidal water body, however local drainage characteristics indicated that the floodwater would not reach the local water body. This scenario was therefore included as a ‘what if’ scenario only.

876. The assessment scenarios for the period following the period of authorisation are summarised in the table below.

Table 110 Summary of scenarios and exposure pathways after the period of authorisation

Event/scenario	Exposure pathway	Description
Access to undisturbed site: recreational use	External irradiation	A member of the public is exposed to external radiation whilst walking over the undisturbed site.
	Gas (including radon) inhalation	A member of the public is exposed to gases emanating from contaminated material in the landfill.
Site erosion: recreational use	External irradiation	A member of the public is exposed to external radiation whilst walking close to the estuary.
	Inadvertent ingestion	A member of the public inadvertently ingests contaminated soil whilst walking close to the estuary.
	Inhalation	A member of the public inhales contaminated soil whilst walking close to the estuary.
Site erosion: fishing family/estuary user	Ingestion of contaminated seafood	A member of the public ingests contaminated seafood obtained from the estuary.
	External irradiation	A member of the public is exposed to external radiation during activities near the estuary. This includes fishing for the adult member of the public.
	Inhalation of spray	A member of the public is exposed to radionuclides incorporated in spray from the estuary.
Bathtubbing: residential occupant	Land contaminated with leachate overspill	A member of the public ingests contaminated foodstuffs as a result of growing crops on contaminated soil, inadvertently ingests or inhales contaminated soil and is exposed through external irradiation to soil.
Inundation: residential occupant	Land contaminated with leachate	A member of the public ingests contaminated foodstuffs as a result of growing crops on contaminated soil, inadvertently ingests or inhales contaminated soil and is exposed through external irradiation to soil.
Inundation: local non-tidal water body	Fish ingestion	Included as a hypothetical ‘what if’ scenario only.

Event/scenario	Exposure pathway	Description
Release to groundwater: abstraction 100m from site boundary	Ingestion of contaminated water	Drinking water contaminated as a result of radionuclide migration into the aquifer and abstracted from a well.
	Irrigation of land with contaminated groundwater	A member of the public ingests contaminated foodstuffs as a result of growing crops on contaminated soil, inadvertently ingests or inhales contaminated soil and is exposed through external irradiation to soil.
Release to groundwater: migration into estuary	Ingestion of contaminated seafood	A member of the public ingests contaminated seafood obtained from the estuary.
	External irradiation	A member of the public is exposed to external radiation during activities near the estuary. This includes fishing for the adult member of the public.
	Inhalation of seaspray	A member of the public is exposed to radionuclides incorporated in spray from the estuary.

877. Intrusion scenarios are considered separately in Section E.5, exposure to heterogeneous wastes is addressed in Section E.6, and the assessment of wildlife exposure is discussed in Section E.7. Additional scenarios which were considered, but not explicitly assessed, are discussed in the following sections.

Enhanced rainfall due to climate change

878. The HRA (MJCA, 2019b) does not explicitly consider long term effective rainfall changes in response to climate change. Notwithstanding that there may be changes to rates of effective rainfall the assumptions made in the HRA with regard to cap infiltration are generally conservative. An infiltration to grassland value of 74.3 mm y^{-1} has been considered based on long term effective rainfall, and an infiltration to grassland that is equal to the effective rainfall is considered representative of the long term situation where the geomembrane element of the cap has fully degraded. The landfill capping system incorporates a GCL and it is likely that the long term infiltration through the capping system will be less than the effective rainfall because the GCL will be less susceptible to chemical or physical degradation than a polyethylene geomembrane. The groundwater assessments in the ESC cautiously assume that the cap will deteriorate. The HRA does not consider a potential increased risk of flooding resulting from climate change. A flood risk assessment (FRA) for the area is presented in Figure 9.

879. The site topography, slope and vegetation plans are designed to limit the formation of preferential channels for run-off and limit the damage that could occur to vegetation from drought or to the integrity of the capping layer from the action of roots. We are not aware of any evidence that for a modern designed and constructed landfill, such as Port Clarence, significant root penetration of the cap occurs or that there is significant uptake of contaminants into the plants (see comments on the Forestry commission research below). The maintenance period will be used to reprofile or replant any problematic areas.

880. The uncontrolled flow of water over the capping and restoration system could result in the erosion of the restoration soils and potentially the underlying mineral layers. Monitoring of erosion will be undertaken by regular walkover surveys in the early years following restoration which is the period when the profile of the site may change as the

wastes settle and the flow of water may also change to produce channeling in previously unaffected areas. These surveys allow early improvement and remediation works to be carried out that minimise the risks of deeper erosion features developing. Significant settlement of the waste is unlikely to occur later than approximately 5 years after waste deposition. The stability risk assessment for the site is provided with the ESC (MJCA, 2019c).

881. The vegetation and restoration infrastructure developed on the restored landfill will be subject to a ten year aftercare period following the completion of the restoration works under the conditions of the planning permission. However, because some planting will have been carried out whilst areas of the landfill remained operational, some areas will have been in the care and management of the operator for a much longer period of time during which time considerable experience will have been gained in ensuring vegetation establishes well and ground cover is sustained. In addition, the landfill site (non-LLW) permit will be in place for at least 60 years after site closure during which any necessary maintenance and improvement works will be carried out.

882. All designs for landfill sites including the capping systems are subject to stability risk assessments as part of the permit applications and construction of the capping systems and subject to CQA and Verification, all of which is approved by the Environment Agency. Accordingly the stability and long-term integrity of the designed and constructed systems have a high degree of reliability and confidence.

883. We note that LLW will be at least 2.3 m below the restored surface. Plant roots are located mainly within 1 m of the surface and few roots can penetrate to greater depth and take up moisture and nutrients. Research has shown that the roots of plants, including trees planted on landfill sites, with at least 1 m (or 1.5 m for trees) of cover soils do not penetrate into the compacted capping layer in the first 16 years after planting and are found to spread laterally above the cap (Department for Communities and Local Government, 2008).

Seismic Events

884. The engineered containment structures at the site are not formed of brittle materials such as concrete that may fracture as a result of a severe earthquake. The HDPE and clay lining materials have a high shear strength and have the flexibility to withstand the stresses which would be imposed during the types of earthquake which occur in the UK. Two fracking licences have been granted in the immediate vicinity of Port Clarence. These are administered by Egdon Resources U.K. Limited and Third Energy UK Gas Limited (Licence references PEDL68 and PEDL259, respectively). We are not aware of any test drilling or site developments being carried out or planned under these licences. The engineered containment structures at the site would be resilient to any minor seismic activity which might result from future fracking. Hence this scenario is not considered in the ESC.

Transport Accidents

885. Transport accidents occurring prior to delivery are not discussed in the ESC because transport is outside of the scope of the permit and is regulated under an existing regime of Dangerous Goods Regulations. Transport accidents on the site are considered as part of the dropped load scenario (see Section E.3.8) and a transport accident involving leachate sent to an aqueous waste treatment facility is specifically considered (see Section E.3.10).

E.4.1. Criticality Event

886. Criticality and heat generation are processes that are mentioned in the guidance (NS-GRA para. 6.4.21 and 7.3.31). Criticality conditions can arise when sufficient fissile materials are present and are arranged in idealised configurations. Criticality results in the release of increased radiation over the period that criticality is sustained. Heat generating radioactive wastes would not be accepted for disposal since these would not be classified as LLW.

887. Theoretically, if fissile materials in the waste move over very long time periods and re-concentrate, it may be possible to achieve criticality if there is enough fissile material present in one of the landfills. This would require a critical mass of fissile materials to be both present in a single cell and subsequently to become arranged in an ideal configuration that allows criticality conditions to arise. The proposition presented in the ESC is that criticality conditions during transport, handling and site operations are prevented effectively through adherence to radioactive materials transport package limits for fissile materials. It is important to note that criticality is not considered realistically feasible for LLW facilities under practical circumstances and has not been observed in such facilities.

888. The criticality assessment prepared for the ENRMF in 2009 CE (Augean, 2009a) was based on a very cautious assessment of the behaviour of fissile material relative to the site radiological capacity. The analysis referred to studies on the issue of criticality control which indicated that if the % by weight of U-235 in U-238 is maintained on average over the wasteform at less than 1 % by weight then the criticality potential in repositories is eliminated under long term future scenarios. The natural level in Uranium is 0.7% by weight U-235.

889. Criticality conditions during transport, handling and site operations are prevented effectively through adherence to radioactive materials transport package limits for fissile materials (IAEA, 2018). Consignments requiring marking as 'fissile' under the transport regulations (IAEA, 2018) would not be accepted for disposal at the Port Clarence landfills without prior agreement with the Environment Agency. The fissile nuclides (U-235, U-233, Pu-239 and Pu-241) are limited by activity content of the wastes and/or by the mass of fissile material in each package and each consignment. Since the LLW that will be sent for disposal at Port Clarence is broadly homogenous decommissioning wastes, the most relevant provisions excepting material and packages from classification as 'fissile' are given in SSR 6 paragraph 417 (a, c, d). These are reproduced in Table 111.

Table 111 Provisions whereby material and packages are excepted from classification as fissile

SSR 6 Para	Requirement
417 (a)	Uranium enriched in uranium-235 to a maximum of 1% by mass, and with a total plutonium and uranium-233 content not exceeding 1% of the mass of uranium-235, provided that the fissile nuclides are distributed essentially homogeneously throughout the material. In addition, if uranium-235 is present in metallic, oxide or carbide forms, it shall not form a lattice arrangement
417 (c)	Uranium with a maximum uranium enrichment of 5% by mass of uranium-235 provided: (i) There is no more than 3.5 g of uranium-235 per package. (ii) The total plutonium and uranium-233 content does not exceed 1% of the mass of uranium-235 per package.

	(iii) Transport of the package is subject to the consignment limit provided in para. 570(c).
417 (d)	Fissile nuclides with a total mass not greater than 2.0 g per package, provided the package is transported subject to the consignment limit provided in para. 570(d).
570 (c)	45 g per consignment
570 (d)	15 g per consignment

890. Paragraph 222 of SSR 6 excludes the following materials from the definition of fissile materials:

- (a) Natural uranium or depleted uranium that is unirradiated;
- (b) Natural uranium or depleted uranium that has been irradiated in thermal reactors only;
- (c) Material with fissile nuclides less than a total of 0.25 g;
- (d) Any combination of (a), (b) and/or (c).

891. Prior agreement will be sought from the Environment Agency for disposal of a package or consignment containing material with more than 0.25 g of fissile material, excluding where material where uranium is enriched in U-235 by less than 1% by mass, with a total plutonium and U-233 content not exceeding 1% of the mass of U-235.

892. Criticality conditions in the emplaced waste at the Port Clarence landfills will be effectively prevented because insufficient material is present to cause criticality. The material will be distributed within the landfills in a large number of waste packages at low concentrations and in a broadly homogeneous form.

E.4.2. Presentation of results of dose assessments

893. The radiological capacity (MBq) for individual radionuclides present in the LLW is obtained from the results of the assessments carried out and reported in the ESC and depends on the radiological characteristics of the radionuclide. The radiological capacity for each scenario is calculated on the basis that the LLW only contains one radionuclide and disposal of that amount of radioactivity would produce a dose or risk equal to the limiting criteria applicable to the scenario.

894. The results of the assessments that could impact the radiological capacity are presented as effective doses per MBq disposed (mSv y^{-1} MBq^{-1} or µSv y^{-1} MBq^{-1}). The radiological impacts after the period of authorisation presented in Sections E.4.3 to E.4.8 show the scenario radiological capacity (MBq) for each radionuclide. Actual waste disposal will be controlled using a sum of fractions approach for each scenario in turn (see Section 1.5 and discussion at paragraph 511).

895. Estimates of radiological impact based on 'illustrative inventories' for waste streams that might be typical of those contributing to the total impact from disposals at the facility have been produced. These estimates are presented in Appendix D.

E.4.3. Exposure of the public on the undisturbed site

896. Radiation exposure of members of the public spending time on the site after the end of the period of authorisation could occur. Two exposure pathways are considered; exposure through inhalation of gases (H-3, C-14 and radon) and direct irradiation to a casual user who walks over the restored site (e.g. on a footpath). The possibility of

housing being built on the site after the period of authorisation is considered in the assessment of intrusion scenarios (Sections E.5.8 and E.5.9).

897. The assessment assumes that the waste is shielded by a 1.3 m thick capping layer and a further layer of cover material to a depth of 1 m. This scenario also covers occupancy of agricultural land by farmers since activities such as ploughing will not disturb the waste.

898. The dose criterion used is a dose of 0.02 mSv y^{-1} for the public (this is equivalent to the risk guidance level of 10^{-6} y^{-1} for exposure of the public post closure, for situations that are expected to occur).

Potentially exposed group

899. The restored site will include rough grassland, scrub and woodland and the surrounding areas will be restored to areas of shallow open water, aquatic marginal vegetation, scrub, wet meadow and ruderal grassland with small hollows, banks and ridges suitable for nature conservation use, that will be available for access by the public. The area could be used for walking and this scenario considers an occupancy of 750 hours per year on the site for all age groups, equivalent to about 2 hours per day (Oatway & Mobbs, 2003).

900. This occupancy applies to exposure to release of gases through the intact cap and direct exposure whilst using the restored site for recreational purposes. Table 112 details the habit data assumed for the exposed group. Exposure is assessed both immediately after site restoration (in 2075 CE; 0 years) and 60 years after closure (2135 CE).

Table 112 Habit data for exposure to gas releases: applicable after the Period of Authorisation

Parameter	Value	Comment
Inhalation rate – adult (m^3 h^{-1})	1.21	See Table 73 for derivation, blended rates based on ICRP 66 (ICRP, 1994)
Inhalation rate – child (m^3 h^{-1})	0.87	
Inhalation rate – infant (m^3 h^{-1})	0.31	
Time on-site – public (h y^{-1})	750	About 2 hours per day (all ages)

E.4.3.1. Assessment calculations for recreational site use

901. The impact on a member of the public using the site for recreation has been included to illustrate the doses expected from what is likely to be the most probable public use of the site after the period of institutional control.

902. It is expected that the public will get access to the site soon after site restoration is complete. The doses are therefore assessed both at site closure and after 60 years (at the end of the period of authorisation).

Gas generation

903. The method in Section E.3.5 is used to assess the impact of gas generation for recreational site users. The release rate of gases from a landfill is expected to vary over time. A conservative assumption for the operational period assumed all C-14 and H-3 that was associated with organic material would be released over a ten year period. Gas generation within the ENRMF landfill has been simulated using the

GasSim model (Augean, 2010)which shows a rapid build-up in the rate of release after capping followed by an exponential decline. The waste cells are capped sequentially so a series of peaks during the operational period could be expected. A longer timescale for gas generation (20 years) has been applied to the period after closure using the value recommended by IAEA (IAEA, 2003). This timescale is a very cautious assumption.

904. The exposure time (Table 112) reflects recreational use, assumed to be about 2 hours per day (equivalent to an outdoor occupancy factor of 0.0856 based on 750 hours per year).

External Irradiation

905. The external irradiation calculation is presented in Section E.5.7 was used by setting indoor occupation to zero and using the same outdoor occupancy factor above.

E.4.3.2. Dose to recreational user from exposure to gas release and external radiation

906. The dose to a recreational user immediately after the site closes and at the end of the period of authorisation (60 years after closure) are given in Table 113 and Table 114, respectively. Note that the results after 60 years include the effects of ingrowth upon the calculated doses. This scenario limits the radionuclide capacity for C-14, Ni-59, Ni-63, Zr-93 and Nb-93m. The dose from wastes disposed of at Port Clarence will always be lower than 20 µSv y^{-1} due to application of the sum of fractions approach.

907. The dose was also assessed assuming that waste at the maximum activity concentration given in Table 38 was disposed at the top layer of the landfill (at 2.3 m below the restored surface for all radionuclides). Under these circumstances all doses are less than 3 µSv. Hence, no additional restrictions on the activity concentration in the waste are required.

Table 113 Doses to recreational users of restored site at site closure

Radionuclide	Dose (µSv y^{-1} MBq^{-1})			Limiting age group	Scenario radiological capacity (MBq)
	Gas	External	Total		
H-3	$5.19\ 10^{-9}$	$4.31\ 10^{-11}$	$5.23\ 10^{-9}$	Child	$3.82\ 10^{9}$
C-14	$1.69\ 10^{-7}$	$5.76\ 10^{-64}$	$1.69\ 10^{-7}$	Adult	$1.19\ 10^{8}$
Cl-36		$2.22\ 10^{-27}$	$2.22\ 10^{-27}$	Infant	$8.99\ 10^{27}$
Ca-41		0	0		0
Mn-54		$8.99\ 10^{-19}$	$8.99\ 10^{-19}$	Infant	$2.22\ 10^{19}$
Fe-55		$4.46\ 10^{-15}$	$4.46\ 10^{-15}$	Infant	$4.49\ 10^{15}$
Co-60		$1.02\ 10^{-16}$	$1.02\ 10^{-16}$	Infant	$1.96\ 10^{17}$
Ni-59		$5.82\ 10^{-10}$	$5.82\ 10^{-10}$	Infant	$3.44\ 10^{10}$
Ni-63		$5.18\ 10^{-9}$	$5.18\ 10^{-9}$	Infant	$3.86\ 10^{9}$
Zn-65		$6.40\ 10^{-18}$	$6.40\ 10^{-18}$	Infant	$3.13\ 10^{18}$
Se-79		$5.30\ 10^{-62}$	$5.30\ 10^{-62}$	Infant	$3.77\ 10^{62}$
Sr-90		$1.09\ 10^{-24}$	$1.09\ 10^{-24}$	Infant	$1.84\ 10^{25}$

Radionuclide	Dose (µSv y^{-1} MBq^{-1})			Limiting age group	Scenario radiological capacity (MBq)
	Gas	External	Total		
Mo-93		5.37 10^{-9}	5.37 10^{-9}	Infant	3.72 10^{9}
Zr-93		6.13 10^{-9}	6.13 10^{-9}	Infant	3.27 10^{9}
Nb-93m		9.60 10^{-10}	9.60 10^{-10}	Infant	2.08 10^{10}
Nb-94		9.27 10^{-19}	9.27 10^{-19}	Infant	2.16 10^{19}
Tc-99		4.40 10^{-46}	4.40 10^{-46}	Infant	4.55 10^{46}
Ru-106		2.57 10^{-20}	2.57 10^{-20}	Infant	7.78 10^{20}
Ag-108m		7.55 10^{-20}	7.55 10^{-20}	Infant	2.65 10^{20}
Ag-110m		6.46 10^{-18}	6.46 10^{-18}	Infant	3.10 10^{18}
Cd-109		6.05 10^{-49}	6.05 10^{-49}	Infant	3.31 10^{49}
Sb-125		6.55 10^{-21}	6.55 10^{-21}	Infant	3.05 10^{21}
Sn-119m		0	0		0
Sn-123		8.66 10^{-20}	8.66 10^{-20}	Infant	2.31 10^{20}
Sn-126		2.16 10^{-19}	2.16 10^{-19}	Infant	9.27 10^{19}
Te-127m		1.56 10^{-38}	1.56 10^{-38}	Infant	1.28 10^{39}
I-129		2.81 10^{-138}	2.81 10^{-138}	Infant	7.10 10^{138}
Ba-133		1.55 10^{-23}	1.55 10^{-23}	Infant	1.29 10^{24}
Cs-134		3.73 10^{-19}	3.73 10^{-19}	Infant	5.36 10^{19}
Cs-135		3.41 10^{-54}	3.41 10^{-54}	Infant	5.87 10^{54}
Cs-137		7.60 10^{-20}	7.60 10^{-20}	Infant	2.63 10^{20}
Ce-144		1.13 10^{-34}	1.13 10^{-34}	Infant	1.77 10^{35}
Pm-147		3.57 10^{-45}	3.57 10^{-45}	Infant	5.60 10^{45}
Sm-147		0	0		0
Sm-151		0	0		0
Eu-152		4.27 10^{-18}	4.27 10^{-18}	Infant	4.68 10^{18}
Eu-154		5.90 10^{-18}	5.90 10^{-18}	Infant	3.39 10^{18}
Eu-155		2.96 10^{-40}	2.96 10^{-40}	Infant	6.75 10^{40}
Gd-153		3.82 10^{-42}	3.82 10^{-42}	Infant	5.24 10^{42}
Pb-210		1.26 10^{-20}	1.26 10^{-20}	Infant	1.59 10^{21}
Po-210		5.44 10^{-24}	5.44 10^{-24}	Infant	3.68 10^{24}
Ra-226*	2.14 10^{-10}	2.87 10^{-16}	2.14 10^{-10}	Infant	9.36 10^{10}
Ra-228		4.91 10^{-15}	4.91 10^{-15}	Infant	4.07 10^{15}
Ac-227		2.85 10^{-20}	2.85 10^{-20}	Infant	7.01 10^{20}
Th-228		3.15 10^{-15}	3.15 10^{-15}	Infant	6.34 10^{15}
Th-229		9.80 10^{-18}	9.80 10^{-18}	Infant	2.04 10^{18}
Th-230		4.90 10^{-38}	4.90 10^{-38}	Infant	4.08 10^{38}
Th-232		4.91 10^{-15}	4.91 10^{-15}	Infant	4.07 10^{15}
Pa-231		8.90 10^{-26}	8.90 10^{-26}	Infant	2.25 10^{26}
U-232		7.84 10^{-15}	7.84 10^{-15}	Infant	2.55 10^{15}
U-233		8.45 10^{-32}	8.45 10^{-32}	Infant	2.37 10^{32}
U-234		5.19 10^{-45}	5.19 10^{-45}	Infant	3.85 10^{45}

Radionuclide	Dose (μSv y^{-1} MBq^{-1})			Limiting age group	Scenario radiological capacity (MBq)
	Gas	External	Total		
U-235		3.53 10^{-29}	3.53 10^{-29}	Infant	5.67 10^{29}
U-236		4.21 10^{-41}	4.21 10^{-41}	Infant	4.75 10^{41}
U-238		8.03 10^{-20}	8.03 10^{-20}	Infant	2.49 10^{20}
Np-237		3.62 10^{-25}	3.62 10^{-25}	Infant	5.53 10^{25}
Pu-238		6.36 10^{-47}	6.36 10^{-47}	Infant	3.14 10^{47}
Pu-239		3.58 10^{-31}	3.58 10^{-31}	Infant	5.59 10^{31}
Pu-240		4.97 10^{-54}	4.97 10^{-54}	Infant	4.02 10^{54}
Pu-241		2.75 10^{-40}	2.75 10^{-40}	Infant	7.28 10^{40}
Pu-242		7.23 10^{-65}	7.23 10^{-65}	Infant	2.76 10^{65}
Pu-244		1.20 10^{-19}	1.20 10^{-19}	Infant	1.66 10^{20}
Am-241		8.36 10^{-61}	8.36 10^{-61}	Infant	2.39 10^{61}
Am-242m		6.70 10^{-20}	6.70 10^{-20}	Infant	2.98 10^{20}
Am-243		8.56 10^{-29}	8.56 10^{-29}	Infant	2.34 10^{29}
Cm-242		3.68 10^{-41}	3.68 10^{-41}	Infant	5.44 10^{41}
Cm-243		4.62 10^{-29}	4.62 10^{-29}	Infant	4.33 10^{29}
Cm-244		0	0		0
Cm-245		3.13 10^{-34}	3.13 10^{-34}	Infant	6.40 10^{34}
Cm-246		4.79 10^{-136}	4.79 10^{-136}	Infant	4.18 10^{136}
Cm-248		0	0		0

* Assumes Ra-226 distributed with other LLW.

Table 114 Doses to recreational users of restored site 60 years after closure

Radionuclide	Dose (μSv y^{-1} MBq^{-1})			Limiting age group	Scenario radiological capacity (MBq)
	Gas	External	Total		
H-3	7.10 10^{-11}	1.47 10^{-12}	7.25 10^{-11}	Child	2.77 10^{11}
C-14	3.35 10^{-8}	5.72 10^{-64}	3.35 10^{-8}	Adult	5.98 10^{8}
Cl-36	0	2.22 10^{-27}	2.22 10^{-27}	Infant	8.99 10^{27}
Ca-41	0	0	0		0
Mn-54	0	6.65 10^{-40}	6.65 10^{-40}	Infant	3.01 10^{40}
Fe-55	0	1.12 10^{-21}	1.12 10^{-21}	Infant	1.78 10^{22}
Co-60	0	3.81 10^{-20}	3.81 10^{-20}	Infant	5.24 10^{20}
Ni-59	0	5.81 10^{-10}	5.81 10^{-10}	Infant	3.44 10^{10}
Ni-63	0	3.42 10^{-9}	3.42 10^{-9}	Infant	5.85 10^{9}
Zn-65	0	5.77 10^{-45}	5.77 10^{-45}	Infant	3.47 10^{45}
Se-79	0	5.30 10^{-62}	5.30 10^{-62}	Infant	3.77 10^{62}
Sr-90	0	2.56 10^{-25}	2.56 10^{-25}	Infant	7.81 10^{25}
Mo-93	0	5.32 10^{-9}	5.32 10^{-9}	Infant	3.76 10^{9}

Radionuclide	Dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)			Limiting age group	Scenario radiological capacity (MBq)
	Gas	External	Total		
Zr-93	0	$6.13\ 10^{-9}$	$6.13\ 10^{-9}$	Infant	$3.27\ 10^{9}$
Nb-93m	0	$7.29\ 10^{-11}$	$7.29\ 10^{-11}$	Infant	$2.74\ 10^{11}$
Nb-94	0	$9.25\ 10^{-19}$	$9.25\ 10^{-19}$	Infant	$2.16\ 10^{19}$
Tc-99	0	$4.40\ 10^{-46}$	$4.40\ 10^{-46}$	Infant	$4.55\ 10^{46}$
Ru-106	0	$5.68\ 10^{-38}$	$5.68\ 10^{-38}$	Infant	$3.52\ 10^{38}$
Ag-108m	0	$6.84\ 10^{-20}$	$6.84\ 10^{-20}$	Infant	$2.93\ 10^{20}$
Ag-110m	0	$2.53\ 10^{-44}$	$2.53\ 10^{-44}$	Infant	$7.89\ 10^{44}$
Cd-109	0	$3.02\ 10^{-63}$	$3.02\ 10^{-63}$	Infant	$6.61\ 10^{63}$
Sb-125	0	$1.86\ 10^{-27}$	$1.86\ 10^{-27}$	Infant	$1.07\ 10^{28}$
Sn-119m	0	0	0		0
Sn-123	0	$7.53\ 10^{-71}$	$7.53\ 10^{-71}$	Infant	$2.66\ 10^{71}$
Sn-126	0	$2.16\ 10^{-19}$	$2.16\ 10^{-19}$	Infant	$9.27\ 10^{19}$
Te-127m	0	$1.04\ 10^{-100}$	$1.04\ 10^{-100}$	Infant	$1.93\ 10^{101}$
I-129	0	$2.81\ 10^{-138}$	$2.81\ 10^{-138}$	Infant	$7.10\ 10^{138}$
Ba-133	0	$2.97\ 10^{-25}$	$2.97\ 10^{-25}$	Infant	$6.73\ 10^{25}$
Cs-134	0	$6.68\ 10^{-28}$	$6.68\ 10^{-28}$	Infant	$2.99\ 10^{28}$
Cs-135	0	$3.41\ 10^{-54}$	$3.41\ 10^{-54}$	Infant	$5.87\ 10^{54}$
Cs-137	0	$1.92\ 10^{-20}$	$1.92\ 10^{-20}$	Infant	$1.04\ 10^{21}$
Ce-144	0	$7.92\ 10^{-58}$	$7.92\ 10^{-58}$	Infant	$2.53\ 10^{58}$
Pm-147	0	$4.64\ 10^{-52}$	$4.64\ 10^{-52}$	Infant	$4.31\ 10^{52}$
Sm-147	0	0	0		0
Sm-151	0	0	0		0
Eu-152	0	$1.98\ 10^{-19}$	$1.98\ 10^{-19}$	Infant	$1.01\ 10^{20}$
Eu-154	0	$4.66\ 10^{-20}$	$4.66\ 10^{-20}$	Infant	$4.29\ 10^{20}$
Eu-155	0	$4.77\ 10^{-44}$	$4.77\ 10^{-44}$	Infant	$4.20\ 10^{44}$
Gd-153	0	$1.38\ 10^{-69}$	$1.38\ 10^{-69}$	Infant	$1.45\ 10^{70}$
Pb-210	0	$1.94\ 10^{-21}$	$1.94\ 10^{-21}$	Infant	$1.03\ 10^{22}$
Po-210	0	$1.17\ 10^{-71}$	$1.17\ 10^{-71}$	Infant	$1.72\ 10^{72}$
Ra-226*	$2.08\ 10^{-10}$	$2.80\ 10^{-16}$	$2.08\ 10^{-10}$	Infant	$9.61\ 10^{10}$
Ra-228	0	$3.55\ 10^{-18}$	$3.55\ 10^{-18}$	Infant	$5.64\ 10^{18}$
Ac-227	0	$4.22\ 10^{-21}$	$4.22\ 10^{-21}$	Infant	$4.74\ 10^{21}$
Th-228	0	$1.13\ 10^{-24}$	$1.13\ 10^{-24}$	Infant	$1.77\ 10^{25}$
Th-229	0	$9.74\ 10^{-18}$	$9.74\ 10^{-18}$	Infant	$2.05\ 10^{18}$
Th-230	0	$7.37\ 10^{-18}$	$7.37\ 10^{-18}$	Infant	$2.71\ 10^{18}$
Th-232	0	$4.91\ 10^{-15}$	$4.91\ 10^{-15}$	Infant	$4.07\ 10^{15}$
Pa-231	0	$2.43\ 10^{-20}$	$2.43\ 10^{-20}$	Infant	$8.24\ 10^{20}$
U-232	0	$4.29\ 10^{-15}$	$4.29\ 10^{-15}$	Infant	$4.67\ 10^{15}$
U-233	0	$5.54\ 10^{-20}$	$5.54\ 10^{-20}$	Infant	$3.61\ 10^{20}$
U-234	0	$2.70\ 10^{-41}$	$2.70\ 10^{-41}$	Infant	$7.40\ 10^{41}$
U-235	0	$1.48\ 10^{-28}$	$1.48\ 10^{-28}$	Infant	$1.35\ 10^{29}$

Radionuclide	Dose (µSv y^{-1} MBq^{-1})			Limiting age group	Scenario radiological capacity (MBq)
	Gas	External	Total		
U-236	0	$1.45\ 10^{-23}$	$1.45\ 10^{-23}$	Infant	$1.38\ 10^{24}$
U-238	0	$8.03\ 10^{-20}$	$8.03\ 10^{-20}$	Infant	$2.49\ 10^{20}$
Np-237	0	$3.62\ 10^{-25}$	$3.62\ 10^{-25}$	Infant	$5.53\ 10^{25}$
Pu-238	0	$4.03\ 10^{-47}$	$4.03\ 10^{-47}$	Infant	$4.96\ 10^{47}$
Pu-239	0	$3.57\ 10^{-31}$	$3.57\ 10^{-31}$	Infant	$5.60\ 10^{31}$
Pu-240	0	$7.46\ 10^{-47}$	$7.46\ 10^{-47}$	Infant	$2.68\ 10^{47}$
Pu-241	0	$1.51\ 10^{-41}$	$1.51\ 10^{-41}$	Infant	$1.32\ 10^{42}$
Pu-242	0	$7.47\ 10^{-28}$	$7.47\ 10^{-28}$	Infant	$2.68\ 10^{28}$
Pu-244	0	$1.20\ 10^{-19}$	$1.20\ 10^{-19}$	Infant	$1.66\ 10^{20}$
Am-241	0	$6.69\ 10^{-30}$	$6.69\ 10^{-30}$	Infant	$2.99\ 10^{30}$
Am-242m	0	$4.99\ 10^{-20}$	$4.99\ 10^{-20}$	Infant	$4.01\ 10^{20}$
Am-243	0	$8.51\ 10^{-29}$	$8.51\ 10^{-29}$	Infant	$2.35\ 10^{29}$
Cm-242	0	$2.02\ 10^{-49}$	$2.02\ 10^{-49}$	Infant	$9.89\ 10^{49}$
Cm-243	0	$1.11\ 10^{-29}$	$1.11\ 10^{-29}$	Infant	$1.81\ 10^{30}$
Cm-244	0	$1.23\ 10^{-56}$	$1.23\ 10^{-56}$	Infant	$1.63\ 10^{57}$
Cm-245	0	$3.11\ 10^{-34}$	$3.11\ 10^{-34}$	Infant	$6.43\ 10^{34}$
Cm-246	0	$7.99\ 10^{-69}$	$7.99\ 10^{-69}$	Infant	$2.50\ 10^{69}$
Cm-248	0	$6.25\ 10^{-26}$	$6.25\ 10^{-26}$	Infant	$3.20\ 10^{26}$

* Assumes Ra-226 distributed with other LLW.

908. The doses calculated using illustrative inventories are considered further in Appendix D.

E.4.4. Groundwater pathways

909. A mathematical model has been implemented in the GoldSim program (GoldSim Technology Group, 2021a) that considers the groundwater pathways. GoldSim is considered to be appropriate because:

- it provides a flexible modelling environment and was used for the ENRMF ESC;
- decay and ingrowth of radionuclides can be modelled in the standard application; and,
- models for well-mixed compartment and one-dimensional transport are available in the Contaminant Transport Module (GoldSim Technology Group, 2021b).

910. The model has been developed for the Port Clarence site taking into account the characteristics described in Section 2 of the main report. Calculations have been undertaken for the combined landfill comprising the non-hazardous and the hazardous waste cells and sensitivity studies have considered the hazardous and non-hazardous waste cells separately.

911. The model accounts for rising seawater and groundwater levels as a result of climate change, as described in Section E.4.4.1.

912. The scenarios consider the exposures resulting from contaminated groundwater taken from a hypothetical abstraction point close to the site boundary. There are no abstraction wells near to the site and there are unlikely to be any in the future for the following reasons:

- the strata from which abstraction of contaminated water would occur is subject to the subsurface saline interface with the Tees Estuary (MJCA, 2019b) meaning the waters are not suitable for drinking, irrigation or livestock;
- sea level rise is likely to isolate the site over long timescales; and,
- erosion scenarios are considered more likely to occur than water abstraction between the landfill and the estuary.

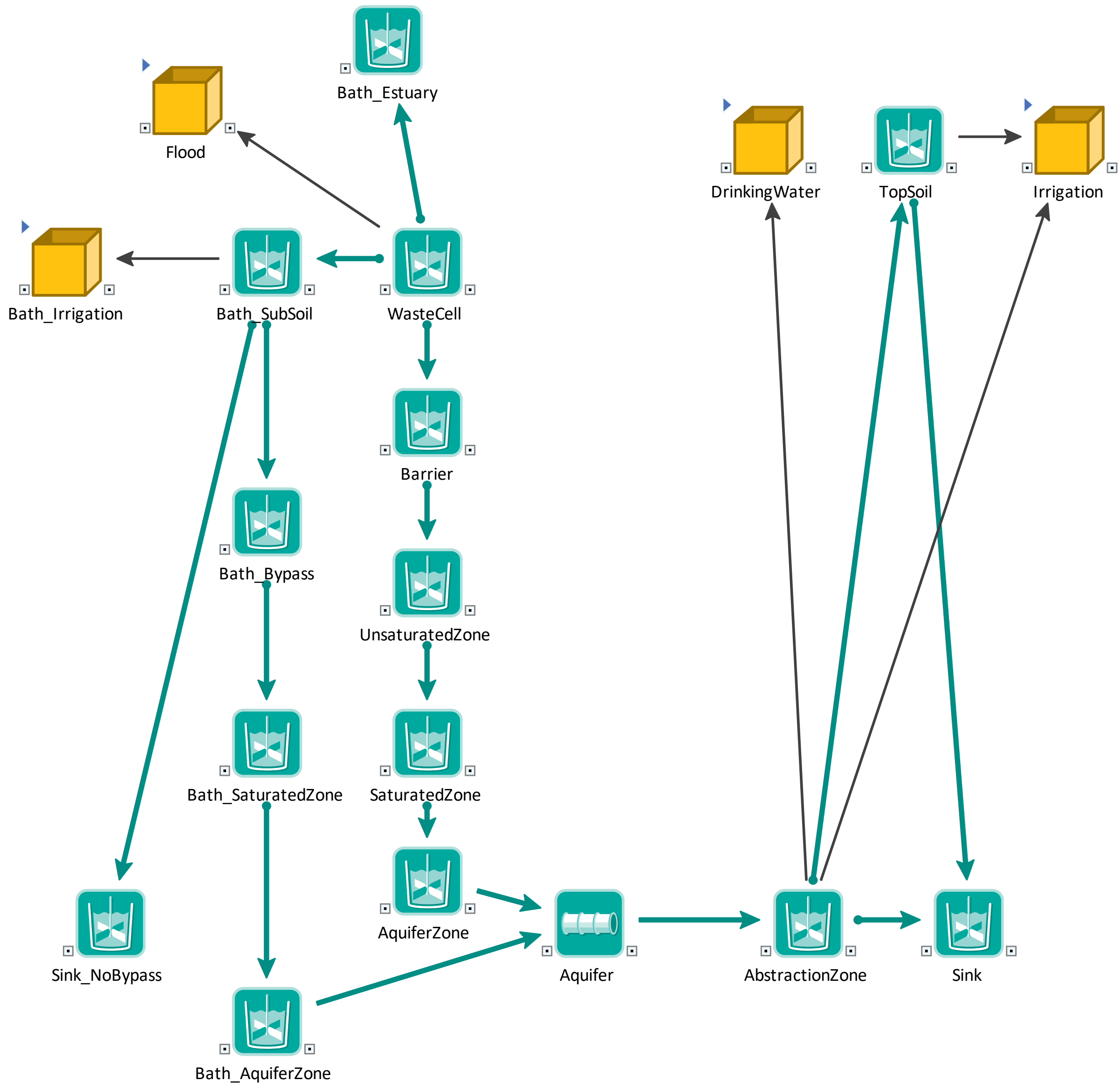
913. Results of groundwater calculations are used in other assessments, such as assessments of releases to the estuary (see Section E.4.5) and the non-human biota assessments (see Section E.7). Calculations consider the concentration of radionuclides in leachate and groundwater as specified below:

- Peak activity concentrations in leachate during the period of authorisation and peak activity concentrations in the leachate after the period of authorisation are calculated.
- Peak activity concentrations in groundwater are calculated for the abstraction points described in paragraph (paragraph 914).
- Peak activity concentrations in groundwater are calculated at the interface with the estuary; this is modelled as migration through an aquifer pathway 280 m in length.
- Peak activity concentrations in subsoil due to bathtubbing are calculated (a fraction of which are assumed to transfer to the topsoil).

914. Although the presence of an abstraction point is not considered credible either during the period of authorization or afterwards, activity concentrations are calculated for information purposes at aquifer lengths of 522.25 m from the non-hazardous waste cell, 260 m from hazardous waste cell and 260 m from the combined landfill (the aquifer pathway length for the combined landfill is taken to be the shortest of the aquifer pathway lengths for the hazardous and non-hazardous landfills).

915. The structure of the GoldSim model is shown in Figure 17. All compartments are assumed to be well mixed cells, apart from the aquifer, in which one-dimensional flow is assumed to occur. More details about the compartments are given below.

Figure 17 Compartments as modelled in GoldSim



916. Table 6 lists the radionuclides of interest with their half-lives, short-lived daughters where applicable and radioactive daughters considered explicitly. GoldSim adds the appropriate terms for radioactive decay and ingrowth to the equations governing the dynamics of the compartments. The equation for radioactive decay and ingrowth is:

$$\left(\frac{dN_{Rn,Comp}}{dt}\right)_{Decay} = \lambda_{PN} \cdot N_{PN,Comp} - \lambda_{RN} \cdot N_{Rn,Comp}$$

$$A_{Rn,Comp} = N_{Rn,Comp} \cdot \lambda_{Rn}$$

where:

- $N_{Rn,Comp}$ is the number of atoms of radionuclide Rn;
- $N_{PN,Comp}$ is the number of atoms of the parent radionuclide PN;
- λ_{Rn} is the decay constant of radionuclide Rn (s^{-1});

- λ_{PN} is the decay constant of the parent radionuclide PN (s^{-1}); and,
- $A_{Rn,Comp}$ the activity of radionuclide Rn.

917. Decay systems corresponding to a number of radionuclide chains are illustrated in Section 3.2 of the main report. Short-lived daughters that are assumed to be in secular equilibrium with a longer-lived parent radionuclide have been omitted from the figure.

918. In all the calculations, the quantities of long-lived daughters that have ingrown from specific parents or were directly disposed were distinguished. For example, the model considers seven variants of U-234, all with identical decay and sorption properties:

- U-234 directly disposed;
- U-234 ingrown from Pu-238;
- U-234 ingrown from U-238;
- U-234 ingrown from Pu-242;
- U-234 ingrown from Cm-242;
- U-234 ingrown from Am-242m; and,
- U-234 ingrown from Cm-246.

919. The dose coefficients include the contribution of all listed short-lived daughters assuming that those daughters are in secular equilibrium. Thus, the dose coefficient for U-238 includes the contributions from Th-234, Pa-234m and Pa-234.

E.4.4.1. Effect of climate change on groundwater level

920. The sea level in the Tees estuary is expected to rise because of climate change. This will lead to the groundwater level around Port Clarence rising. The change in groundwater level will influence the thicknesses of the saturated and unsaturated zones and may also lead to eventual groundwater ingress into the landfill.

921. The GoldSim groundwater model models the changing groundwater level and the effects this has on:

- the saturated and unsaturated zone thicknesses (and, thus, transport of radionuclides in the geosphere);
- ingress of groundwater to the landfill through the base and through the edges of the cap (and, thus, generation and release of leachate).

922. Sea-level rise projections were taken from (Met Office Hadley Centre, 2018). The rate of sea-level rise (SLR_{rate} m y^{-1}) was then determined by fitting a linear function to the RCP8.5 data for the location closest to Port Clarence (lat 54.72, long -1.08) for the years 2007-2299. Fitting was done using sea level anomalies relative to 2019 and with the function constrained to 0 m anomaly in 2019. The 50th percentile projections were used. These gave a sea-level rise rate of .0077 m y^{-1}. For calculations that did not account for the effects of climate change, a sea-level rise rate of 0 m y^{-1} was used.

923. The seawater (and groundwater) level increase (compared to the start of the model run) (SLR, m) is then calculated by:

$$\mathrm{SLR} = \begin{cases} t \cdot \mathrm{SLR}_{rate} \text{ if } t \cdot \mathrm{SLR}_{rate} < 15 \text{ m} \\ 15 \text{ m if } t \cdot \mathrm{SLR}_{rate} \geq 15 \text{ m} \end{cases}$$

where:

- SLR is the sea level rise (m);
- *t* is the time since landfill closure (y);
- SLR_{rate} is the rate of sea-level rise using the 50th percentile projections for future sea levels (0.0077 m y^{-1} or 0 m y^{-1}) (see paragraph 922)

924. The clay basal barrier for the landfill is shaped into a basin, with the clay barrier extending several metres up the side of the landfill. The seawater level above the top of the low-permeability basin is given by:

$$h_{gw,basin} = \begin{cases} \mathrm{SLR} - \left(d_{unsat,i} + d_{barrier} + d_{basin}\right) \text{ if } > 0 \\ 0 \text{ m} \quad \text{otherwise} \end{cases}$$

where:

- $h_{gw,basin}$ is the height of the groundwater level above the basin (m);
- SLR is the sea-level rise (m);
- $d_{unsat,i}$ is the initial thickness of the unsaturated zone (m) (Table 120);
- $d_{barrier}$ is the thickness of the clay barrier (m) (Table 119); and,
- d_{basin} is the heigh of the basin (m) (Table 119).

E.4.4.2. Waste cells

925. The engineered cap and the waste cell design are discussed in Section E.1.3. Further details are presented below on the relevant equations and parameter values used in the GoldSim model. Compartments have been defined corresponding to the different landfill components identified above. In each compartment, the waste is assumed to be well mixed. The compartment is assumed to be saturated and contaminants are distributed between pore water and soil according to a linear equilibrium sorption model.

Activity in the waste inventories

926. Calculations were undertaken for a nominal disposal inventory of 1 MBq, distributed evenly through the landfill. As all radiological impacts from the groundwater pathway scale with the disposed inventory, the results of these calculations serve as a basis for calculation of:

- the scenario radiological capacity for disposal of specific radionuclides; and,
- the contribution to radiological impact from the disposal of example wastes (similar to those disposed of at the ENRMF).

Water flux

927. The water flux through the waste cell is determined by the infiltration flux through the cap and by the efficiency of the basal liner and the clay barrier.

928. The infiltration flux through the cap, $q_{Infiltration}$, (m^3 y^{-1}) has been defined as:

$$q_{Infiltration} = q_{Infiltration,rain} + q_{Infiltration,ground}$$

where

- $q_{Infiltration,rain}$ is the rate of rainwater infiltration through the cap (m^3 y^{-1}); and,
- $q_{Infiltration,ground}$ is the rate of groundwater infiltration through the cap, once the groundwater level has risen above the base of the cap (m^3 y^{-1}).

- The rainwater infiltration flux through the cap, $q_{Infiltration,rain}$, (m^3 y^{-1}) has been defined as:

$$q_{Infiltration,rain} = P_{eff} \cdot A_{Surface}$$

where :

- $A_{Surface}$ represents the surface area of the component of the landfill being considered (m^2) (Table 119);

- P_{eff} represents the effective rainfall infiltration into the waste cell, defined as:

$$P_{eff} = \begin{cases} P_{Cap} \; if \; t < t_{StartCapDegradation} \\ P_{Grassland} \; if \; t > t_{EndCapDegradation} \\ P_{Cap} + \dfrac{(t - t_{StartCapDegradation}) \cdot (P_{Grassland} - P_{Cap})}{t_{EndCapDegradation} - t_{StartCapDegradation}} \; \text{otherwise} \end{cases}$$

929. Before cap degradation starts (i.e. before $t_{StartCapDegradation}$), the cap design infiltration rate P_{Cap} is assumed to be valid. When the polyethylene component of the cap has fully degraded at $t_{EndCapDegradation}$, the vegetation on top of the landfill area is assumed to be grassland, and hence the infiltration into the waste cells would be defined by the infiltration to grassland $P_{Grassland}$. The cap is assumed to degrade in such a way that the infiltration increases linearly between $t_{StartCapDegradation}$ and $t_{EndCapDegradation}$ (Eden NE, 2023).

930. The parameters used to calculate the effective rainwater infiltration have been assigned values as defined in Table 115. All these parameter values are taken from the HRA (MJCA, 2019a).

Table 115 Parameters to calculate the effective rainfall infiltration through the cap

Parameter	Description	Value	Basis for single value (if taken from PDF)
P_{Cap}	Cap design infiltration (consistent with HRA)	0.0315 m y^{-1}	Mean of distribution
$P_{Grassland}$	Infiltration to grassland (consistent with HRA)	0.202 m y^{-1}	Mean of distribution
$t_{StartCapDegradation}$	Start of cap degradation	250 y	Single value

Parameter	Description	Value	Basis for single value (if taken from PDF)
$t_{EndCapDegradation}$	End of cap degradation	1,000 y	Single value

931. The groundwater infiltration flux through the cap, $q_{Infiltration,rain}$, (m^3 y^{-1}) has been defined assuming Darcy flow through the region of the cap that is in contact with the groundwater:

$$q_{Infiltration,ground} = K_{Cap} \cdot A_{submerged} \cdot \frac{h_{gw,cap}}{t_{cap}}$$

where:

- K_{Cap} is the hydraulic conductivity of the cap (315 m y^{-1}) (degraded cap assumed to have hydraulic properties of soil (Table 118);
- $A_{submerged}$ is the area of the cap above the low-permeability liner and below the groundwater (m^2), given by $h_{gw,basin} \cdot c$;
- $h_{gw,cap}$ is the groundwater head above the higher of the leachate level in the landfill or the top of the low-permeability barrier (m) or 0 m if the groundwater level is below either; and,
- t_{cap} is the thickness of the engineered cap (see Section E.1.3.1).
- $h_{gw,basin}$ is the groundwater level above the basin (m), or 0 m if the groundwater level is below it;
- c is the circumference of the cap (2000 m for non-hazardous, 3000 m for hazardous and 3000 m for combined landfill)

932. The potential flux from the waste cell out of the HDPE liner is modelled using the same formula as in LandSim (Gane, 2014). The maximum leachate flux $q_{Liner,out}$ through the basal liner (m^3 y^{-1}) is defined as:

$$q_{Liner,out} = \sum_{Defect} n_{Defect} \cdot q_{Defect,out}$$

where:

- n_{Defect} is the number of defects of each type present (Table 116);
- $q_{Defect} = c \cdot a_{Defect}^{0.1} \cdot h^{0.9} \cdot K_{Barrier}^{0.74} \cdot 3.16E + 07$
- c is the contact quality parameter (1.05) (dimensionless);
- a is the area of that type of defect (m^2) (Table 116);
- h is the head of leachate in the landfill above the liner or above the groundwater level (if higher than the liner) (m), or 0 m if the leachate level is below the groundwater level (paragraph 949);
- $K_{Barrier}$ is the hydraulic conductivity of the underlying clay barrier (5.91×10^{-11} m s^{-1});
- 3.16×10^7 s y^{-1} is the conversion from seconds to years.

933. The maximum groundwater flux $q_{Liner,in}$ in through the basal liner ($m^3\ y^{-1}$) is defined as:

$$q_{Liner,in} = \sum_{Defect} n_{Defect} \cdot q_{Defect,in}$$

where:

- n_{Defect} is the number of defects of each type present (Table 116);
- $q_{Defect,in} = c \cdot a_{Defect}^{0.1} \cdot h_{gw}{}^{0.9} \cdot K_{Barrier}^{0.74} \cdot 3.16E + 07$
- *c* is the contact quality parameter (1.05) (dimensionless);
- *a* is the area of that type of defect (m^2) (Table 116);
- h_{gw} is the groundwater head above the leachate level in the landfill (m) or 0 m if the groundwater level is below the leachate level (paragraph 950);
- $K_{Barrier}$ is the hydraulic conductivity of the underlying clay barrier (5.91×10^{-11} m s^{-1});
- 3.16×10^7 s y^{-1} is the conversion from seconds to years.

934. The number of defects is assumed to increase linearly from zero to the numbers in Table 116 over 150 years, then double every 100 years for 1350 years (exponential degradation). After 1500 years following closure, liner degradation is assumed to be complete and the number of defects remains constant (Environment Agency, 2003).

935. The number and type of defects present when exponential degradation starts are as defined in Table 116 and other parameters are as defined in Table 117.

Table 116 Assumptions regarding defects in the liner (MJCA, 2019a)

Defect	Area defect a_{Defect} (mm^2)	Number of defects at onset of exponential degradation (150 y) n_{Defect} (ha^{-1})	Basis for single value (if taken from PDF)
Pinhole	2.55	25	Maximum from distribution (No. of defects)
Hole	52.5	5	Maximum from distribution (No. of defects)
Tear	5050	2	Maximum from distribution (No. of defects)

Table 117 Parameters to calculate the flow through the waste cells

Parameter	Units	Value	Description	Basis for single value (if taken from PDF)
c		1.05	Contact quality parameter (credible value from (Environment Agency, 2003). Potential distribution from 0.21 to 1.15.	Selected from distribution
$K_{Barrier}$	m s^{-1}	5.91 10^{-11}	Hydraulic conductivity of the clay barrier used in the HRA	Most likely value
$d_{Barrier}$	m	1 or 1.5	Thickness of the clay barrier, 1 m for the non-hazardous waste cell,1.5 m for the hazardous waste cell and 1 m for the combined landfill.	Single value

936. The areas of defects (a_{Defect}) and numbers of defects (n_{Defect}) when exponential degradation starts (Table 116) were derived from the LandSim runs for the 2019 HRA (MJCA, 2019a). The parameter values in Table 117 were taken from (MJCA, 2019a), except for the liner contact quality parameter *c*, which is taken from LandSim (Environment Agency, 2003).

937. The potential flux out of the landfill through the clay barrier (m^3 y^{-1}) is defined as:

$$q_{Barrier,out} = K_{Barrier} \cdot A_{Basal} \cdot \frac{h}{d_{Barrier}} \cdot 3.16E7$$

where:

- $K_{Barrier}$ is the hydraulic conductivity of the underlying clay barrier (5.91 10^{-11} m s^{-1});
- A_{Basal} is the basal area (m^2) of the landfill component being considered (Table 119);
- h is the head of leachate in the landfill above the liner or above the groundwater level (if higher than the liner) (m), or 0 m if the leachate level is below the groundwater level;
- $d_{Barrier}$ is the thickness of the clay barrier (m) (Table 119);
- 3.16E7 s y^{-1} is the conversion from seconds to years.

938. The potential flux of groundwater into the landfill through the clay barrier (m^3 y^{-1}) is defined as:

$$q_{Barrier,in} = K_{Barrier} \cdot A_{Basal} \cdot \frac{h_{gw}}{d_{Barrier}} \cdot 3.16E7$$

where:

- $K_{Barrier}$ is the hydraulic conductivity of the underlying clay barrier (5.91 10^{-11} m s^{-1}) (MJCA, 2019b);

- A_{Basal} is the basal area (m^2) of the landfill component being considered (Table 119);
- h_{gw} is the groundwater head above the leachate level in the landfill (m) or 0 m if the groundwater level is below the leachate level;
- $d_{Barrier}$ is the thickness of the clay barrier (m)) (Table 119); and,
- 3.16E7 s y^{-1} is the conversion from seconds to years.

939. It is assumed that the flow through the liner and barrier controls the flow of water through the base of the landfill (q_{base}, m^3 y^{-1}). When the leachate head is above the groundwater level, leachate will flow out through the base of the landfill (i.e., q_{base} will be negative) at a rate determined as -1 times the minimum of $q_{Barrier,out}$ and $q_{Liner,out}$. When the leachate head is below the groundwater level, groundwater will flow in through the base of the landfill (i.e., q_{base} will be positive) at a rate determined as the minimum of $q_{Barrier,in}$ and $q_{Liner,in}$.

940. Algebraically, this can be given as:

$$q_{base} = q_{base,in} - q_{base,out}$$

$$q_{base,in} = \begin{cases} \mathrm{Min}\left(q_{Barrier,in}, q_{Liner,in}\right) & \text{if } > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$q_{base,out} = \begin{cases} \mathrm{Min}\left(q_{Barrier,out}, q_{Liner,out}\right) & \text{if } > 0 \\ 0 & \text{otherwise} \end{cases}$$

941. Leachate can also leave the landfill by active management or by overtopping the clay barrier ($V_{overflow}$, m^3 y^{-1}). During the period of active management, leachate above a certain level is removed for active management. $V_{overflow}$ during the period of active management is given by:

$$V_{overflow} = \begin{cases} (h_{leach} - h_{controlled}) \cdot A_{Basal} \cdot \varepsilon / \Delta t & \text{if } h_{leach} > h_{controlled} \\ 0 \ \mathrm{m^3 y^{-1}} & \text{otherwise} \end{cases}$$

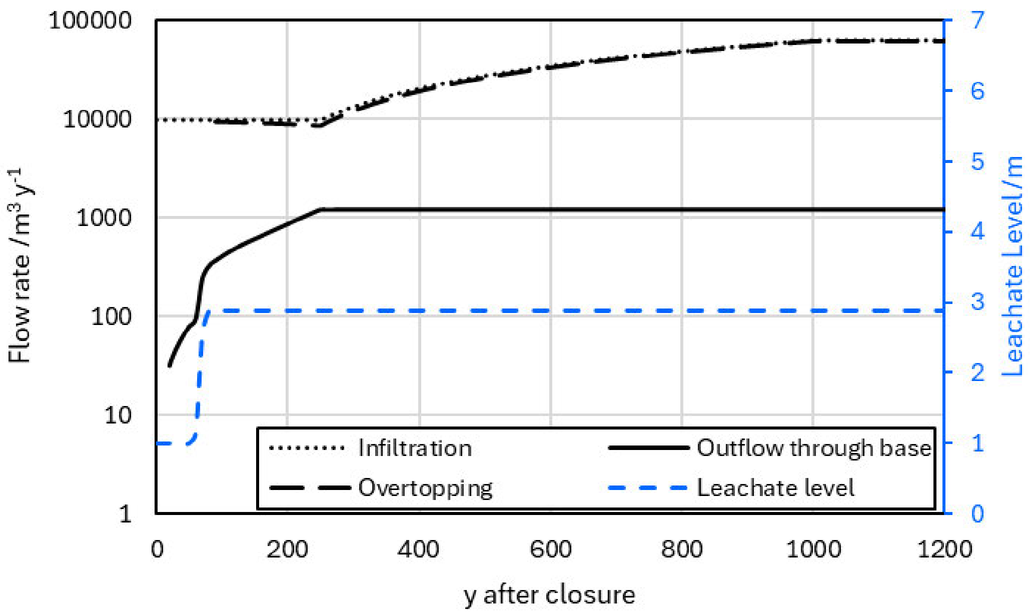
where:

- $V_{overflow}$ is the rate at which leachate leaves the landfill by active management (m^3 y^{-1});
- h_{leach} is the level of leachate above the basal liner (m) (paragraph 947);
- $h_{controlled}$ is the maximum leachate level permitted by the active management arrangements (1 m) (MJCA, 2012);
- A_{Basal} is the basal area of the landfill (m^2) (Table 119);
- ε is the moisture content of the waste cell by volume (dimensionless) (paragraph 954).

942. After the period of active management, leachate will not be removed. However, once the leachate head exceeds the height of the basin, any excess leachate generated will overtop the landfill and be released to the surrounding soil. $V_{overflow}$ after the period of active management is described in paragraph 982).

943. The water fluxes into the waste cell and from the waste cell to the clay barrier for the combined landfill and the leachate level are shown in Figure 18. Where the flow out through the liner is less than the flow in through the cap, the excess is either removed for treatment (during the first 60 y), leads to an increase in the leachate level in the landfill or overtops the landfill.

Figure 18 Water flux through the waste cells for the combined landfill (without considering the effects of climate change)



944. Contaminants are also modelled leaving the waste cell through diffusion into the barrier (although this does not affect the water level or head in the waste cell). This is modelled using GoldSim's standard approach for modelling diffusive fluxes (GoldSim Technology Group, 2021b). A diffusion length of 1.5 m is use for both the waste cell and the clay barrier. A porous medium with the properties of clay is assumed to be present in the barrier and no porous medium is assumed to be present in the waste cell. The diffusive area is given by:

$$A_{diffusion} = A_{basal} \cdot \sum_{Defect} n_{Defect} \cdot A_{Defect}$$

where:

- $A_{diffusion}$ is the area of the surface through which diffusion can occur (m^2);
- A_{basal} is the basal area of the landfill (m^2) (Table 119);
- n_{defect} is the density of defects at the time of interest (m^{-2}) (see paragraph 935); and,
- A_{Defect} is the area of an individual defect (m^2) (Table 116).

945. Until the end of the management phase (MJCA, 2019b), leachate is monitored and managed to ensure that leachate levels remain below the permitted limits (trigger levels: head < 2 m in sumps and head < 1 m in boreholes). Excess leachate is pumped

off and either used in the adjacent treatment plant or transported off-site by tanker for treatment. The fate of leachate after the end of the management phase is addressed in Section E.4.4.6.

Leachate head and level

946. The behaviour of the leachate level in the waste cell is modelled by:

$$\frac{dh_{leach}}{dt} = \frac{q_{Infiltration} + q_{base} - V_{overflow}}{A_{basal}.\varepsilon}$$

where:

- dh_{leach}/dt is the rate of change in the leachate level above the base of the landfill (m y^{-1});
- $q_{infiltration}$ is the rate of water ingress through the cap from rain and from rising groundwater levels (m^3 y^{-1}) (paragraph 927);
- q_{base} is the flow of water through the base (m^3 y^{-1}), either outwards owing to the leachate head in the landfill (negative value) or inwards owing to rising groundwater level (positive value) depending on the water levels at the time of interest (paragraph 939);
- $V_{overflow}$ is the loss of water to active leachate management (during the PoA) and overtopping (after the PoA) (m^3 y^{-1}) (paragraph 942 and 982)
- A_{basal} is the basal area of the landfill (m^2) (Table 119); and,
- ε is the moisture content of the waste cell (dimensionless) (paragraph 954).

947. Once the groundwater level has risen above the base of the landfill, the head in the landfill will be controlled by the difference between the groundwater level and the leachate level (paragraph 939) If the groundwater level is below the leachate level, leachate will continue to flow out through the base, driven by the head of leachate above the groundwater level. If the groundwater level is above the leachate level, groundwater will flow in through the base, driven by the head of groundwater above the leachate level.

948. The effective head of leachate (that is, the head of leachate above the higher of the groundwater level and the landfill base) (h, m) is given by:

$$h = \begin{cases} h_{leach} \quad \text{if} \quad \text{SLR} \leq d_{barrier} + d_{unsat,i} \\ h_{leach} + d_{barrier} + d_{unsat,i} - \text{SLR} \quad \text{if} \quad d_{barrier} + d_{unsat,i} < \text{SLR} < h_{leach} + d_{barrier} + d_{unsat,i} \\ 0 \text{ m} \quad \text{if} \quad \text{SLR} \geq h_{leach} + d_{barrier} + d_{unsat,i} \end{cases}$$

where:

- h is the effective head of the leachate that drives the flow through the base of the landfill (m);
- h_{leach} is the level of the leachate above the base of the landfill (m) (paragraph 946)

- SLR is the rise in sea level since the start of the model run (m) (paragraph 923);
- $d_{barrier}$ is the thickness of the clay barrier (m) (Table 119); and,
- $d_{unsat,i}$ is the initial thickness of the unsaturated zone (m) (Table 120).

949. The effective head of groundwater (that is, the head of groundwater above the leachate level) (h_{gw}, m) is given by:

$$h_{gw} = \begin{cases} \text{SLR} - \left(h_{leach} + d_{barier} + d_{unsat,i}\right) & \text{if} \;\; \text{SLR} > \left(h_{leach} + d_{barier} + d_{unsat,i}\right) \\ 0\ \text{m} & \text{if} \;\; \text{SLR} \le \left(h_{leach} + d_{barier} + d_{unsat,i}\right) \end{cases}$$

where:

- h_{gw} is the effective head of the groundwater that drives inflow through the base of the landfill (m);
- h_{leach} is the level of the leachate above the base of the landfill (m) (paragraph 946);
- SLR is the rise in sea level since the start of the model run (m) (paragraph 923);
- $d_{barrier}$ is the thickness of the clay barrier (m) (Table 119); and,
- $d_{unsat,i}$ is the initial thickness of the unsaturated zone (m) (Table 120).

950. The head of groundwater driving infiltration through the cap ($h_{gw,cap}$, m) is given by:

$$h_{gw,cap} = \begin{cases} 0\ \text{m} \;\; \text{if} \;\; \text{SLR} \le \left(h_{leach} + d_{barier} + d_{unsat,i}\right) \text{ or } \text{SLR} \le \left(d_{unsat,i} + d_{barier} + d_{basin}\right) \\ \text{SLR} - \left(h_{leach} + d_{barier} + d_{unsat,i}\right) \;\; \text{if} \;\; h_{leach} > d_{basin} \text{ and SLR} > \left(h_{leach} + d_{barier} + d_{unsat,i}\right) \\ \text{SLR} - \left(d_{unsat,i} + d_{barier} + d_{basin}\right) \;\; \text{if} \;\; h_{leach} \le d_{basin} \text{ and SLR} > \left(d_{basin} + d_{barier} + d_{unsat,i}\right) \end{cases}$$

where:

- $h_{gw,cap}$ is the head of groundwater that drives inflow through the cap (m);
- h_{leach} is the level of the leachate above the base of the landfill (m) (paragraph 946)
- SLR is the rise in sea level since the start of the model run (m) (paragraph 923);
- $d_{barrier}$ is the thickness of the clay barrier (m) (Table 119);
- $d_{unsat,i}$ is the initial thickness of the unsaturated zone (m) (Table 120); and,
- d_{basin} is the height that the clay barrier extends up the side of the landfill basin) (Table 119).

Materials

951. Proportions and properties of waste and filling materials are given in Table 118. The density, water content and hydraulic conductivity of waste and clay were taken from

the HRA (MJCA, 2019b) and the density of soil was taken from a previous assessment (Eden NE, 2023).

Table 118 Proportions and properties of waste and filling materials

Material	Proportion	Density (kg m^{-3})	Water Content	Hydraulic conductivity (m s^{-1})	Basis for single value (if taken from PDF)
Waste	5%	920	0.3725	1 10^{-5}	Mean of distribution (density, water content)
Soil (incl. soil type waste)	95%	1,300	0.25	1 10^{-5}	
Clay	0%	1920	0.164	5.91 10^{-11}	Most likely (density, water content, hydraulic conductivity)

952. The sorption distribution coefficients (K_ds) for soil and clay are given in Table 224. Waste is assumed to be non-sorbing (K_d = 0 m^3 kg^{-1}) for all elements except Technetium. The sorption coefficient (Kd) for Tc-99 for LLW has been set to 4 10^{-2} m^3 kg^{-1} because of the anoxic nature of the waste cells when sealed.

953. Radionuclides sorb to different materials in the waste cells such that the activity concentration in leachate ($a_{Leachate}$) in Bq m^{-3} is:

$$a_{RN,Leachate} = \frac{A_{Rn,Cell}}{\sum_{Mat} M_{Mat,Cell} \cdot K_{d,Rn,Mat} + V_{Water,Cell}}$$

where:

- $a_{RN,Leachate}$ is the activity concentration in leachate for radionuclide *Rn* (Bq m^{-3});
- $A_{Rn,Cell}$ is the total activity of radionuclide *Rn* in the waste cell (Bq);
- $M_{Mat,Cell}$ is the mass of material *Mat* in the waste cell (kg);
- $K_{d,Rn,Mat}$ is the distribution coefficient for radionuclide *Rn* in material Mat (m^3 kg^{-1}); and,
- $V_{Water,Cell}$ is the volume of water in the waste cell (m^3).

954. The mass of the different materials ($M_{Mat,Cell}$), the average water content of the waste cell (ε) and the volume of water in the waste cell ($V_{Water,Cell}$) are determined by the proportions and properties of the materials:

$$M_{Mat,Cell} = \rho_{Mat} \cdot V_{Cell} \cdot pr_{Mat}$$

$$V_{Water,Cell} = V_{Cell} \cdot \sum_{Mat} \varepsilon_{Mat} \cdot pr_{Mat}$$

$$\varepsilon = \sum_{Mat} \varepsilon_{Mat} \cdot pr_{Mat}$$

where:

- $M_{Mat,Cell}$ is the mass of the different materials (kg);

- $V_{Water,Cell}$ is the volume of water in the waste cell (m^3);
- ρ_{Mat} is the density of material *Mat* (kg m^{-3});
- V_{Cell} is the volume of the waste *cell* (m^3);
- pr_{Mat} is the proportion of material *Mat* (dimensionless);
- ε_{Mat} is the water content in material *Mat* (dimensionless); and,
- ε is the average water content of the waste cell (dimensionless) (paragraph 954).

955. The leaching rate of radionuclide *Rn* is defined as:

$$\left(\frac{dN_{Rn,Cell}}{dt}\right)_{Leaching} = -n_{Rn,Leachate} \cdot q_{base,out}$$
$$= -\frac{N_{Rn,Cell} \cdot q_{base,out}}{\sum_{Mat} M_{Mat,Cell} \cdot K_{d,Rn,Mat} + V_{Water,Cell}}$$

where:

- $N_{Rn,Cell}$ is the number of atoms of radionuclide *Rn* in the waste cells;
- $n_{Rn,Leachate}$ is the number of atoms per unit volume of leachate (m^{-3});
- $q_{base,out}$ is the flow of water out through the base of the landfill (m^3 y^{-1}) (paragraph 940);
- $M_{Mat,Cell}$ is the mass of the different materials (kg);
- $K_{d,Rn,Mat}$ is the distribution coefficient for radionuclide *Rn* in material Mat (m^3 kg^{-1}); and,
- $V_{Water,Cell}$ is the volume of water in the waste cell (m^3).

956. Radioactive decay and ingrowth are also applied to the atoms of radionuclide *Rn* in the waste cells.

E.4.4.3. Clay barrier

957. The clay barrier is represented as a well-mixed compartment with equilibrium sorption of contaminants to the clay. Flow through the barrier is subvertical from the waste cell to the unsaturated zone.

958. The dimensions of the barrier for the different calculation cases are defined in Table 119. The barrier thicknesses for the non-hazardous and hazardous waste cells have been taken from the HRA (MJCA, 2019a). The minimum barrier thickness has been selected for the assessment of the combined landfill as a conservative assumption.

Table 119 Dimensions of the barrier

Site	Basal area (m^2)	Clay barrier thickness (m)	Height to which clay barrier is installed at the side of the landfill basin (m)	Basis for single value (if taken from PDF)
Non-hazardous waste cell	143,350	1	2.882	Single value
Hazardous waste cell	122,840	1.5	6.448	Single value
Combined landfill	266,190	1	2.882	Single value

959. The clay barrier is assumed to be in hydrological equilibrium, which means that the water flux through the barrier is assumed to be equal to the water flux through the waste cells, i.e. q_{base}.

960. The barrier is constructed out of Upper Lias Clay. The properties and K_d values for clay have been defined in Table 118 and Table 224.

961. The behaviour of radionuclide *Rn* in the barrier is described by the following differential equation.

$$\left(\frac{dN_{Rn,Barrier}}{dt}\right)_{GW} = \frac{N_{Rn,Cell} \cdot q_{base,out}}{\sum_{Mat} M_{Mat,Cell} \cdot K_{d,Rn,Mat} + V_{Water,Cell}} - \frac{N_{Rn,Barrier} \cdot q_{base,out}}{M_{Clay,Barrier} \cdot K_{d,Rn,Clay} + V_{Water,Barrier}}$$

962. The first term relates to the flux from the waste cell into the clay barrier. The second term relates to the flux from the clay barrier into the unsaturated zone. The subscript index *GW* indicates that the equation includes the contributions from groundwater movement, and not radioactive decay. Radioactive decay and ingrowth are also applied to the atoms of radionuclide *Rn* in the barrier. The clay mass in the barrier ($M_{Clay,Barrier}$) and the water volume in the clay barrier ($V_{Water,Barrier}$) are given by:

$$M_{Clay,Barrier} = \rho_{Clay} \cdot V_{Barrier}$$

$$V_{Water,Barrier} = \varepsilon_{Clay} \cdot V_{Barrier}$$

where:

- $M_{Clay,Barrier}$ is the mass of the clay barrier materials (kg);
- $V_{Water,Barrier}$ is the volume of water in the barrier (kg);
- $K_{d,Rn}$ is the distribution coefficient for radionuclide *Rn* in material or clay ($m^3\ kg^{-1}$);
- ρ_{Clay} is the density of clay ($kg\ m^{-3}$);

- ε_{Clay} is the water content of clay (dimensionless); and,
- $V_{Barrier}$ is the volume of the clay barrier (m^3).

E.4.4.4. Unsaturated zone

963. An unsaturated zone underlies the clay barrier and flow in the unsaturated zone is subvertical. The zone is represented as a well-mixed compartment.

964. The initial thicknesses of the unsaturated zone for the non-hazardous and hazardous waste cells are the same, see Table 120, and have been taken from the HRA (MJCA, 2019a). This thickness has also been selected for the assessment of the combined landfill.

965. The groundwater level will rise because of climate change. The thickness of the unsaturated zone will, therefore, reduce over time until the groundwater reaches the base of the landfill. Once the groundwater reaches the base of the landfill there is effectively no unsaturated zone. The thickness of the unsaturated zone is given by:

$$d_{unsat} = \begin{cases} d_{unsat,i} - \text{SLR} & \text{if } > 0 \\ 0 \text{ m} & \text{otherwise} \end{cases}$$

where:

- d_{unsat} is the thickness of the unsaturated zone accounting for sea-level rise (m);
- $d_{unsat,i}$ is the thickness of the unsaturated zone at the start of the model run (m) (Table 120); and,
- SLR is the sea-level rise that has occurred (relative to the start of the model run) (m) (paragraph 923).

Table 120 Dimensions of the unsaturated zone

Site	Basal area (m^2)	Unsaturated zone initial thickness (m)	Basis for single value (if taken from PDF
Non-hazardous waste cell	143,350	1	Single value
Hazardous waste cell	122,840	1	Single value
Combined landfill	266,190	1	Single value

966. The water flux through the unsaturated zone is assumed to be equal to the water flux through the barrier and the waste cells.

967. The unsaturated zone consists of made ground, the properties of which have been taken from (MJCA, 2019b) and reproduced in Table 121. The K_ds for made ground are taken to be the same as those for soil (Table 224).

Table 121 Properties of unsaturated made ground

Material	Density ($kg^1 m^{-3}$)	Water content	Hydraulic conductivity ($m s^{-1}$)	Basis for single value (if taken from PDF
Unsaturated made ground	1155	0.19	$2.73\ 10^{-5}$	Mean value

968. The behaviour of radionuclide *Rn* in the unsaturated zone is represented by the following equation:

$$\left(\frac{dN_{Rn,Unsat}}{dt}\right)_{GW} = \frac{N_{Rn,Barrier} \cdot q_{base,out}}{M_{Clay,Barrier} \cdot K_{d,Rn,Clay} + V_{Water,Barrier}} - \frac{N_{Rn,Unsat} \cdot q_{base,out}}{M_{UnsatMadeGround,Unsat} \cdot K_{d,Rn,UnsatMadeGround} + V_{Water,Unsat}}$$

969. The first term relates to the flux from the clay barrier into the unsaturated zone. The second term relates to the flux from the unsaturated zone into the saturated zone. The volume of water in the unsaturated zone ($V_{Water,Unsat}$, m^3) is given by:

$$V_{Water,Unsat} = \varepsilon_{UnsatMadeGround} \cdot V_{Unsat}$$

where:

- $V_{Water,Unsat}$ is the volume of water in the unsaturated zone (m^3);
- $\varepsilon_{UnsatMadeGround}$ is the water content of unsaturated made ground; and,
- V_{Unsat} is the volume of the unsaturated zone (m^3).

970. Radioactive decay and ingrowth is also applied to radionuclide Rn, separately.

E.4.4.5. Saturated zone

971. A saturated zone underlies the unsaturated zone and flow in the saturated zone is subvertical. The zone is represented as a well-mixed compartment.

972. The initial thicknesses of the saturated zone for the non-hazardous and hazardous waste cells are the same, see Table 122, and have been taken from the HRA (MJCA, 2019b). The thickness has also been selected for the assessment of the combined landfill.

973. The groundwater level will rise because of climate change. The thickness of the saturated zone will, therefore, increase over time until the groundwater reaches the base of the landfill. Once the groundwater reaches the base of the landfill, leachate from the barrier effectively enters the saturated zone directly. The thickness of the saturated zone is given by:

$$d_{sat} = \begin{cases} d_{sat,i} + \text{SLR} \quad \text{if } \leq d_{sat,i} + d_{unsat,i} \\ d_{sat,i} + d_{unsat,i} \quad \text{otherwise} \end{cases}$$

where:

- d_{sat} is the thickness of the saturated zone accounting for sea-level rise (m);
- $d_{sat,i}$ is the thickness of the unsaturated zone at the start of the model run (m) (Table 122);
- $d_{unsat,i}$ is the thickness of the unsaturated zone at the start of the model run (m) (Table 120); and,
- SLR is the sea-level rise that has occurred (relative to the start of the model run) (m) (paragraph 923).

Table 122 Dimensions of the saturated zone

Site	Basal area (m^2)	Saturated zone initial thickness (m)	Basis for single value (if taken from PDF)
Non-hazardous waste cell	143,350	2.7	Single value (area); most likely value (thickness)
Hazardous waste cell	122,840	2.7	Single value (area); most likely value (thickness)
Combined landfill	266,190	2.7	Single value (area); most likely value (thickness)

974. The saturated zone is assumed to be in hydrological equilibrium, which means that the water flux through the saturated zone is assumed to be equal to the water flux through the unsaturated zone, the barrier and the waste cells.

975. The saturated zone consists of made ground, the properties of which have been taken from (MJCA, 2019b) and reproduced in Table 123. The K_ds for made ground are taken to be the same as those for soil(Table 224).

Table 123 Properties of saturated made ground

Material	Density (kg m^{-3})	Water content	Hydraulic conductivity (m s^{-1})	Basis for single value (if taken from PDF)
Saturated made ground	1155	0.25	2.73 10^{-5}	Mean values

976. The behaviour of radionuclide *Rn* in the saturated zone is represented by the following equation:

$$\left(\frac{dN_{Rn,Sat}}{dt}\right)_{GW} = \frac{N_{Rn,Unsat} \cdot q_{base,out}}{M_{UnsatMadeGround,Unsat} \cdot K_{d,Rn,UnsatMadeGround} + V_{Water,Unsat}} - \frac{N_{Rn,Sat} \cdot q_{base,out}}{M_{SatMadeGround,Unsat} \cdot K_{d,Rn,SatMadeGround} + V_{Water,Sat}}$$

977. The first term relates to the flux from the unsaturated zone into the saturated zone. The second term relates to the flux from the saturated zone into the aquifer. The volume of water in the saturated zone ($V_{Water,Sat}$, m^3) is given by:

$$V_{Water,Sat} = \varepsilon_{SatMadeGround} \cdot V_{Sat}$$

where:

- $V_{Water,Sat}$ is the volume of water in the saturated zone (m^3);
- $\varepsilon_{SatMadeGround}$ is the water content of saturated made ground; and,
- V_{Sat} is the volume of the saturated zone (m^3).

978. Radioactive decay and ingrowth are also applied to radionuclide *Rn*, separately.

E.4.4.6. Bathtubbing

979. After the management control period, the leachate level is no longer controlled, and the base of a waste cell may gradually fill up if the infiltration flow through the cap is higher than the flow through the basal liner and the clay barrier. When the clay barrier basin is full (the leachate in part of the landfill reaches the height given in Table 119), leachate overflow will occur (unless the groundwater level is equal to or above the leachate level), and leachate will disperse into the subsoil around the area. The clay layer proposed for the landfill engineered barrier (below the liner) will not degrade in the same way as an artificial membrane (therefore, the bathtubbing calculations assume that the hydraulic conductivity of the clay barrier remains constant throughout the modelled duration).

980. Some overflow leachate will percolate through the soil into the saturated layer, bypassing the engineered barriers put in place for the landfill. This is represented using a bypass compartment in the model (see paragraphs 988 to 991). This bypass compartment is enabled for the Bathtubbing scenario and the flow of groundwater to the estuary. For other scenarios, the bypass compartment is disabled and activity leaving the subsoil is modelled as leaving the system into a sink compartment.

981. The rate at which water can percolate through the subsoil is limited (paragraph 987); the rate of seepage to groundwater, q_{seep}, is thus the minimum of $V_{overflow}$ and $q_{soil,max}$. If the rate of overtopping is greater than the rate at which water can percolate through the subsoil, the excess leachate will flow rapidly to the estuary as surface water ($q_{est,fast} = V_{overflow} - q_{seep}$ if >0 m^3 y^{-1} and 0 m^3 y^{-1} otherwise).

982. The rate of leachate overflow ($V_{overflow}$) owing to overtopping after the period of active control is determined as:

$$V_{overflow} = \begin{cases} 0\ \mathrm{m}^3 y^{-1} \quad \text{if} \quad h_{leach} < d_{basin} \text{ or } h = 0\ \mathrm{m} \\ (h_{leach} - d_{basin}) \cdot A_{Basal} \cdot \varepsilon / \Delta t \quad \text{if} \quad h_{leach} \geq d_{basin} \text{ and SLR} < t_{unsati,i} + d_{barrier} + d_{basin} \\ h \cdot A_{Basal} \cdot \varepsilon / \Delta t \quad \text{if} \quad \text{SLR} \geq t_{unsati,i} + d_{barrier} + d_{basin} \text{ and } h > 0\ \mathrm{m} \end{cases}$$

where:

- $V_{overflow}$ is the annual volume of leachate overflow (m3 y-1);
- h_{leach} is the level of leachate above the basal liner (m) (paragraph 946);
- d_{basin} is the height that the clay barrier extends up the side of the landfill basin) (Table 119).

- h is the is the effective head of leachate in the landfill, above the higher of the landfill base and the groundwater level (m) (paragraph 947);
- A_{Basal} is the basal area of the landfill (m2) (Table 119);
- ε is the moisture content of the waste cell (dimensionless) (paragraph 954)
- Δt is the simulation timestep (y);
- $t_{unsat,i}$ is the initial thickness of the unsaturated zone (m) (Table 120).

983. During the period of active control, bathtubbing cannot occur because leachate is actively removed. $V_{overflow}$ for the period of active management is the rate at which leachate is actively removed and is defined in paragraph 941.

984. The affected area (A_{Flood}) is 5×10^5 m^2. This assumes that the flow goes in the same direction as the groundwater flow and is not influenced by the southern raised bund, as shown in Figure 19.

985. The maximum rate at which leachate can percolate through the soil ($q_{soil,max}$, m^3 y^{-1}) is:

$$q_{soil,max} = K_{soil} \cdot A_{Flood} \cdot \theta_{soil} \cdot (1 - sat_{soil})$$

where:

- K_{soil} is the hydraulic conductivity of soil (m y^{-1}) (Table 118);
- A_{Flood} is the area affected by bathtubbing (500,000 m^2);
- θ_{soil} is the porosity of topsoil (0.3) (dimensionless) (Eden NE, 2023); and,
- sat_{soil} is the saturation of topsoil (0.5) (dimensionless) (Eden NE, 2023).

986. There will also be a vertical flow percolating through the soil as a result of natural infiltration (for example, owing to rainfall). This is given by:

$$q_{inf,seepage} = P_{Grassland} \cdot A_{Flood}$$

where:

- $q_{inf,seepage}$ is the natural infiltration rate in the seepage zone (m^3 y^{-1});
- $P_{Grassland}$ is the natural infiltration for farmland (treated as grassland) (m y^{-1}) (Table 115); and,
- A_{Flood} is the area affected by seepage (m^2).

Figure 19 Area between landfill and River Tees affected by bathtubbing

987. The total vertical flow in the bathtubbing compartments is then given by:

$$q_{tot,seep} = q_{seep} + q_{inf,seepage}$$

where:

- $q_{tot,seep}$ is the total vertical flow in the seepage compartments ($m^3\ y^{-1}$);
- q_{seep} is the vertical flow arising from bathtubbing ($m^3\ y^{-1}$) (paragraph 981)
- $q_{inf,seepage}$ is the vertical flow owing to natural infiltration in the bathtubbing region ($m^3\ y^{-1}$).

988. The initial thickness of the bypass compartment is defined as:

$$d_{overflow} = d_{UnsatZone} + d_{Barrier} + d_{Basin} - d_{subsoil}$$

where:

- $d_{overflow}$ is the thickness of the receiving overflow compartment (m);
- $d_{UnsatZone}$ is the initial thickness of the unsaturated zone (m);
- $d_{Barrier}$ is the thickness of the clay barrier (m);
- d_{Basin} is the height of the basin (m); and,
- $d_{Topsoil}$ is the thickness of the subsoil (m).

989. As sea level rises, the thickness of the bypass compartment is given by:

$$d_{overflow} = \begin{cases} d_{overflow,i} - \mathrm{SLR} & \text{if} > 0\ \mathrm{m} \\ 0\ \mathrm{m} & \text{otherwise} \end{cases}$$

where:

- $d_{overflow}$ is the thickness of the bypass (m);
- $d_{overflow,i}$ is the initial thickness of the bypass (m); and,
- SLR is the sea level rise (m) (paragraph 923).

990. The bypass compartment has the same water content and the hydraulic conductivity as the unsaturated zone as it contains unsaturated made ground. A saturated zone is located beneath the bypass compartment unsaturated zone, with the same water content and hydraulic conductivity as the saturated zone beneath the landfill.

991. The thickness of the bypass saturated zone is given by:

$$d_{over,sat} = d_{SatZone,i} + d_{overflow,i} - d_{overflow}$$

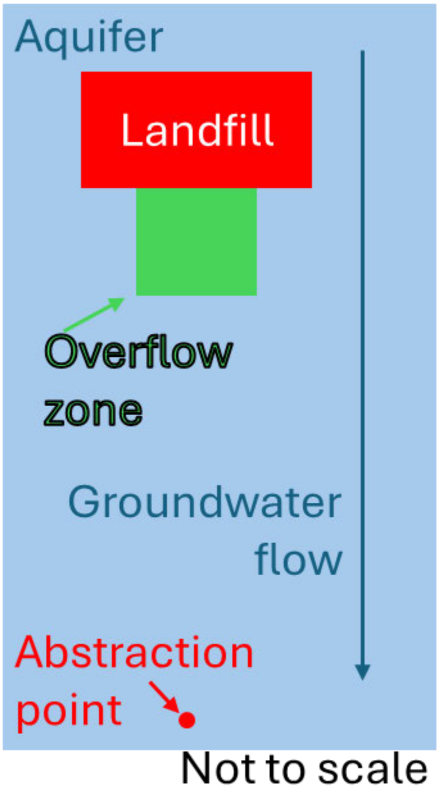
where:

- $d_{over,sat}$ is the thickness of the bypass saturated zone (m);
- $d_{SatZone,i}$ is the initial thickness of the saturated zone (the same for both the bypass and the main saturated zones) (m) (Table 122);
- $d_{overflow,i}$ is the initial thickness of the bypass compartment (m) (paragraph 988); and,
- $d_{overflow}$ is the thickness of the bypass compartment, accounting for climate change (m) (paragraph 989).

E.4.4.7. Aquifer

992. The layout of the aquifer, landfill, bathtubbing ("overflow") area and the abstraction point are shown in Figure 20. Bathtubbing is assumed to lead to leachate entering the aquifer downstream of the landfill.

Figure 20 Layout of the aquifer, landfill, overflow zone and abstraction point



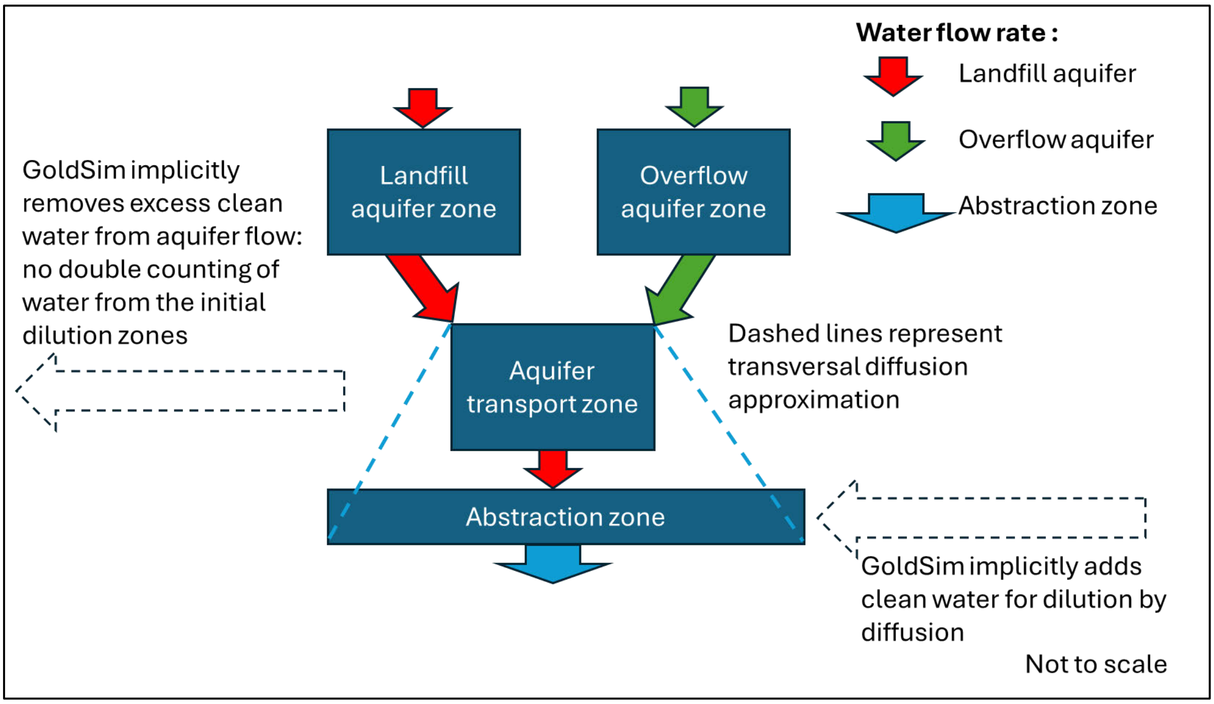
993. The GoldSim model represents the aquifer using a simplified version of the conceptual model shown in Figure 20. This simplified conceptual model is shown in Figure 21.

994. Although the aquifer is assumed to be a continuous medium, it is modelled in four zones:

- The aquifer zone: this is the volume of alluvium right beneath the waste cells. This zone is modelled as a single aquifer cell. Modelling this zone separately allows us to define the length of the aquifer transport zone as the migration distance down gradient from the landfill to the point of interest. The contaminant flux into this zone is assumed to be equal to the contaminant flux out of the saturated zone. This contaminated water is also mixed with clean water from the upstream part of the aquifer.
- The overflow aquifer zone: this is the volume of alluvium right beneath the flooded area when leachate overflow occurs. This zone is modelled in a similar way to the aquifer zone.
- The aquifer transport zone: a one-dimensional transport model has been used to represent transport in the aquifer away down gradient from the landfill, modelled as a sequence of 10 aquifer cells. The groundwater migration distance is assumed to be equal to the distance between the landfill and the well or the estuary.
- The abstraction zone: in order to evaluate the activity concentration at the position where the well is located, an additional aquifer cell is introduced in the model. The width of the abstraction zone is wider than the aquifer to allow for extra dilution to represent transversal diffusion (see paragraph $$$945).

995. Initial dilution of leachate from the landfill and initial dilution of breakout occurs separately in the aquifer and overflow aquifer zones, respectively. The diluted leachate from each of these zones then enters the aquifer transport zone at a rate determined by the flow through the initial dilution zone (paragraph 1000) The aquifer transport zone is assumed to have the same width and water flow rate as the landfill aquifer zone. The abstraction zone is assumed to be wider than the aquifer transport zone to account for transversal diffusion (paragraph 1021 to 1024).

Figure 21 Simplified conceptual model of aquifer used by GoldSim (plan view)



996. The water flow from the overflow aquifer zone is not added to the total water flow through the aquifer transport zone. This is because it is already included in the flow through the landfill aquifer zone (see Figure 20). The contaminants from the overflow aquifer zone are transferred to the aquifer transport zone, but GoldSim implicitly removes clean water from the aquifer transport zone such that overflow aquifer zone does not influence the total water flow rate through the aquifer transport zone.

997. Contaminants enter the landfill aquifer zone in the vertical leachate flow through the base (*via* the unsaturated and saturated zones), $q_{base,out}$ (paragraph 940). This contribution of the water in this flow to the total flow rate in the aquifer is disregarded. This is consistent with the approach taken in (SNIFFER, 2006).

998. Contaminants enter the overflow aquifer zone in the vertical flow $q_{tot,seep}$ (paragraph 986). This includes natural infiltration and additional water from the leachate that overtops the landfill. These are potentially significant compared to the aquifer flow rate. However, the contribution of the water in these flows to the total flow rate in the aquifer is disregarded. The aquifer flow is based on saturated Darcy flow in an aquifer with a hydraulic conductivity and hydraulic gradient appropriate for the geology at Port Clarence. This flow must be sufficient to accommodate all water that enters the aquifer (the aquifer has no capacity to take additional water without either varying one of these parameters or becoming thicker). Moreover, equivalent rates of natural infiltration would enter the aquifer all along the aquifer transport zone, which is not represented

in this model (nor in (SNIFFER, 2006)). For these reasons, we consider disregarding the contribution of these flows to total water flow in the aquifer to be appropriate. If these flows did influence transport in the aquifer, they would add to the dilution and omitting them would be cautious.

999. The aquifer consists of alluvium. In addition to the properties defined in Table 124, the hydraulic gradient in the aquifer is taken as 0.00095, based on the LandSim models reported in (MJCA, 2019b).

1000. The horizontal groundwater volume flux (m^3 s^{-1}) in the aquifer is defined as:

$$q_{Aquifer} = K_{Alluvium} \cdot \Delta_H \cdot W_{Aquifer} \cdot d_{Aquifer}$$

where:

- $q_{Aquifer}$ is the horizontal groundwater volume flux (m^3 s^{-1});
- $K_{Alluvium}$ is the hydraulic conductivity of Alluvium (m s^{-1});
- Δ_H is the hydraulic gradient (dimensionless);
- $W_{Aquifer}$ is the width of the aquifer pathway (m); and,
- $d_{Aquifer}$ is the thickness of the aquifer (m).

Aquifer Zone

1001. The aquifer zone is a compartment corresponding to the area of the aquifer located beneath the waste cells and serves as an interface between the leaching zone and the aquifer.

1002. The dimensions of the aquifer zone for the different calculation cases are defined in Table 124. The thicknesses of the aquifer zone for the non-hazardous and hazardous waste cells have been taken from the HRA (MJCA, 2019b) and are the same value. This thickness has been selected for the assessment of the combined landfill.

Table 124 Dimensions of the aquifer zone

Site	Basal area (m^2)	Aquifer zone thickness (m)	Width of aquifer perpendicular to flow direction (m)	Basis for single value (if taken from PDF)
Non-hazardous waste cell	143,350	7.66	845.6	Single value
Hazardous waste cell	122,840	7.66	743.0	Single value
Combined landfill	266,190	7.66	845.6	Single value

1003. The water flux into the aquifer zone has two components; the vertical water flux through the saturated zone (coming from the unsaturated zone, the barrier and the waste cells), and the horizontal groundwater flux.

1004. Since the vertical flux through the landfill is a small fraction of the horizontal flux, the contribution of this flow to the total flow rate of the aquifer is disregarded.

1005. In order to conserve water, the outward flux is equal to the sum of the two inward fluxes. Since the vertical flux through the landfill is a small fraction of the horizontal flux, this adjustment is negligible.

1006. The behaviour of radionuclide *Rn* in the aquifer zone is represented by the following equation:

$$\left(\frac{dN_{Rn,AquiferZone}}{dt}\right)_{GW} = \frac{N_{Rn,Sat} \cdot q_{base,out}}{M_{SatMadeGround,sat} \cdot K_{d,Rn,SatMadeGround} + V_{Water,Sat}} - \frac{N_{Rn,\text{Aquifer}} \cdot q_{Aquifer}}{M_{Alluvium,aquifer} \cdot K_{d,Rn,Alluvium} + V_{Water,AquiferZone}}$$

1007. The first term relates to the flux from the saturated zone into the aquifer zone right beneath the waste cell. The second term relates to the flux from the aquifer zone horizontally downgradient and away from the landfill, and into the aquifer transport zone. The volume of water in the aquifer zone ($V_{Water,AquiferZone}$, m^3) is given by:

$$V_{Water,AquiferZone} = \varepsilon_{Alluvium} \cdot V_{AquiferZone}$$

where:

- $V_{Water,AquiferZone}$ is the volume of water in the aquifer zone (m^3);
- $\varepsilon_{Alluvium}$ is the water content of alluvium (dimensionless); and,
- $V_{AquiferZone}$ is the volume of the dilution zone (m^3).

1008. Radioactive decay and ingrowth are also applied to radionuclide *Rn*, separately.

Overflow Aquifer Zone

1009. The overflow aquifer zone is a compartment corresponding to the area of the aquifer located beneath the flooded area when leachate overflow occurs; it serves as an interface to the aquifer transport zone.

1010. The surface area of the overflow aquifer zone is equal to the flooded area when leachate overflow occurs. The width of the overflow aquifer is defined as:

$$w_{OverAquifer} = \sqrt{A_{Flood}}$$

1011. The water flux into the aquifer zone has two components; the vertical water flux through the saturated bypass zone (from the unsaturated overflow zone and the flooded subsoil), and the horizontal groundwater flux.

1012. The behaviour of radionuclide *Rn* in the overflow aquifer zone is represented by the following equation:

$$\left(\frac{dN_{Rn,OverflowAquiferZone}}{dt}\right)_{GW} = \frac{N_{Rn,\mathrm{Over}Sat} \cdot q_{tot,seep}}{M_{UnsatMadeGround,Unsat} \cdot K_{d,Rn,UnsatMadeGround} + V_{Water,\mathrm{Over}Sat}} - \frac{N_{Rn,\mathrm{OverAquifer}} \cdot q_{OverAquifer}}{M_{UnsatMadeGround,Unsat} \cdot K_{d,Rn,UnsatMadeGround} + V_{Water,\mathrm{Over}AquiferZone}}$$

1013. The first term relates to the flux from the saturated zone into the bypass aquifer zone right beneath the flooded area. The second term relates to the flux from the aquifer zone horizontally away from the flooded area and into the aquifer transport zone. The volume of water in the bypass aquifer zone ($V_{Water,\mathrm{Bypass}AquiferZone}$, m^3) is given by:

$$V_{Water,\mathrm{Over}AquiferZone} = \varepsilon_{Alluvium} \cdot V_{OverAquiferZone}$$

where:

- $V_{Water,\mathrm{Over}AquiferZone}$ is the water volume in the bypass aquifer zone (m^3);
- $\varepsilon_{Alluvium}$ is the water content of alluvium (dimensionless); and
- $V_{OverAquiferZone}$ is the volume of the dilution zone (m^3).

1014. $q_{overaquifer}$ is given by the equation in paragraph 1000, but using the width of the overflow aquifer zone (paragraph 1010), rather than the width of the main aquifer zone.

1015. Radioactive decay and ingrowth are also applied to radionuclide *Rn*, separately.

Aquifer Transport Zone

1016. The aquifer transport zone is the region of the aquifer between the aquifer zone beneath the waste cells and the flooded area, and the abstraction zone, where the abstraction well is located or the estuary.

1017. The dimensions of the aquifer transport zone for the different calculation cases are given in Table 125. As noted previously, the length of the pathway has been taken to be equivalent to the minimum length considered in the HRA.

1018. The "aquifer" model in GoldSim represents a one-dimensional transport pathway as a series of cells. Advection and dispersion in the aquifer are modelled, together with radioactive decay and ingrowth. The GoldSim model was set up with a default value of ten cells. The dispersivity was set to the length of the aquifer pathway divided by ten.

Table 125 Dimensions of the aquifer transport zone

Site	Length of Aquifer Pathway (m)	Width of Aquifer Pathway (m)	Thickness of Aquifer (m)	Basis for single value (if taken from PDF)
Abstraction well				
Non-hazardous waste cell	522	846	7.66	Single value (width and thickness); minimum value (length)
Hazardous waste cell	260	743	7.66	Single value (width and thickness); minimum value (length)
Combined landfill	260	846	7.66	Single value (width and thickness); minimum value (length)
Discharge into the estuary				
Non-hazardous waste cell	280	846	7.66	Single values
Hazardous waste cell	280	743	7.66	Single values
Combined landfill	280	846	7.66	Single values

Abstraction Zone

1019. The abstraction zone is the section of the aquifer in which an abstraction well is assumed to be located. This compartment has been introduced in the GoldSim model to allow evaluation of the activity concentration in the groundwater at the location of abstraction.

1020. The dimensions of the abstraction zone for the different calculation cases are defined in Table 126. The thicknesses are the same as the values for the aquifer transport zone. The length of the abstraction zone will not significantly affect the results because a strong gradient is not expected. An arbitrary value of 10 m is chosen.

Table 126 Dimensions of the abstraction zone

Site	Length of abstraction zone (m)	Thickness of abstraction zone (m)	Basis for single value (if taken from PDF)
Non-hazardous waste cell	10	7.66	Single values
Hazardous waste cell	10	7.66	Single values
Combined landfill	10	7.66	Single values

1021. The abstraction zone is wider than the aquifer transport zone. This allows for dilution representing transversal diffusion. This is given by (SNIFFER, 2006):

$$w_{Abz} = \sqrt{w_{Aqi}^2 + 2.4 \cdot w_{Aqi} \cdot l_{Aqi}}$$

where:

- w_{Abz} is the width of the abstraction zone (m);
- w_{Aqi} is the width of the (beginning of) the aquifer transport zone (m) (Table 125); and,

- l_{Aqi} is the length of the aquifer transport zone (m) (Table 125).

1022. The flow of contaminated aquifer water into the abstraction zone is given by $q_{Aquifer}$, paragraph 1000.

1023. The downstream outflow from the abstraction zone (which in the model is directed to a sink compartment or to the estuary) is given by:

$$q_{AbZ} = K_{Alluvium} \cdot \Delta_H \cdot w_{AbZ} \cdot d_{Aquifer} - r_{irrigation} \cdot A_{Farm}$$

where:

- q_{AbZ} is the horizontal groundwater volume flux ($m^3\ y^{-1}$);
- $K_{Alluvium}$ is the hydraulic conductivity of alluvium ($m\ y^{-1}$);
- Δ_H is the hydraulic gradient (dimensionless);
- w_{AbZ} is the width of the abstraction zone (m);
- $d_{Aquifer}$ is the thickness of the aquifer (m);
- $r_{irrigation}$ is the rate at which water is removed for irrigation of farmland ($m\ y^{-1}$) (paragraph 1034);
- A_{Farm} is the area of farmland being irrigated (7000 m^2).

1024. q_{AbZ} will always be greater than $q_{Aquifer}$. GoldSim implicitly adds clean water to the abstraction zone to maintain the water balance. This clean water provides the dilution required to represent transversal diffusion.

1025. Radioactive decay and ingrowth are also applied, separately.

E.4.4.8. Assessment calculations for a hypothetical abstraction point

1026. The contamination of groundwater under the landfill is expected to occur at some point in the future. The HRA shows degradation of the landfill basal liner and cap over time resulting in leachate flows to the underlying substrate and then to groundwater.

1027. If contaminated groundwater discharges to a surface water body (spring, river, sea), then ingestion of drinking water and foodstuffs from the surface water body is also a potential exposure pathway and this is considered. These discharges would be subject to additional dilution by groundwater, surface runoff and drainage water thereby reducing exposure relative to an abstraction point. Discharge of groundwater to the estuary is considered in Section E.4.5.

1028. The dose criterion used is a dose of 0.02 mSv y^{-1} for the public (this is equivalent to the risk guidance level of 10^{-6} y^{-1} for exposure of the public post closure, for situations that are expected to occur). However, the groundwater pathway is not used to limit the radiological capacity for the reasons given above.

Exposed group

1029. Exposure of members of the public is assumed to occur as a result of using abstracted water for irrigation and drinking water. Members of the exposed group are assumed to be adults, children and infants and to be exposed as a result of:

- consumption of drinking water from the borehole;
- consumption of food produced on irrigated land including milk, green vegetables, root vegetables and meat products;
- external irradiation from radionuclides incorporated in contaminated soil;
- inadvertent inhalation of contaminated dust; and,
- inadvertent ingestion of contaminated soil.

1030. The drinking water consumption rate for adults used in the assessment is 600 l y^{-1}, for children 350 l y^{-1} and infants 260 l y^{-1} (Smith & Jones, 2003). The habit assumptions applied to a farming family irrigating soil are used for the irrigation pathways (see Table 90).

1031. The National Dose Assessments Working Group published guidance on the use of habit data in prospective dose assessments (NDAWG, 2013). This suggested that the two foodstuffs likely to be most restrictive in terms of their radionuclide content (hence dose potential), should be assumed to be consumed at an elevated rate and all other foodstuffs, that may be reasonably assumed to be sourced locally, are assumed to be consumed at mean consumption rates expressed on a per consumer basis.

1032. The NRPB issued generic consumption data (Smith & Jones, 2003). In general, the consumption rates assumed in the EA methodology represent, for every food group considered, the 97.5th percentile consumption rate. Summing over foodstuffs will therefore give a conservative dose assessment that is appropriate for preliminary scoping assessments. For more realistic assessments it is not appropriate to assume that all foods are consumed at this high rate, in terms of diet and calorific intake, particularly for longer term assessments. The ESC has therefore followed the approach in the NDAWG guidance.

1033. Table 90 details the habit data assumed for a farming family irrigating land with abstracted groundwater. They are also used for scenarios involving the application of sewage sludge to farmland, spillage resulting in contamination of a water body and intrusion after the period of authorisation leading to contamination of land used by a smallholding. For each of these cases, the two most restrictive pathways use 97.5th percentile consumption rates and the mean consumption rate is used for the remaining pathways.

Table 127 Habit data for the farming family irrigating soil with groundwater

Pathway	Adult		Child		Infant	
	mean	97.5th	mean	97.5th	mean	97.5th
Milk consumption[1] ($l\ y^{-1}$)	95	240	110	240	130	320
Meat consumption[1] ($kg\ y^{-1}$)	23	70	19	40	3.8	13
Green & other domestic veg consumption[1] ($kg\ y^{-1}$)	35	80	15	35	5	15
Root veg & potatoes consumption[1] ($kg\ y^{-1}$)	60	130	50	95	15	45
Breathing rate[2] ($m^3\ h^{-1}$)	1.69		0.87		0.31	
Inadvertent soil ingestion[2] ($kg\ y^{-1}$)	0.0083		0.018		0.044	
Dust load while farming ($kg\ m^{-3}$)	$1\ 10^{-7}$		$1\ 10^{-7}$		$1\ 10^{-7}$	
Indoor shielding factor[3]	0.1		0.1		0.1	
Fraction of time spent indoors[4]	0.72		0.84		0.91	

Notes: 1) From (Smith & Jones, 2003). 2) Inhalation rates based on ICRP 66 (ICRP, 1994), see Table 73 for derivation. 3) Standard assumption in (Environment Agency, 2022b). 4) Values child and infant from (Oatway & Mobbs, 2003), value for adult from (Stewart, et al., 1990).

1034. The GoldSim model used to model the groundwater migration scenario also includes a soil compartment which receives inputs from abstracted water that is used for irrigation and losses due to leaching from top soil. Direct contamination of crops (green vegetables and root vegetables) by irrigation water is also considered. The applicable irrigation rate will be crop dependent but based on green crops (Finch, et al., 2002) it would be about 0.108 m y^{-1}. This is the value used in the assessment. It is further assumed that sufficient water is extracted from the borehole to provide the implied demand.

1035. The peak activity concentration in the groundwater to 100,000 years after closure is used to calculate the doses to the exposed group.

Use of Groundwater as Drinking Water

1036. The dose (Sv y^{-1}) due to drinking abstracted groundwater is given by:

$$Dose_{drinkwater} = Q_{water} \cdot C_{R,groundwater}(t) \cdot D_{Rn,ing}$$

where:

- $Dose_{drinkwater}$ is the dose due to drinking abstracted groundwater (Sv y^{-1});
- Q_{water} is the drinking water consumption rate (l y^{-1});
- $C_{Rn,groundwater}(t)$ is the activity concentration of radionuclide Rn in the groundwater used for irrigation at time t (Bq l^{-1}); and,
- $D_{Rn,ing}$ is the dose coefficient for ingestion of radionuclide *Rn* (Sv Bq^{-1}).

1037. Drinking water consumption rates are taken from (Smith & Jones, 2003).

1038. The activity concentrations of radionuclides in irrigation water are determined by the groundwater transport model outlined above.

1039. Dose coefficients are presented in Table 225 and Table 226 for all radionuclides except those listed in Table 128, which use the values shown below to account for different assumptions concerning daughter radionuclides in Goldsim.

Table 128 Dose coefficients used in Goldsim to match the modelling of the decay chains

Radionuclide	Ingestion (Sv Bq^{-1})	Inhalation (Sv Bq^{-1})	External Irradiation from slab (Sv y^{-1} Bq^{-1} kg)
Adult			
Pb-210	6.91 10^{-7}	5.69 10^{-6}	3.54 10^{-8}
Ra-226	2.80 10^{-7}	9.53 10^{-6}	7.58 10^{-6}
Ra-228	6.90 10^{-7}	1.60 10^{-5}	1.39 10^{-6}
Th-232	2.30 10^{-7}	1.10 10^{-4}	1.38 10^{-10}
U-232	3.30 10^{-7}	3.70 10^{-5}	3.82 10^{-6}
Am-242m	1.90 10^{-7}	9.19 10^{-5}	2.78 10^{-8}
Cm-243	1.50 10^{-7}	6.90 10^{-5}	1.45 10^{-7}
Child			
Pb-210	1.90 10^{-6}	7.33 10^{-6}	3.90 10^{-8}
Ra-226	8.01 10^{-7}	1.20 10^{-5}	8.34 10^{-6}
Ra-228	3.90 10^{-6}	2.01 10^{-5}	1.54 10^{-6}
Th-232	2.90 10^{-7}	1.30 10^{-4}	1.70 10^{-10}
U-232	5.70 10^{-7}	4.30 10^{-5}	4.17 10^{-6}
Am-242m	2.00 10^{-7}	9.39 10^{-5}	3.13 10^{-8}
Cm-243	1.60 10^{-7}	7.30 10^{-5}	1.63 10^{-7}
Infant			
Pb-210	3.61 10^{-6}	1.83 10^{-5}	4.35 10^{-8}
Ra-226	9.62 10^{-7}	2.91 10^{-5}	9.24 10^{-6}
Ra-228	5.70 10^{-6}	4.82 10^{-5}	1.71 10^{-6}
Th-232	4.50 10^{-7}	2.20 10^{-4}	2.01 10^{-10}
U-232	8.20 10^{-7}	9.70 10^{-5}	4.56 10^{-6}
Am-242m	3.02 10^{-7}	1.50 10^{-4}	3.52 10^{-8}
Cm-243	3.30 10^{-7}	1.50 10^{-4}	1.84 10^{-7}

Use of Groundwater for Irrigation of Farmland

1040. If abstracted water is used for irrigation, then doses can result from:

- ingestion of foodstuff grown or raised on contaminated soil;
- ingestion or inhalation of dust from the soil; and,
- external exposure to the soil.

1041. Abstracted groundwater is applied to the top soil compartment at the irrigation rate. As infiltration (rain water) will also enter the top soil compartment (on different days from irrigation water), the annual water flux out of the top soil compartment is the sum of the irrigation rate and the infiltration rate. As farmland is similar to grassland in terms of runoff and evapotranspiration, the infiltration rate for grassland has been used for farmland (MJCA, 2019b).

1042. Activity builds up in the top soil over time, as irrigation with contaminated groundwater continues. The behaviour of radionuclide *Rn* in the top soil is represented by the following equation:

$$\left(\frac{dN_{Rn,TopSoil}}{dt}\right)_{GW} = n_{RnN,Water,Sat} \cdot a_{Farmland} \cdot r_{irrigation} - \frac{N_{Rn,TopSoil} \cdot a_{Farmland} \cdot \left(r_{irrigation} + r_{infiltration}\right)}{M_{Soil,TopSoil} \cdot K_{d,RN,Soil} + V_{Water,TopSoil}}$$

1043. The first term relates to irrigation of top soil with groundwater. The second term relates to leaching from the top soil. Radioactive decay and ingrowth are also addressed, separately. The parameters are:

- $n_{Rn,Water,Sat}$ number of atoms of radionuclide *Rn* per unit volume of groundwater (m^{-3});
- $a_{Farmland}$ area of farmland (m^2);
- $r_{irrigation}$ irrigation rate ($m\ y^{-1}$);
- $N_{Rn,TopSoil}$ number of atoms of radionuclide Rn in the top soil compartment;
- $r_{Infiltration}$ infiltration rate ($m\ y^{-1}$); and,
- $K_{d,Rn,Soil}$ the distribution coefficient for radionuclide *Rn* in material *Soil* ($m^3\ kg^{-1}$).

1044. The mass of soil ($M_{Soil,TopSoil}$) and volume of water ($V_{Water,TopSoil}$) in the top soil compartment are given by:

$$V_{Water,TopSoil} = \varepsilon_{TopSoil} \cdot \vartheta_{TopSoil} \cdot a_{Farmland} \cdot d_{TopSoil}$$

$$M_{Soil,TopSoil} = \rho_{Soil} \cdot a_{Farmland} \cdot d_{TopSoil}$$

where:

- $\varepsilon_{TopSoil}$ porosity of top soil (dimensionless);
- $\vartheta_{TopSoil}$ degree of saturation of top soil (dimensionless);
- ρ_{Soil} density of soil ($kg\ m^{-3}$); and,
- $d_{TopSoil}$ the depth of top soil (m).

1045. Assumptions regarding the top soil compartment, used to calculate the volume of water and the mass of soil, are summarised in Table 129. The area of farmland assumed is arbitrary and does not affect the calculated doses since it cancels out when the activity concentration in the soil is calculated (see later). Soil properties are taken from the ENRMF assessment (Eden NE, 2023).

Table 129 Dimensions and properties of top soil used for farming.

Parameter	Units	Value
Area of farmland	m^2	7,000
Density of soil	kg m^3	1300
Depth of soil irrigated	m	0.25
Top soil porosity	dimensionless	0.3
Top soil saturation	dimensionless	0.5

1046. The dose from ingesting crops grown on contaminated soil is given by a combination of interception of contaminated irrigation water by plants and root uptake in plants from contaminated soil (Eden NE, 2023):

$$Dose_{ing,crops} = \sum_{crop} \left\{ Q_{crop} \cdot \left[C_{Rn,water}(t) \cdot \left(\frac{Irrig \cdot Int_{crop} \cdot F_{crop}}{Yield_{crop}} \right) + C_{Rn,soil}(t) \cdot UF_{Rn,crop} \right] \right\} \cdot D_{Rn,ing}$$

where:

- $Dose_{ing,crops}$ is the dose from ingesting crops (Sv y^{-1});
- Q_{crop} is the crop consumption rate (kg y^{-1});
- $C_{Rn,water}$ is the concentration of radionuclide *Rn* in the irrigation water at time *t* (Bq l^{-1});
- *Irrig* is the irrigation rate (m y^{-1});
- Int_{crop} is the effective interception factor;
- F_{crop} is the fraction remaining after processing;
- $Yield_{crop}$ is the crop yield (kg m^{-2} y^{-1});
- $C_{Rn,soil}$ is the soil activity concentration of radionuclide *Rn* at time *t* (Bq kg^{-1});
- $UF_{Rn,crop}$ is the soil to crop transfer factors for radionuclide *Rn* (Bq kg^{-1} fresh weight of crop per Bq kg^{-1} of soil); and,
- $D_{Rn,ing}$ is the dose coefficient for ingestion of radionuclide *Rn* (Sv Bq^{-1}), see Table 225.

1047. Habit data are discussed above (see Table 127) and other parameter values are summarised in Table 130. The grain crop processing factor is set to zero on the basis that it is not common for grain crops to be irrigated (Finch, et al., 2002). The irrigation rate is derived from a soil moisture deficit calculated from monthly average rainfall (May to August is 257 mm) and a daily water requirement for green vegetables (about 365 mm over the same period). This gives an irrigation rate of 0.108 m y^{-1}.

Table 130 Overview of parameters used for the irrigation scenario

Parameter	Substance	Units	Value
Irrigation rate [derived from requirement in (Finch, et al., 2002)]	All crops	m y^{-1}	0.108
Crop interception factor	All crops		0.33
Crop processing factor	Grain		1
	Green vegetables		0.3
	Root vegetables		1
Yield (crops)	Grain	kg m^{-2} y^{-1}	0.4
	Green vegetables	kg m^{-2} y^{-1}	3.0
	Root vegetables	kg m^{-2} y^{-1}	3.5
	Pasture	kg m^{-2} y^{-1}	1.7
Consumption rate (animal)	Pasture	kg d^{-1}	55
	Soils	kg d^{-1}	0.6

Note: From (Eden NE, 2023) except where specified otherwise

1048. The activity concentration of radionuclides in water within the soil ($C_{Rn,Water}$) is determined by GoldSim as the activity in water within the soil divided by the volume of water. The activity concentration of radionuclides in soil ($C_{Rn,Soil}$) is determined as the total activity in the soil including water divided by the dry mass of soil.

1049. Soil to crop transfer factors are given in Table 230 and dose coefficients for ingestion are given in Table 225 except for Pb-210, Ra-226, Ra-228, Th-232, U-232, Am-242m and Cm-243 (Table 128).

1050. The dose (Sv y^{-1}) from ingesting animal foodstuffs (e.g. meat and milk) raised on contaminated land is given by (Eden NE, 2023):

$$Dose_{ing,animal} = \sum_{animal} \{Q_{animal} \cdot [Q_{soil,A} \cdot C_{Rn,soil}(t) + Q_{pasture,A} \cdot C_{Rn,soil}(t) \cdot UF_{Rn,grass}] \cdot TF_{Rn,animal}\} \cdot D_{Rn,ing}$$

where:

- $Dose_{ing,animal}$ is the dose from ingesting animal foodstuffs (Sv y^{-1});
- Q_{animal} is the consumption rate of animal foodstuff (kg y^{-1});
- $Q_{soil,A}$ is the soil consumption rate by the animal (kg day^{-1});
- $Q_{pasture,A}$ is the pasture consumption rate by the animal (kg day^{-1});
- $C_{Rn,soil}$ is the activity concentration of radionuclide *Rn* in soil (Bq kg^{-1});
- $UF_{Rn,Grass}$ is the uptake factor of radionuclide *Rn* by crop *Grass* (Bq kg^{-1} fresh weight per Bq kg^{-1} soil);
- $TF_{Rn,Animal}$ is the transfer factor of radionuclide *Rn* in animal produce *Animal* (d kg^{-1}); and,
- $D_{Rn,ing}$ is the dose coefficient for ingestion of radionuclide *Rn* (Sv Bq^{-1}).

1051. Parameter values are summarised in Table 130.

1052. The sorption distribution coefficients are defined in Table 224 for soil.

1053. Dose (Sv y^{-1}) from inadvertent ingestion of soil is given by (Eden NE, 2023):

$$Dose_{ing,soil} = Q_{soil,H} \cdot C_{Rn,soil}(t) \cdot D_{Rn,ing}$$

where:

- $Dose_{ing,soil}$ is the dose from inadvertent ingestion of soil (Sv y^{-1});
- $Q_{soil,H}$ is the soil consumption rate by humans (kg y^{-1});
- $C_{RN,soil}(t)$ is the activity concentration of radionuclide *Rn* at time *t* (Bq kg^{-1}); and,
- $D_{Rn,ing}$ is the dose coefficient for ingestion of radionuclide *Rn* (Sv Bq^{-1}).

1054. The soil consumption rate is given in Table 130.

1055. The activity concentration of radionuclides in soil ($C_{Rn,Soil}$) is determined as the total activity in the soil including water divided by the dry mass of soil.

1056. Dose coefficients for ingestion are given in Table 225 except for Pb-210, Ra-226, Ra-228, Th-232, U-232, Am-242m and Cm-243 which are given in Table 128.

1057. The dose (Sv y^{-1}) from external irradiation while living and working on contaminated soil is given by (Eden NE, 2023):

$$Dose_{irr,soil} = (O_{out} + O_{in} \cdot SF) \cdot C_{Rn,soil}(t) \cdot DF_{Rn,irr,slab}$$

where:

- $Dose_{irr,soil}$ is the dose from external irradiation (Sv y^{-1});
- O_{out} is the fraction of time spent outside, exposed to contaminated soil (y y^{-1});
- O_{in} is the fraction of time spent inside (y y^{-1});
- *SF* is the shielding factor from the ground while indoors;
- $C_{Rn,soil}(t)$ is the activity concentration of radionuclide *Rn* at time *t* in soil (Bq kg^{-1}); and,
- $DF_{Rn,irr,slab}$ is the dose coefficient for irradiation from radionuclide *Rn* (Sv y^{-1} Bq^{-1} kg), based on the receptor being 1 m from the ground and assuming a semi-infinite slab of contamination.

1058. Parameter values are summarised in Table 130.

1059. The activity concentration of radionuclides in soil ($C_{Rn,Soil}$) is determined as the total activity in the soil including water divided by the dry mass of soil.

1060. Dose coefficients for irradiation are given in Table 226, except for Pb-210, Ra-226, Ra-228, Th-232, U-232, Am-242m and Cm-243, which are given in Table 128.

1061. The dose (Sv y^{-1}) from inhalation of contaminated soil is given by (Eden NE, 2023):

$$Dose_{inh,soil} = B \cdot O_{dust} \cdot C_{Rn,soil}(t) \cdot Dustload \cdot D_{Rn,inh}$$

where:

- $Dose_{inh,soil}$ is the dose from inhalation of contaminated soil (Sv y^{-1});
- B is the breathing rate (m^3 h^{-1});
- O_{dust} is the fraction of time spent exposed to dust from the soil (h y^{-1});
- $C_{Rn,soil}(t)$ is the activity concentration of radionuclide Rn at time t in soil (Bq kg^{-1});
- $Dustload$ is the dust concentration in air (kg m^{-3}); and,
- $D_{Rn,inh}$ is the dose coefficient for inhalation of radionuclide Rn (Sv Bq^{-1}).

1062. Parameter values are summarised in Table 130.

1063. The activity concentration of radionuclides in soil ($C_{Rn,Soil}$) is determined as the total activity in the soil including water divided by the dry mass of soil.

1064. Dose coefficients for inhalation are given in Table 225, except for Pb-210, Ra-226, Ra-228, Th-232, U-232, Am-242m and Cm-243, which are given in Table 128.

Element and Radionuclide Specific Parameters

1065. Radionuclide specific dose coefficients and with element specific parameters for plant and animal uptake specified in Table 225, Table 226, Table 227, Table 230 and Table 231. Note that the dose coefficients for Po-210, Ra-226, Ra-228, Th-232, U-232, Am-242m and Cm-243 used in the groundwater model are shown in Table 128.

E.4.4.9. Bathtubbing causing contamination of farmland

1066. Bathtubbing results in leachate spilling over the top of the landfill liner at the sides of the landfill. The release is assumed to affect subsoil in an area of surrounding land, calculated in GoldSim as specified in Section E.4.4.6. The GoldSim model is set up to calculate the affected area based on a surface water head that is 10% of the leachate head in the waste cells.

1067. The scenario is based on characteristics similar to those for the residential occupation group considered above. We have conservatively assumed that any water that overspills from the landfill is not diluted by any other standing or draining water around the site.

1068. The dose criterion used is a dose of 0.02 mSv y^{-1} (this is equivalent to the risk guidance level of 10^{-6} y^{-1} for exposure of the public at times after the period of authorisation, for situations that are likely to occur). Hence use of this dose criterion is conservative since this scenario is unlikely to occur.

1069. There are no local hydrological features that suggest there will be a build-up of surface water following overtopping in the direction of flow. This is why we consider it likely that overtopping will drain to sub-soil rather than flood. Although the model does not show transfer to local water bodies, contamination of a local water body is considered as a what-if scenario.

1070. Water that overtops the basal liner will be below restoration profile and will not therefore directly contaminate the soil surface layer because water will drain to lower soil layers. With a restoration layer of at least 1.3 m a mechanism is needed to transfer radionuclides from a saturated layer to a shallower depth where the majority of root activity occurs (noting that the roots of some plants will extend to a depth of 1.3 m). It is assumed that a proportion of the activity introduced at depth (>1 m) reaches the cultivated surface soils based on experimental observations (Shaw, et al., 2004). The remainder is assumed to drain to sub-strata based on the drainage observed in the surrounding area.

1071. Recent work at Imperial College on the transfer of radionuclides from a water table to crops considered a range of elements that are of interest to a bathtubbing event (Shaw, et al., 2004). Shaw *et al.* reported the movement of two very mobile radionuclides, Tc-99 and Cl-36 from a water table at 0.7 m depth to the upper soil layers. For Tc-99 the activity in upper soil layers was two orders of magnitude lower than that at the water table and Shaw *et al*. reported much lower transport of less mobile radionuclides. The study showed Cl-36 with upper soil activity at about 10% of that in the lowest layers but declining with distance above the water table.

1072. A later, more detailed report (Wheater, et al., 2007) provides information for other radionuclides (Co, Na, Cs). This information has been used to assign percentage transfer from lower layers to surface soil by scaling the observations based on Kd. This was done simply by dividing Kd's into bands (less than 0.0001 through to greater than 1) and assigning the factors shown in Table 131 below. The assigned transfer fractions are shown in Table 224.

Table 131 Sub-soil to topsoil transfer assigned to Kd bands

Kd band	Sub-soil to topsoil factor	Count of radionuclides assigned to band
<=0.0001	1	1
>0.0001 to <=0.001	0.1	4
>0.001 to <=0.01	0.01	3
>0.01 to <=1	0.001	38
>1	0.0001	8

1073. Using this approach lower Kd values result in the highest rates of sub-soil to topsoil transfer as observed by Wheater et al.

1074. The overflow leads to contamination of subsoil adjacent to the site. It is assumed that this topsoil is farmland. The model for calculating the doses from the bathtubbing scenario is very similar to the irrigation model, and most parameters values are the same. The main difference is that in the bathtubbing scenario there is no foliar deposition and retention by crops.

Element and Radionuclide Specific Parameters

1075. Radionuclide specific dose coefficients and with element specific parameters for plant and animal uptake specified in Table 225, Table 226, Table 227, Table 230 and Table 231. Note that the dose coefficients for Po-210, Ra-226, Ra-228, Th-232, U-232, Am-242m and Cm-243 used in the groundwater model are shown in Table 128.

E.4.4.10. Groundwater doses after the Period of Authorisation

1076. The construction of a water abstraction borehole downstream of the site is not expected since the groundwater at this point is affected by the saline water of the estuary. Nevertheless, this scenario considers the exposures resulting from water taken from a hypothetical point near the site boundary. The scenario is not used to limit radiological capacity and is provided for information. Exposure of members of the public is assumed to occur as a result of using water for irrigation and drinking water. Doses can result from ingestion of foodstuffs grown on contaminated soil (including pasture supporting grazing livestock), inhalation of dust from the soil, external exposure to the soil and from drinking contaminated water.

1077. The dose criterion used is a dose of 0.02 mSv y-1 (this is equivalent to the risk guidance level of 10^{-6} y^{-1} for exposure of the public post closure, for situations that are expected to occur).

1078. GoldSim output has a low value cut-off and reports a lower limit of 1 10^{-13} µSv y^{-1} MBq^{-1}, which can occur for short lived radionuclides (half-life of less than about 5 years) where radioactive decay reduces activity to very low levels or where there is limited radionuclide transport in groundwater. The cut-off produces reported values of zero dose.

1079. The results of the dose calculations for water at the point close to the site boundary are given in Table 132 for each age group. The radiological capacity for each radionuclide is shown, and the year when the maximum dose occurs, are also shown. The results for Ra-226 are independent of the Ra-226 placement depth in the site. The scenario has not been used to limit the radiological capacity at the site since it is most unlikely to occur and is only provided for information. The revised groundwater model that takes climate change into account impacts the transfer to groundwater such that as sea level rises the flow to groundwater reduces after about 600 years resulting in peak doses at that time.

1080. The results of the bathtubbing scenario are given in Table 133 for each age group. The scenario radiological capacity for each radionuclide is shown. The results for Ra-226 are independent of the Ra-226 placement depth in the site. The scenario has been used for the radiological capacity at the site and limits disposal of 21 radionuclides: Ca-41, Mo-93, I-129, Sm-147, Th-229, Th-232, Pa-231, U-233, U-234, U-235, U-236, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-242, Pu-244, Am-243, Cm-245, Cm-246 and Cm-248.

1081. The second bathtubbing scenario modelled transfer of overtopping leachate to the nearest surface water body on the site and considered exposure of a fishing family through fish consumption. Although this pathway was included in the model, results showed that no activity reached a nearby pond and hence there was no exposure through this pathway due to the drainage properties of the soils surrounding the landfill. Scoping calculations were therefore undertaken on a what-if basis. This used the leachate spillage assumptions (see Appendix E.3.10) and cautiously assumed that 10% of the seepage outflow entered a hypothetical water body. Whilst the doses for a 97.5^{th} percentile fish consumer shown below are low, the peak dose was 5.7 µSv y^{-1} from Ca-41 at the maximum inventory, all other doses are less than 0.5 µSv y^{-1}. However, because Goldsim modelling shows that there is unlikely to be transfer to a local waterbody (other than to the estuary), the fish consumption scenario is therefore considered as a 'what if' scenario and is not used to limit the radiological capacity.

Table 132 Maximum annual doses from groundwater for all age groups for an abstraction point

Radionuclide	Adult dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Child dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Infant dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Time of max (y)	Age group with highest dose`	Scenario radiological capacity (MBq)$^{\$}$
H-3	0	0	0			nd
C-14	0	0	0			nd
Cl-36	$6.27\ 10^{-6}$	$8.65\ 10^{-6}$	$1.75\ 10^{-5}$	546	Infant	$1.14\ 10^{6}$
Ca-41	$4.07\ 10^{-11}$	$6.96\ 10^{-11}$	$4.62\ 10^{-11}$	630	Child	$2.87\ 10^{11}$
Mn-54	0	0	0			nd
Fe-55	0	0	0			nd
Co-60	0	0	0			nd
Ni-59	0	0	0			nd
Ni-63	0	0	0			nd
Zn-65	0	0	0			nd
Se-79	0	0	0			nd
Sr-90	0	0	0			nd
Mo-93	0	0	0			nd
Zr-93	0	0	0			nd
Nb-93m	0	0	0			nd
Nb-94	0	0	0			nd
Tc-99	$4.17\ 10^{-8}$	$5.53\ 10^{-8}$	$1.08\ 10^{-7}$	547	Infant	$1.85\ 10^{8}$
Ru-106	0	0	0			nd
Ag-108m	0	0	0			nd
Ag-110m	0	0	0			nd
Cd-109	0	0	0			nd

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Time of max (y)	Age group with highest dose`	Scenario radiological capacity (MBq)$^{\$}$
Sb-125	0	0	0			nd
Sn-119m	0	0	0			nd
Sn-123	0	0	0			nd
Sn-126	0	0	0			nd
Te-127m	0	0	0			nd
I-129	3.24 10^{-8}	3.68 10^{-8}	2.29 10^{-8}	630	Child	5.43 10^{8}
Ba-133	0	0	0			nd
Cs-134	0	0	0			nd
Cs-135	0	0	0			nd
Cs-137	0	0	0			nd
Ce-144	0	0	0			nd
Pm-147	0	0	0			nd
Sm-147	0	0	0			nd
Sm-151	0	0	0			nd
Eu-152	0	0	0			nd
Eu-154	0	0	0			nd
Eu-155	0	0	0			nd
Gd-153	0	0	0			nd
Pb-210	0	0	0			nd
Po-210	0	0	0			nd
Ra-226	0	0	0			nd
Ra-228	0	0	0			nd
Ac-227	0	0	0			nd
Th-228	0	0	0			nd

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Time of max (y)	Age group with highest dose`	Scenario radiological capacity (MBq)$
Th-229	0	0	0			nd
Th-230	0	0	0			nd
Th-232	0	0	0			nd
Pa-231	0	0	0			nd
U-232	0	0	0			nd
U-233	$5.06\ 10^{-12}$	$4.05\ 10^{-12}$	$3.48\ 10^{-12}$	635	Adult	$3.95\ 10^{12}$
U-234	$8.08\ 10^{-13}$	$6.60\ 10^{-13}$	$5.48\ 10^{-13}$	635	Adult	$2.48\ 10^{13}$
U-235	$9.61\ 10^{-12}$	$7.96\ 10^{-12}$	$6.46\ 10^{-12}$	635	Adult	$2.08\ 10^{12}$
U-236	$3.32\ 10^{-13}$	$2.69\ 10^{-13}$	$2.27\ 10^{-13}$	635	Adult	$6.02\ 10^{13}$
U-238	$4.51\ 10^{-13}$	$3.61\ 10^{-13}$	$3.10\ 10^{-13}$	635	Adult	$4.44\ 10^{13}$
Np-237	$3.42\ 10^{-9}$	$2.19\ 10^{-9}$	$1.43\ 10^{-9}$	634	Adult	$5.84\ 10^{9}$
Pu-238	0	0	0			nd
Pu-239	0	0	0			nd
Pu-240	0	0	0			nd
Pu-241	0	0	0			nd
Pu-242	0	0	0			nd
Pu-244	0	0	0			nd
Am-241	0	0	0			nd
Am-242m	0	0	0			nd
Am-243	0	0	0			nd
Cm-242	0	0	0			nd
Cm-243	0	0	0			nd
Cm-244	0	0	0			nd
Cm-245	0	0	0			nd

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Time of max (y)	Age group with highest dose`	Scenario radiological capacity (MBq)$
Cm-246	0	0	0			nd
Cm-248	0	0	0			nd

$ "nd" indicates that a radiological capacity was not determined due to the low dose.

Table 133 Maximum annual doses for all age groups from bathtubbing (adjacent resident)

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Time of max (y)	Age group with highest dose	Scenario radiological capacity (MBq)$
H-3	$3.95\ 10^{-9}$	$3.41\ 10^{-9}$	$6.33\ 10^{-9}$	77	Infant	$3.16\ 10^{9}$
C-14	$4.55\ 10^{-10}$	$3.09\ 10^{-10}$	$2.83\ 10^{-10}$	1615	Infant	$4.40\ 10^{10}$
Cl-36	$2.09\ 10^{-6}$	$3.18\ 10^{-6}$	$1.16\ 10^{-5}$	85	Infant	$1.72\ 10^{6}$
Ca-41	$1.03\ 10^{-8}$	$1.70\ 10^{-8}$	$1.91\ 10^{-8}$	816	Infant	$1.05\ 10^{9}$
Mn-54	0	0	0		Infant	nd
Fe-55	0	0	0		Infant	nd
Co-60	0	0	0		Infant	nd
Ni-59	$2.52\ 10^{-11}$	$1.42\ 10^{-11}$	$9.40\ 10^{-12}$	4015	Adult	$7.94\ 10^{11}$
Ni-63	$3.55\ 10^{-13}$	$1.97\ 10^{-13}$	$1.26\ 10^{-13}$	207	Infant	$5.63\ 10^{13}$
Zn-65	0	0	0		Infant	nd
Se-79	$3.44\ 10^{-9}$	$7.62\ 10^{-9}$	$1.38\ 10^{-8}$	3140	Infant	$1.44\ 10^{9}$
Sr-90	$2.57\ 10^{-10}$	$1.66\ 10^{-10}$	$1.36\ 10^{-10}$	112	Child	$7.77\ 10^{10}$
Mo-93	$1.53\ 10^{-7}$	$1.69\ 10^{-7}$	$3.36\ 10^{-7}$	1130	Infant	$5.95\ 10^{7}$

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Time of max (y)	Age group with highest dose	Scenario radiological capacity (MBq)$
Zr-93	$1.36\ 10^{-9}$	$2.17\ 10^{-10}$	$2.89\ 10^{-11}$	5820	Adult	$1.48\ 10^{10}$
Nb-93m	0	0	0		Infant	nd
Nb-94	$6.70\ 10^{-9}$	$5.65\ 10^{-9}$	$4.36\ 10^{-9}$	10385	Adult	$2.99\ 10^{9}$
Tc-99	$2.98\ 10^{-7}$	$1.72\ 10^{-7}$	$2.67\ 10^{-7}$	467	Adult	$6.70\ 10^{7}$
Ru-106	0	0	0		Infant	nd
Ag-108m	$5.51\ 10^{-9}$	$4.79\ 10^{-9}$	$3.76\ 10^{-9}$	1065	Adult	$3.63\ 10^{9}$
Ag-110m	0	0	0		Infant	nd
Cd-109	0	0	0		Infant	nd
Sb-125	0	0	0		Infant	nd
Sn-119m	0	0	0		Infant	nd
Sn-123	0	0	0		Infant	nd
Sn-126	$1.13\ 10^{-8}$	$1.03\ 10^{-8}$	$8.90\ 10^{-9}$	18905	Adult	$1.77\ 10^{9}$
Te-127m	0	0	0		Infant	nd
I-129	$2.14\ 10^{-7}$	$1.90\ 10^{-7}$	$1.32\ 10^{-7}$	773	Child	$9.36\ 10^{7}$
Ba-133	$2.22\ 10^{-12}$	$1.95\ 10^{-12}$	$1.55\ 10^{-12}$	79	Child	$9.00\ 10^{12}$
Cs-134	0	0	0		Adult	nd
Cs-135	$5.36\ 10^{-10}$	$2.92\ 10^{-10}$	$1.55\ 10^{-10}$	15835	Adult	$3.73\ 10^{10}$
Cs-137	$5.78\ 10^{-13}$	$4.35\ 10^{-13}$	$3.18\ 10^{-13}$	116	Child	$3.46\ 10^{13}$
Ce-144	0	0	0		Infant	nd
Pm-147	0	0	0		Infant	nd
Sm-147	$5.22\ 10^{-7}$	$2.46\ 10^{-7}$	$1.02\ 10^{-7}$	12520	Adult	$3.83\ 10^{7}$
Sm-151	$2.70\ 10^{-13}$	$1.26\ 10^{-13}$	$5.57\ 10^{-14}$	198	Adult	$7.40\ 10^{13}$
Eu-152	$2.58\ 10^{-13}$	$2.14\ 10^{-13}$	$1.62\ 10^{-13}$	93	Infant	$7.75\ 10^{13}$
Eu-154	$2.22\ 10^{-14}$	$1.83\ 10^{-14}$	$1.38\ 10^{-14}$	86	Infant	$9.00\ 10^{14}$

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Time of max (y)	Age group with highest dose	Scenario radiological capacity (MBq)$^{\$}$
Eu-155	0	0	0		Infant	nd
Gd-153	0	0	0		Infant	nd
Pb-210	1.57 10^{-11}	8.87 10^{-12}	4.84 10^{-12}	105	Infant	1.27 10^{12}
Po-210	0	0	0		Infant	nd
Ra-226	7.73 10^{-8}	4.28 10^{-8}	2.26 10^{-8}	2625	Adult	2.59 10^{8}
Ra-228	4.30 10^{-14}	2.37 10^{-14}	1.22 10^{-14}	82	Infant	4.65 10^{14}
Ac-227	8.95 10^{-10}	4.83 10^{-10}	2.12 10^{-10}	105	Adult	2.23 10^{10}
Th-228	0	0	0		Infant	nd
Th-229	4.68 10^{-6}	2.34 10^{-6}	8.27 10^{-7}	7000	Adult	4.27 10^{6}
Th-230	5.40 10^{-6}	2.46 10^{-6}	9.01 10^{-7}	18180	Adult	3.70 10^{6}
Th-232	9.24 10^{-6}	4.72 10^{-6}	1.92 10^{-6}	24975	Adult	2.16 10^{6}
Pa-231	2.59 10^{-5}	1.14 10^{-5}	3.46 10^{-6}	14685	Adult	7.73 10^{5}
U-232	1.60 10^{-7}	8.42 10^{-8}	4.18 10^{-8}	167	Adult	1.25 10^{8}
U-233	7.93 10^{-5}	4.08 10^{-5}	2.02 10^{-5}	3115	Adult	2.52 10^{5}
U-234	1.29 10^{-5}	6.81 10^{-6}	3.28 10^{-6}	3135	Adult	1.55 10^{6}
U-235	9.58 10^{-5}	5.11 10^{-5}	2.39 10^{-5}	3170	Adult	2.09 10^{5}
U-236	4.71 10^{-6}	2.46 10^{-6}	1.19 10^{-6}	3170	Adult	4.24 10^{6}
U-238	4.80 10^{-6}	2.47 10^{-6}	1.22 10^{-6}	3170	Adult	4.17 10^{6}
Np-237	2.68 10^{-4}	1.10 10^{-4}	4.06 10^{-5}	1160	Adult	7.47 10^{4}
Pu-238	9.37 10^{-9}	3.86 10^{-9}	1.32 10^{-9}	194	Adult	2.13 10^{9}
Pu-239	5.13 10^{-6}	2.12 10^{-6}	6.97 10^{-7}	7095	Adult	3.89 10^{6}
Pu-240	3.34 10^{-6}	1.38 10^{-6}	4.54 10^{-7}	4575	Adult	5.98 10^{6}
Pu-241	1.86 10^{-9}	8.02 10^{-10}	1.91 10^{-10}	94	Adult	1.07 10^{10}
Pu-242	5.87 10^{-6}	2.64 10^{-6}	8.25 10^{-7}	9745	Adult	3.41 10^{6}

Radionuclide	Adult dose (µSv y-1 MBq-1)	Child dose (µSv y-1 MBq-1)	Infant dose (µSv y-1 MBq-1)	Time of max (y)	Age group with highest dose	Scenario radiological capacity (MBq)$
Pu-244	$1.11\ 10^{-5}$	$5.00\ 10^{-6}$	$1.56\ 10^{-6}$	10075	Adult	$1.80\ 10^{6}$
Am-241	$5.42\ 10^{-8}$	$2.33\ 10^{-8}$	$8.28\ 10^{-9}$	1150	Adult	$3.69\ 10^{8}$
Am-242m	$3.08\ 10^{-8}$	$1.33\ 10^{-8}$	$4.34\ 10^{-9}$	487	Adult	$6.48\ 10^{8}$
Am-243	$2.59\ 10^{-6}$	$1.11\ 10^{-6}$	$3.73\ 10^{-7}$	7725	Adult	$7.73\ 10^{6}$
Cm-242	$4.79\ 10^{-11}$	$2.74\ 10^{-11}$	$1.39\ 10^{-11}$	0	Adult	$4.18\ 10^{11}$
Cm-243	$6.26\ 10^{-9}$	$2.73\ 10^{-9}$	$1.11\ 10^{-9}$	115	Adult	$3.20\ 10^{9}$
Cm-244	$9.25\ 10^{-9}$	$4.08\ 10^{-9}$	$1.72\ 10^{-9}$	99	Adult	$2.16\ 10^{9}$
Cm-245	$1.38\ 10^{-6}$	$5.76\ 10^{-7}$	$2.05\ 10^{-7}$	11070	Adult	$1.45\ 10^{7}$
Cm-246	$4.19\ 10^{-7}$	$1.76\ 10^{-7}$	$6.26\ 10^{-8}$	6795	Adult	$4.78\ 10^{7}$
Cm-248	$1.60\ 10^{-5}$	$6.77\ 10^{-6}$	$2.35\ 10^{-6}$	84995	Adult	$1.25\ 10^{6}$

$ “nd” indicates that a radiological capacity was not determined due to the low dose.

Table 134 Maximum annual doses from ‘what-if’ scenario of fish caught in a hypothetical local pond following bathtubbing

Radionuclide	Adult dose (µSv y-1 MBq-1)	Child dose (µSv y-1 MBq-1)	Infant dose (µSv y-1 MBq-1)	Time of max (y)	Age group with highest dose`	Dose at maximum inventory (µSv y-1)$
H-3	$1.07\ 10^{-14}$	$6.85\ 10^{-15}$	$1.07\ 10^{-14}$	77	Infant	$2.02\ 10^{-6}$
C-14	$5.60\ 10^{-10}$	$3.86\ 10^{-10}$	$5.80\ 10^{-10}$	1615	Infant	$6.88\ 10^{-2}$
Cl-36	$1.89\ 10^{-9}$	$1.93\ 10^{-9}$	$4.79\ 10^{-9}$	85	Infant	$2.43\ 10^{-3}$
Ca-41	$3.04\ 10^{-9}$	$2.84\ 10^{-9}$	$5.45\ 10^{-9}$	816	Infant	$5.72\ 10^{0}$
Mn-54	0	0	0		Infant	nd
Fe-55	0	0	0		Child	nd
Co-60	0	0	0		Infant	nd

Radionuclide	Adult dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Child dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Infant dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Time of max (y)	Age group with highest dose`	Dose at maximum inventory ($\mu Sv\ y^{-1}$)$
Ni-59	$5.50\ 10^{-12}$	$4.81\ 10^{-12}$	$9.79\ 10^{-12}$	4015	Infant	$1.07\ 10^{-2}$
Ni-63	$5.48\ 10^{-13}$	$9.13\ 10^{-13}$	$1.49\ 10^{-12}$	207	Infant	$1.64\ 10^{-3}$
Zn-65	0	0	0		Infant	nd
Se-79	$1.27\ 10^{-10}$	$1.40\ 10^{-10}$	$3.51\ 10^{-10}$	3140	Infant	$1.54\ 10^{-1}$
Sr-90	$2.33\ 10^{-11}$	$3.77\ 10^{-11}$	$6.93\ 10^{-11}$	112	Infant	$3.04\ 10^{-3}$
Mo-93	$1.51\ 10^{-11}$	$1.65\ 10^{-11}$	$4.32\ 10^{-11}$	1130	Infant	$2.57\ 10^{-3}$
Zr-93	$1.27\ 10^{-11}$	$1.33\ 10^{-11}$	$3.03\ 10^{-11}$	5820	Infant	$3.33\ 10^{-2}$
Nb-93m	0	0	0		Infant	nd
Nb-94	$1.36\ 10^{-13}$	$1.19\ 10^{-13}$	$2.76\ 10^{-13}$	10385	Infant	$6.06\ 10^{-6}$
Tc-99	$1.77\ 10^{-11}$	$1.65\ 10^{-11}$	$3.72\ 10^{-11}$	467	Infant	$6.44\ 10^{-4}$
Ru-106	0	0	0		Infant	nd
Ag-108m	$8.07\ 10^{-12}$	$1.95\ 10^{-11}$	$2.92\ 10^{-11}$	1065	Infant	$6.41\ 10^{-4}$
Ag-110m	0	0	0		Adult	nd
Cd-109	0	0	0		Infant	nd
Sb-125	0	0	0		Infant	nd
Sn-119m	0	0	0		Adult	nd
Sn-123	0	0	0		Adult	nd
Sn-126	$2.10\ 10^{-11}$	$1.36\ 10^{-11}$	$1.75\ 10^{-11}$	18905	Adult	$2.31\ 10^{-4}$
Te-127m	0	0	0		Adult	nd
I-129	$1.09\ 10^{-9}$	$2.88\ 10^{-10}$	$2.83\ 10^{-10}$	773	Adult	$4.79\ 10^{-2}$
Ba-133	$8.53\ 10^{-13}$	$9.59\ 10^{-13}$	$2.42\ 10^{-12}$	79	Infant	$5.14\ 10^{-4}$
Cs-134	0	0	0		Infant	nd
Cs-135	$1.41\ 10^{-10}$	$1.49\ 10^{-10}$	$3.97\ 10^{-10}$	15835	Infant	$4.35\ 10^{-1}$
Cs-137	$3.26\ 10^{-12}$	$3.31\ 10^{-12}$	$9.17\ 10^{-12}$	116	Infant	$4.02\ 10^{-4}$

Radionuclide	Adult dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Child dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Infant dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Time of max (y)	Age group with highest dose`	Dose at maximum inventory ($\mu Sv\ y^{-1}$)$^{\$}$
Ce-144	0	0	0		Infant	nd
Pm-147	0	0	0		Infant	nd
Sm-147	$1.71\ 10^{-11}$	$1.12\ 10^{-11}$	$1.84\ 10^{-11}$	12520	Infant	$7.04\ 10^{-4}$
Sm-151	$1.96\ 10^{-14}$	$2.00\ 10^{-14}$	$4.79\ 10^{-14}$	198	Infant	$5.25\ 10^{-5}$
Eu-152	$3.80\ 10^{-13}$	$3.55\ 10^{-13}$	$6.82\ 10^{-13}$	93	Infant	$2.99\ 10^{-4}$
Eu-154	$5.58\ 10^{-14}$	$5.18\ 10^{-14}$	$1.05\ 10^{-13}$	86	Infant	$1.15\ 10^{-4}$
Eu-155	0	0	0		Infant	nd
Gd-153	0	0	0		Infant	nd
Pb-210	$5.72\ 10^{-11}$	$3.28\ 10^{-11}$	$4.23\ 10^{-11}$	105	Adult	$4.48\ 10^{-4}$
Po-210	0	0	0		Infant	nd
Ra-226	$2.86\ 10^{-9}$	$6.00\ 10^{-9}$	$7.38\ 10^{-9}$	2625	Infant	$1.03\ 10^{-2}$
Ra-228	$7.94\ 10^{-16}$	$8.26\ 10^{-16}$	$1.89\ 10^{-15}$	82	Infant	$8.29\ 10^{-8}$
Ac-227	$3.97\ 10^{-14}$	$4.35\ 10^{-14}$	$1.13\ 10^{-13}$	105	Infant	$1.24\ 10^{-6}$
Th-228	0	0	0		Infant	nd
Th-229	$2.48\ 10^{-12}$	$2.80\ 10^{-12}$	$7.27\ 10^{-12}$	7000	Infant	$3.11\ 10^{-5}$
Th-230	$9.88\ 10^{-10}$	$8.02\ 10^{-10}$	$1.10\ 10^{-9}$	18180	Infant	$2.23\ 10^{-3}$
Th-232	$6.68\ 10^{-10}$	$4.27\ 10^{-10}$	$4.51\ 10^{-10}$	24975	Adult	$1.45\ 10^{-3}$
Pa-231	$2.03\ 10^{-10}$	$4.39\ 10^{-10}$	$5.18\ 10^{-10}$	14685	Infant	$4.01\ 10^{-4}$
U-232	$1.36\ 10^{-12}$	$1.45\ 10^{-12}$	$3.67\ 10^{-12}$	167	Infant	$4.03\ 10^{-5}$
U-233	$2.32\ 10^{-10}$	$2.41\ 10^{-10}$	$3.49\ 10^{-10}$	3115	Infant	$8.81\ 10^{-5}$
U-234	$2.77\ 10^{-11}$	$2.37\ 10^{-11}$	$3.06\ 10^{-11}$	3135	Infant	$4.74\ 10^{-5}$
U-235	$2.35\ 10^{-12}$	$1.82\ 10^{-12}$	$2.65\ 10^{-12}$	3170	Infant	$5.54\ 10^{-7}$
U-236	$6.37\ 10^{-12}$	$4.16\ 10^{-12}$	$6.83\ 10^{-12}$	3170	Infant	$2.90\ 10^{-5}$
U-238	$3.13\ 10^{-12}$	$1.85\ 10^{-12}$	$2.82\ 10^{-12}$	3170	Adult	$1.31\ 10^{-5}$

Radionuclide	Adult dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Child dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Infant dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Time of max (y)	Age group with highest dose`	Dose at maximum inventory ($\mu Sv\ y^{-1}$)$
Np-237	$2.45\ 10^{-12}$	$1.47\ 10^{-12}$	$2.09\ 10^{-12}$	1160	Adult	$1.83\ 10^{-7}$
Pu-238	$7.73\ 10^{-14}$	$5.98\ 10^{-14}$	$1.12\ 10^{-13}$	194	Infant	$4.92\ 10^{-6}$
Pu-239	$1.90\ 10^{-14}$	$2.01\ 10^{-14}$	$4.85\ 10^{-14}$	7095	Infant	$1.89\ 10^{-7}$
Pu-240	$2.84\ 10^{-14}$	$2.38\ 10^{-14}$	$4.79\ 10^{-14}$	4575	Infant	$2.87\ 10^{-7}$
Pu-241	$3.33\ 10^{-12}$	$3.97\ 10^{-12}$	$8.20\ 10^{-12}$	94	Infant	$9.00\ 10^{-3}$
Pu-242	$1.27\ 10^{-10}$	$1.55\ 10^{-10}$	$2.94\ 10^{-10}$	9745	Infant	$1.00\ 10^{-3}$
Pu-244	$1.83\ 10^{-12}$	$1.39\ 10^{-12}$	$1.94\ 10^{-12}$	10075	Infant	$3.49\ 10^{-6}$
Am-241	$1.34\ 10^{-10}$	$1.45\ 10^{-10}$	$3.68\ 10^{-10}$	1150	Infant	$8.06\ 10^{-3}$
Am-242m	$3.14\ 10^{-10}$	$2.80\ 10^{-10}$	$5.09\ 10^{-10}$	487	Infant	$1.12\ 10^{-2}$
Am-243	$1.49\ 10^{-10}$	$1.62\ 10^{-10}$	$4.10\ 10^{-10}$	7725	Infant	$3.17\ 10^{-3}$
Cm-242	$8.01\ 10^{-15}$	$5.95\ 10^{-15}$	$8.27\ 10^{-15}$	0	Infant	$3.63\ 10^{-6}$
Cm-243	$1.37\ 10^{-10}$	$3.56\ 10^{-10}$	$4.20\ 10^{-10}$	115	Infant	$1.84\ 10^{-2}$
Cm-244	$7.00\ 10^{-11}$	$5.71\ 10^{-11}$	$9.29\ 10^{-11}$	99	Infant	$4.08\ 10^{-3}$
Cm-245	$8.65\ 10^{-10}$	$2.08\ 10^{-9}$	$2.47\ 10^{-9}$	11070	Infant	$3.57\ 10^{-2}$
Cm-246	$1.12\ 10^{-9}$	$9.13\ 10^{-10}$	$1.48\ 10^{-9}$	6795	Infant	$6.52\ 10^{-2}$
Cm-248	$1.34\ 10^{-10}$	$1.96\ 10^{-10}$	$3.83\ 10^{-10}$	84995	Infant	$4.80\ 10^{-4}$

$ “nd” indicates that a radiological capacity was not determined due to the low dose.

E.4.5. Release of contaminated water to the estuary

1082. The Groundwater model developed in GoldSim (Section E.4.4) has been extended to calculate release rates of radionuclides into the estuary via groundwater by calculating activity concentrations in groundwater after migration through an aquifer 280 m in length. The activity release rate to the estuary is then calculated as the groundwater flow rate at this point multiplied by the activity concentration in groundwater at this point.

1083. The dose criterion used is a dose of 0.02 mSv y-1 (this is equivalent to the risk guidance level of 10^{-6} y^{-1} for exposure of the public post closure, for situations that are expected to occur).

1084. The release rates of radionuclides into the estuary as a result of overland flow of overtopping leachate were also calculated using the groundwater model developed in GoldSim (see Section E.4.4.6). This is relevant to the bathtubbing and inundation scenarios. Bathtubbing is assumed to occur from around 70 to 80 y after the period of authorisation, although the peak radionuclide release rates assessed here may occur later.

1085. Leachate breakout can enter the subsoil close to the landfill and migrate downwards to the underlying aquifer or flow overland and enter the estuary directly. The former is modelled by migration through the bypass compartment in the groundwater model. The overland flow is treated as a 'fast pathway' and is modelled as entering the estuary directly. Here, it is cautiously assumed that all the leachate breakout flows overland and enters the estuary. This is cautious inasmuch as it maximises the rate at which leachate breakout enters the estuary and it does not account for any retardation of radionuclides in the geosphere. The rate at which leachate enters the estuary is given by $V_{overflow}$ (see paragraph 982) and the concentration in the leachate breakout is given by $a_{RN,Leachate}$ (see paragraph 953).[1]

1086. The peak activity concentrations released to the estuary via groundwater and via overland flow were summed to derive a total peak release to the estuary. This approach is cautious, as the peaks for the two routes do not necessarily occur at the same time. The groundwater model runs for this assessment account for the rising groundwater level as a result of climate change (see Section E.4.4.1).

1087. Table 135 presents the calculated total peak activity concentrations and fluxes released to the estuary (i.e. for each radionuclide, the sum of the peak release from breakout directly entering the estuary and the peak release from the aquifer of radionuclides that have leached through the base of the landfill). Activity concentrations of daughters released to the estuary were also extracted from GoldSim and used as input, but are not shown in Table 135.

[1] This is different to the treatment in some other runs of the groundwater model, where a portion of the leachate breakout (based on the absorptive capacity of the soil) is assumed to enter the aquifer, as described in paragraph 980.

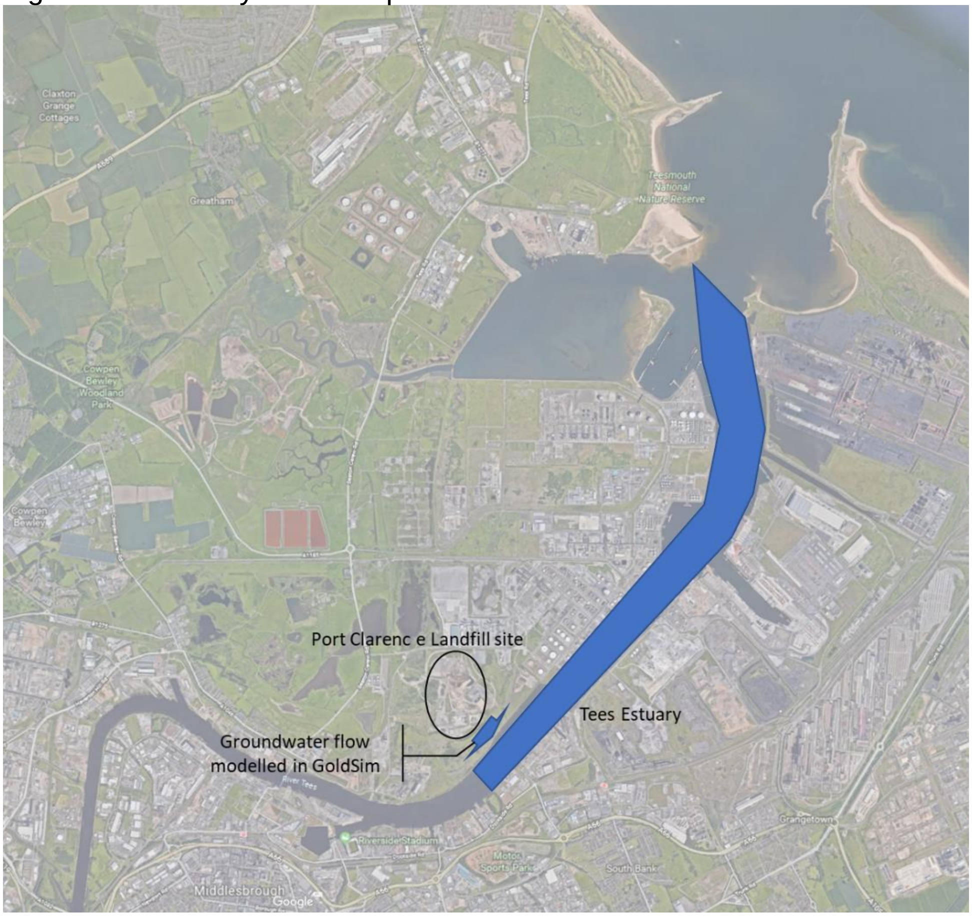
Table 135 Peak activity released to the estuary from aquifer and breakout flow

Radionuclide	Flux to estuary ($Bq\ y^{-1}/MBq$)	Radionuclide	Flux to estuary ($Bq\ y^{-1}/MBq$)
H-3	$8.90\ 10^{1}$	Eu-154	$1.94\ 10^{-2}$
C-14	$9.47\ 10^{1}$	Eu-155	$1.82\ 10^{-4}$
Cl-36	$3.37\ 10^{3}$	Gd-153	$2.94\ 10^{-10}$
Ca-41	$7.32\ 10^{2}$	Pb-210	$8.61\ 10^{-2}$
Mn-54	$2.54\ 10^{-10}$	Po-210	$4.08\ 10^{-10}$
Fe-55	$2.51\ 10^{-8}$	Ra-226	$2.92\ 10^{0}$
Co-60	$2.49\ 10^{-4}$	Ra-228	$1.05\ 10^{-4}$
Ni-59	$3.93\ 10^{1}$	Ac-227	$9.68\ 10^{-2}$
Ni-63	$3.68\ 10^{0}$	Th-228	$1.51\ 10^{-11}$
Zn-65	$1.81\ 10^{-10}$	Th-229	$5.39\ 10^{0}$
Se-79	$5.48\ 10^{1}$	Th-230	$5.87\ 10^{0}$
Sr-90	$5.57\ 10^{0}$	Th-232	$5.94\ 10^{0}$
Mo-93	$2.08\ 10^{2}$	Pa-231	$5.51\ 10^{0}$
Zr-93	$2.72\ 10^{1}$	U-232	$4.08\ 10^{0}$
Nb-93m	$4.85\ 10^{-2}$	U-233	$5.47\ 10^{1}$
Nb-94	$7.25\ 10^{0}$	U-234	$5.48\ 10^{1}$
Tc-99	$1.41\ 10^{3}$	U-235	$5.50\ 10^{1}$
Ru-106	$3.02\ 10^{-10}$	U-236	$5.50\ 10^{1}$
Ag-108m	$6.13\ 10^{0}$	U-238	$5.50\ 10^{1}$
Ag-110m	$3.13\ 10^{-10}$	Np-237	$2.77\ 10^{2}$
Cd-109	$5.93\ 10^{-10}$	Pu-238	$1.29\ 10^{0}$
Sb-125	$4.08\ 10^{-7}$	Pu-239	$1.47\ 10^{1}$
Sn-119m	$9.55\ 10^{-11}$	Pu-240	$1.36\ 10^{1}$
Sn-123	$5.90\ 10^{-11}$	Pu-241	$6.65\ 10^{-2}$
Sn-126	$7.01\ 10^{0}$	Pu-242	$1.51\ 10^{1}$
Te-127m	$1.74\ 10^{-10}$	Pu-244	$1.52\ 10^{1}$
I-129	$7.88\ 10^{2}$	Am-241	$9.34\ 10^{-1}$
Ba-133	$2.24\ 10^{1}$	Am-242m	$4.72\ 10^{-1}$
Cs-134	$6.27\ 10^{-11}$	Am-243	$3.95\ 10^{0}$
Cs-135	$9.37\ 10^{0}$	Cm-242$	0
Cs-137	$2.63\ 10^{-1}$	Cm-243	$3.19\ 10^{-2}$
Ce-144	$6.36\ 10^{-11}$	Cm-244	$1.10\ 10^{-2}$
Pm-147	$2.28\ 10^{-8}$	Cm-245	$1.12\ 10^{0}$
Sm-147	$1.21\ 10^{1}$	Cm-246	$1.05\ 10^{0}$
Sm-151	$1.05\ 10^{0}$	Cm-248	$1.22\ 10^{0}$
Eu-152	$1.66\ 10^{-1}$		

$Daughter radionuclides of Cm-242 are modelled

1088. The estuary was modelled in PC CREAM as a local marine compartment, representative of the area of the estuary shown in Figure 22. The length of 'coastline' of the compartment was taken to be 12,000 m, equal to the length of both sides of the estuary added together. The width of the estuary was taken to be 400 m, based on measurements on a map, and the depth was taken to be 15 m (Le Guillou, 1978). The change in height with the tide, 3.4 m (https://riverlevels.uk/north-yorkshire-tees-dock-tidal#.XSRfruhKhPa), was used to derive a volumetric exchange rate of 5.96 10^9 m^3 y^{-1}, assuming that the tide rises and falls twice per day. All other local compartment values within PC CREAM were set to default values.

Figure 22 Estuary local compartment



1089. The DORIS module within PC CREAM was used to derive activity concentrations in the estuary compartment and the estuary bed. The output from DORIS was used as input to the ASSESSOR module within PC CREAM to calculate doses to a fishing family that collects seafood from the estuary and consumes it. All input data for PC CREAM-08 were set to default values. The habits data for this family are presented in Table 136.

Table 136 Habits data for a fishing family exposed to activity in the estuary from groundwater

	Adult	Child	Infant
Fish consumption (kg y^{-1})*	100	20	5
Crustacean consumption (kg y^{-1})*	20	5	0
Mollusc consumption (kg y^{-1})*	20	5	0
Inhalation rate (m^3 y^{-1})	8100	5600	1900
Time spent near the estuary (h y^{-1})	2000	2000	2000
Distance from the estuary (m)	100	100	100

*Values are 97.5th percentile (Smith & Jones, 2003)

1090. GoldSim output has a low value cut-off and reports a lower limit of 1 10^{-13} µSv y^{-1} MBq^{-1}, which can occur for short lived radionuclides (half-life of less than about 5 years) where radioactive decay reduces activity to very low levels or where there is limited radionuclide transport in groundwater. The cut-off produces reported values of zero dose.

1091. The results of the dose calculations for a fishing family are given in for each age group (see Table 137). The scenario radiological capacity for each radionuclide is shown, and the year when the maximum dose occurs, are also shown. The results for Ra-226 are independent of the Ra-226 placement depth in the site. The scenario was considered as a limiting scenario for the site but does not constrain radiological capacity.

Table 137 Doses to a fishing family from groundwater and breakout flow to estuary

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Limiting age group	Scenario radiological capacity (MBq)$^{\$}$
H-3	1.35 10^{-14}	4.13 10^{-15}	3.62 10^{-16}	Adult	1.48 10^{15}
C-14	6.60 10^{-9}	2.19 10^{-9}	1.83 10^{-10}	Adult	3.03 10^{9}
Cl-36	8.45 10^{-12}	4.47 10^{-12}	3.55 10^{-12}	Adult	2.37 10^{12}
Ca-41	7.03 10^{-12}	5.83 10^{-12}	4.07 10^{-12}	Adult	2.85 10^{12}
Mn-54	2.60 10^{-21}	2.18 10^{-21}	1.84 10^{-21}	Adult	7.70 10^{21}
Fe-55	9.25 10^{-20}	7.66 10^{-20}	2.35 10^{-21}	Adult	2.16 10^{20}
Co-60	2.70 10^{-14}	2.65 10^{-14}	2.57 10^{-14}	Adult	7.41 10^{14}
Ni-59	1.50 10^{-11}	1.41 10^{-11}	1.36 10^{-11}	Adult	1.33 10^{12}
Ni-63	2.87 10^{-13}	1.32 10^{-13}	6.36 10^{-15}	Adult	6.96 10^{13}
Zn-65	0	0	0		nd
Se-79	0	0	0		nd

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Limiting age group	Scenario radiological capacity (MBq)$
Sr-90	0	0	0		nd
Mo-93	4.20 10^{-10}	3.98 10^{-10}	3.89 10^{-10}	Adult	4.77 10^{10}
Zr-93	0	0	0		nd
Nb-93m	7.19 10^{-15}	7.01 10^{-15}	6.88 10^{-15}	Adult	2.78 10^{15}
Nb-94	1.72 10^{-9}	1.70 10^{-9}	1.70 10^{-9}	Adult	1.16 10^{10}
Tc-99	0	0	0		nd
Ru-106	0	0	0		nd
Ag-108m	8.15 10^{-10}	4.97 10^{-10}	2.21 10^{-10}	Adult	2.45 10^{10}
Ag-110m	3.77 10^{-20}	1.81 10^{-20}	1.17 10^{-21}	Adult	5.30 10^{20}
Cd-109	9.06 10^{-20}	3.98 10^{-20}	2.41 10^{-22}	Adult	2.21 10^{20}
Sb-125	0	0	0		nd
Sn-119m	0	0	0		nd
Sn-123	0	0	0		nd
Sn-126	0	0	0		nd
Te-127m	0	0	0		nd
I-129	7.25 10^{-9}	3.02 10^{-9}	1.58 10^{-10}	Adult	2.76 10^{9}
Ba-133	3.05 10^{-10}	3.01 10^{-10}	3.00 10^{-10}	Adult	6.55 10^{10}
Cs-134	1.03 10^{-21}	7.95 10^{-22}	7.55 10^{-22}	Adult	1.94 10^{22}
Cs-135	4.97 10^{-12}	1.14 10^{-12}	4.18 10^{-13}	Adult	4.03 10^{12}
Cs-137	7.05 10^{-12}	6.31 10^{-12}	6.19 10^{-12}	Adult	2.84 10^{12}
Ce-144	5.86 10^{-23}	5.22 10^{-23}	4.79 10^{-23}	Adult	3.42 10^{23}
Pm-147	5.99 10^{-20}	1.96 10^{-20}	7.98 10^{-22}	Adult	3.34 10^{20}
Sm-147	0	0	0		nd
Sm-151	0	0	0		nd
Eu-152	1.52 10^{-11}	1.44 10^{-11}	1.42 10^{-11}	Adult	1.32 10^{12}
Eu-154	1.45 10^{-12}	1.43 10^{-12}	1.42 10^{-12}	Adult	1.38 10^{13}
Eu-155	4.45 10^{-16}	4.29 10^{-16}	4.21 10^{-16}	Adult	4.49 10^{16}
Gd-153	2.27 10^{-22}	2.19 10^{-22}	2.14 10^{-22}	Adult	8.82 10^{22}
Pb-210	6.74 10^{-8}	3.64 10^{-8}	4.08 10^{-10}	Adult	2.97 10^{8}
Po-210	3.29 10^{-17}	1.77 10^{-17}	1.98 10^{-19}	Adult	6.09 10^{17}
Ra-226	0	0	0		nd
Ra-228	0	0	0		nd
Ac-227	2.79 10^{-11}	2.84 10^{-11}	6.24 10^{-12}	Child	7.04 10^{11}
Th-228	0	0	0		nd
Th-229	0	0	0		nd
Th-230	0	0	0		nd
Th-232	0	0	0		nd
Pa-231	2.10 10^{-9}	2.10 10^{-9}	6.00 10^{-10}	Child	9.51 10^{9}

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Limiting age group	Scenario radiological capacity (MBq)$
U-232	0	0	0		nd
U-233	0	0	0		nd
U-234	0	0	0		nd
U-235	0	0	0		nd
U-236	0	0	0		nd
U-238	0	0	0		nd
Np-237	4.47 10^{-8}	1.24 10^{-8}	1.69 10^{-9}	Adult	4.47 10^{8}
Pu-238	3.07 10^{-10}	1.23 10^{-10}	1.31 10^{-12}	Adult	6.52 10^{10}
Pu-239	1.91 10^{-9}	5.17 10^{-10}	4.34 10^{-12}	Adult	1.05 10^{10}
Pu-240	0	0	0		nd
Pu-241	0	0	0		nd
Pu-242	0	0	0		nd
Pu-244	0	0	0		nd
Am-241	4.28 10^{-11}	1.39 10^{-11}	3.26 10^{-12}	Adult	4.67 10^{11}
Am-242m	3.68 10^{-10}	1.59 10^{-10}	3.73 10^{-12}	Adult	5.43 10^{10}
Am-243	5.81 10^{-10}	2.58 10^{-10}	1.39 10^{-10}	Adult	3.44 10^{10}
Cm-242	1.56 10^{-12}	6.27 10^{-13}	6.67 10^{-15}	Adult	1.28 10^{13}
Cm-243	3.97 10^{-12}	1.39 10^{-12}	4.49 10^{-13}	Adult	5.04 10^{12}
Cm-244	5.23 10^{-12}	1.43 10^{-12}	2.11 10^{-14}	Adult	3.83 10^{12}
Cm-245	2.85 10^{-10}	9.89 10^{-11}	3.00 10^{-11}	Adult	7.01 10^{10}
Cm-246	7.49 10^{-11}	2.01 10^{-11}	3.93 10^{-13}	Adult	2.67 10^{11}
Cm-248	2.43 10^{-10}	6.69 10^{-11}	8.38 10^{-13}	Adult	8.23 10^{10}

$ "nd" indicates that a radiological capacity was not determined due to the low dose.

1092. The doses calculated using illustrative inventories are considered further in Appendix D.

E.4.6. Inundation from the sea

1093. The effects of very long term climate change are assessed due to the location of the site close to the Tees Estuary. Consideration has been given to the timescale over which sea level rise could occur (see Section 2.10) and lead to the erosion of the site.

1094. With sea level rise the area surrounding the landfill is likely in due course to be subject to periodic flooding. At some stage the peak flood height will begin to overlap the edge of the basal liner low permeability basin and water may enter the base of the landfill. The bathtubbing and the groundwater scenarios may occur earlier.

1095. The dose criterion used is a dose of 0.02 mSv y-1 (this is equivalent to the risk guidance level of 10^{-6} y^{-1} for exposure of the public post closure, for situations that are expected to occur).

1096. Flooding is included in the GoldSim model as a one-off event that doesn't influence the contaminant or water balance of the other pathways. Flooding is assumed to occur to a height of 1 m above the edge of the low-permeability basin (the base of the engineered liner varies from 5.4 to 8.5 m AOD (see Figure 10), requiring a minimum flood depth of about 9 m AOD). This leads to 1 m head of excess leachate that is generated in and can then seep out of the landfill. It is then absorbed by the surrounding soil, leading to contamination of the soil by the radionuclides in the excess leachate. The concentration of these radionuclides in the soil is then used for dose assessment calculations.

1097. The activity concentration of each radionuclide is taken as its maximum activity concentration over the period being assessed. Two periods are considered: between the end of the Period of Authorisation and 100,000 years after closure of the facility; and between 140 y after the end of the Period of Authorisation (200 y after closure) and 100,000 years after closure of the facility.

1098. The total volume of excess leachate released during a flooding event is

$$V_{Leachate\_excess} = A_{Surface} \cdot h_{Leachate\_excess} \cdot wc_{Waste}$$

Where:

- $V_{Leachate\_excess}$ is the volume of leachate above the edge of the low-permeability basin (m^3 per flooding event);
- $A_{Surface}$ is the surface area of the landfill (m^2);
- $h_{Leachate\_excess}$ is the height that the flooding event extends above the low-permeability basin (assumed to be 1 m); and,
- wc_{Waste} is the water content of waste (fraction).

1099. The excess leachate absorbed by subsoil is limited by

$$V_{Subsoil\_absorbed} = Min\left(A_{Floodzone} \cdot th_{Subsoil} \cdot p_{Subsoil} \cdot (1 - s_{Subsoil}), V_{Leachate\_excess}\right)$$

where:

- $VL_{Subsoil\_absorbed}$ is the volume limit on released leachate that can be absorbed in the topsoil (m^3 per flooding event);
- $A_{Floodzone}$ is the surface area of the flood zone, which extends between the landfill and the estuary (m^2);
- $th_{Subsoil}$ is the thickness of the subsoil (assumed to be 1 m);
- $p_{Subsoil}$ is the porosity of the subsoil; and,
- $s_{Subsoil}$ is the saturation of the subsoil.

1100. The activity concentration calculated per radionuclide in subsoil is

$$AC_{Subsoil} = AC_{Leachate\_peak} \cdot V_{Subsoil\_absorbed} / m_{Subsoil}$$

where:

- $AC_{Subsoil}$ is the activity concentration in subsoil (Bq kg^{-1});
- $AC_{Leachate\_peak}$ is the peak activity concentration in leachate (Bq m^{-3}); and,
- $m_{Subsoil}$ is the mass of subsoil, calculated as

$$m_{Subsoil} = A_{Floodzone} \cdot th_{Subsoil} \cdot d_{Soil}$$

where:

- d_{Soil} is the density of soil.

1101. Doses due to inhalation, external irradiation, inadvertent ingestion of dust and consumption of food produced on contaminated land were calculated.

1102. After the flood event, the water level is expected to subside within one week. During this time, any excess leachate that was not absorbed by the subsoil would be released to the estuary via a fast flow mechanism ($V_{Estuary\_fast\_flow}$ in m^3 per flooding event).

$$V_{Estuary\_fast\_flow} = V_{Leachate\_excess} - V_{Subsoil\_absorbed}$$

1103. The activity released into the estuary during a flooding event ($A_{Estuary\_fast\_flow}$ in Bq per flooding event) is

$$A_{Estuary\_fast\_flow} = V_{Estuary\_fast\_flow} \cdot AC_{Leachate\_peak}$$

1104. GoldSim output has a low value cut-off and reports a lower limit of 1 10^{-13} µSv y^{-1} MBq^{-1}, which can occur for short lived radionuclides (half-life of less than about 5 years) where radioactive decay reduces activity to very low levels or where there is limited radionuclide transport in groundwater. The cut-off produces reported values of zero dose.

1105. The results of the dose calculations for a farming family with flooding occurring from 60 years are given for each age group (see Table 138). The scenario radiological capacity for each radionuclide is shown, and the year when the maximum dose occurs, are also shown. The results for Ra-226 are independent of the Ra-226 placement depth in the site. The scenario was considered as a limiting scenario for the site and constrains the radiological capacity of three radionuclide: H-3, Cl-36 and Tc-99. The calculation is very cautious and only impacts relatively mobile radionuclides.

1106. Consideration was given to the consumption of fish from a local pond that may have received contaminated leachate from a flood event. Although this is conceptually similar to the 'what-if' bathtubbing scenario of contamination of a hypothetical local pond, a large amount of dilution would occur from the receding floodwaters. Fish consumption has not therefore been considered as a what-if scenario for a flooding event.

1107. The flooding calculation is very cautious and takes no account of the time it would take for floodwater to enter and then drain from the landfill that would potentially reduce the impacts shown here.

Table 138 Doses to a farming family from flooding of landfill after 60 years

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Limiting age group	Scenario radiological capacity (MBq)$
H-3	6.49 10^{-8}	5.73 10^{-8}	1.06 10^{-7}	Infant	1.88 10^{8}
C-14	1.65 10^{-12}	1.34 10^{-12}	1.22 10^{-12}	Adult	1.21 10^{13}
Cl-36	7.00 10^{-6}	1.08 10^{-5}	3.94 10^{-5}	Infant	5.08 10^{5}

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Limiting age group	Scenario radiological capacity (MBq)$^{\$}$
Ca-41	6.61 10^{-10}	1.11 10^{-9}	1.25 10^{-9}	Infant	1.60 10^{10}
Mn-54	0	0	0		nd
Fe-55	0	0	0		nd
Co-60	4.05 10^{-14}	3.81 10^{-14}	3.04 10^{-14}	Adult	4.94 10^{14}
Ni-59	2.38 10^{-14}	1.81 10^{-14}	1.20 10^{-14}	Adult	8.41 10^{14}
Ni-63	4.55 10^{-14}	3.43 10^{-14}	2.19 10^{-14}	Adult	4.39 10^{14}
Zn-65	0	0	0		nd
Se-79	5.87 10^{-12}	1.34 10^{-11}	2.43 10^{-11}	Infant	8.22 10^{11}
Sr-90	1.54 10^{-10}	1.24 10^{-10}	1.02 10^{-10}	Adult	1.30 10^{11}
Mo-93	1.66 10^{-9}	1.86 10^{-9}	3.70 10^{-9}	Infant	5.41 10^{9}
Zr-93	8.26 10^{-13}	1.85 10^{-13}	2.46 10^{-14}	Adult	2.42 10^{13}
Nb-93m	1.20 10^{-15}	9.58 10^{-16}	4.92 10^{-16}	Adult	1.67 10^{16}
Nb-94	2.30 10^{-12}	2.09 10^{-12}	1.61 10^{-12}	Adult	8.70 10^{12}
Tc-99	1.15 10^{-6}	6.88 10^{-7}	1.07 10^{-6}	Adult	1.73 10^{7}
Ru-106	0	0	0		nd
Ag-108m	7.76 10^{-11}	7.16 10^{-11}	5.61 10^{-11}	Adult	2.58 10^{11}
Ag-110m	0	0	0		nd
Cd-109	0	0	0		nd
Sb-125	0	0	0		nd
Sn-119m	0	0	0		nd
Sn-123	0	0	0		nd
Sn-126	2.52 10^{-12}	2.39 10^{-12}	2.06 10^{-12}	Adult	7.93 10^{12}
Te-127m	0	0	0		nd
I-129	1.43 10^{-8}	1.51 10^{-8}	1.05 10^{-8}	Child	1.32 10^{9}
Ba-133	2.13 10^{-11}	2.02 10^{-11}	1.60 10^{-11}	Adult	9.38 10^{11}
Cs-134	0	0	0		nd
Cs-135	1.18 10^{-13}	8.53 10^{-14}	4.53 10^{-14}	Adult	1.70 10^{14}
Cs-137	3.40 10^{-13}	2.89 10^{-13}	2.11 10^{-13}	Adult	5.88 10^{13}
Ce-144	0	0	0		nd
Pm-147	0	0	0		nd
Sm-147	1.40 10^{-10}	9.22 10^{-11}	3.81 10^{-11}	Adult	1.43 10^{11}
Sm-151	3.66 10^{-14}	2.38 10^{-14}	1.06 10^{-14}	Adult	5.46 10^{14}
Eu-152	4.98 10^{-13}	4.48 10^{-13}	3.40 10^{-13}	Adult	4.02 10^{13}
Eu-154	9.56 10^{-14}	8.60 10^{-14}	6.51 10^{-14}	Adult	2.09 10^{14}
Eu-155	1.00 10^{-16}	8.59 10^{-17}	5.60 10^{-17}	Adult	1.99 10^{17}
Gd-153	0	0	0		nd
Pb-210	5.01 10^{-11}	3.96 10^{-11}	2.20 10^{-11}	Adult	3.99 10^{11}
Po-210	0	0	0		nd

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Limiting age group	Scenario radiological capacity (MBq)$
Ra-226	3.64 10^{-10}	2.81 10^{-10}	1.53 10^{-10}	Adult	5.50 10^{10}
Ra-228	3.97 10^{-13}	3.07 10^{-13}	1.60 10^{-13}	Adult	5.04 10^{13}
Ac-227	6.54 10^{-10}	4.94 10^{-10}	2.17 10^{-10}	Adult	3.06 10^{10}
Th-228	0	0	0		nd
Th-229	1.81 10^{-9}	1.27 10^{-9}	4.48 10^{-10}	Adult	1.10 10^{10}
Th-230	1.05 10^{-9}	6.67 10^{-10}	2.46 10^{-10}	Adult	1.91 10^{10}
Th-232	1.18 10^{-9}	8.45 10^{-10}	3.43 10^{-10}	Adult	1.69 10^{10}
Pa-231	5.45 10^{-9}	3.37 10^{-9}	1.02 10^{-9}	Adult	3.67 10^{9}
U-232	1.54 10^{-8}	1.13 10^{-8}	5.65 10^{-9}	Adult	1.30 10^{9}
U-233	1.47 10^{-8}	1.06 10^{-8}	5.22 10^{-9}	Adult	1.36 10^{9}
U-234	7.44 10^{-9}	5.48 10^{-9}	2.62 10^{-9}	Adult	2.69 10^{9}
U-235	1.65 10^{-8}	1.23 10^{-8}	5.75 10^{-9}	Adult	1.21 10^{9}
U-236	5.88 10^{-9}	4.29 10^{-9}	2.08 10^{-9}	Adult	3.40 10^{9}
U-238	5.58 10^{-9}	4.03 10^{-9}	1.99 10^{-9}	Adult	3.58 10^{9}
Np-237	1.92 10^{-6}	1.11 10^{-6}	4.08 10^{-7}	Adult	1.04 10^{7}
Pu-238	1.24 10^{-9}	7.16 10^{-10}	2.44 10^{-10}	Adult	1.61 10^{10}
Pu-239	2.19 10^{-9}	1.26 10^{-9}	4.16 10^{-10}	Adult	9.13 10^{9}
Pu-240	2.18 10^{-9}	1.26 10^{-9}	4.14 10^{-10}	Adult	9.18 10^{9}
Pu-241	1.71 10^{-11}	1.03 10^{-11}	2.45 10^{-12}	Adult	1.17 10^{12}
Pu-242	2.01 10^{-9}	1.26 10^{-9}	3.96 10^{-10}	Adult	9.95 10^{9}
Pu-244	3.44 10^{-9}	2.16 10^{-9}	6.77 10^{-10}	Adult	5.81 10^{9}
Am-241	4.56 10^{-10}	2.74 10^{-10}	9.74 10^{-11}	Adult	4.39 10^{10}
Am-242m	1.15 10^{-9}	6.97 10^{-10}	2.27 10^{-10}	Adult	1.73 10^{10}
Am-243	8.32 10^{-10}	4.99 10^{-10}	1.68 10^{-10}	Adult	2.40 10^{10}
Cm-242	6.35 10^{-12}	5.08 10^{-12}	2.57 10^{-12}	Adult	3.15 10^{12}
Cm-243	2.62 10^{-11}	1.60 10^{-11}	6.49 10^{-12}	Adult	7.63 10^{11}
Cm-244	1.41 10^{-11}	8.67 10^{-12}	3.65 10^{-12}	Adult	1.42 10^{12}
Cm-245	6.21 10^{-10}	3.62 10^{-10}	1.29 10^{-10}	Adult	3.22 10^{10}
Cm-246	1.60 10^{-10}	9.43 10^{-11}	3.35 10^{-11}	Adult	1.25 10^{11}
Cm-248	5.25 10^{-10}	3.11 10^{-10}	1.08 10^{-10}	Adult	3.81 10^{10}

$ “nd” indicates that a radiological capacity was not determined due to the low dose.

1108. The results of the dose calculations for a farming family with flooding occurring from 200 years are given in for each age group (see Table 139). The scenario radiological capacity for each radionuclide is shown, and the year when the maximum dose occurs, are also shown. The results for Ra-226 are independent of the Ra-226 placement depth in the site.

1109. The impact of a delay to flooding is to reduce the doses that occur from the shorter half-life radionuclides. The mobile radionuclides H-3, Cl-36 and Tc-99 would likely drain with recurring flood water or through rainfall so would not accumulate in the local area through repeated flooding. Other radionuclides would require in excess of 40 (I-129) flood events for the scenario radiological capacity to reduce to and approach the maximum inventory, 140 events would be needed for Np-237 and for other radionuclides in excess of 1000 events.

Table 139 Doses to a farming family from flooding of landfill after 200 years

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Limiting age group	Scenario radiological capacity (MBq)$
H-3	6.40 10^{-12}	2.68 10^{-12}	2.28 10^{-12}	Adult	3.12 10^{12}
C-14	9.51 10^{-13}	6.45 10^{-13}	3.30 10^{-13}	Adult	2.10 10^{13}
Cl-36	1.93 10^{-6}	1.16 10^{-6}	1.63 10^{-6}	Adult	1.04 10^{7}
Ca-41	3.69 10^{-10}	2.75 10^{-10}	1.31 10^{-10}	Adult	5.42 10^{10}
Mn-54	0	0	0		nd
Fe-55	0	0	0		nd
Co-60	0	0	0		nd
Ni-59	2.33 10^{-14}	1.75 10^{-14}	9.73 10^{-15}	Adult	8.57 10^{14}
Ni-63	1.70 10^{-14}	1.26 10^{-14}	6.93 10^{-15}	Adult	1.17 10^{15}
Zn-65	0	0	0		nd
Se-79	4.85 10^{-12}	6.36 10^{-12}	5.63 10^{-12}	Child	3.15 10^{12}
Sr-90	5.08 10^{-12}	3.40 10^{-12}	1.79 10^{-12}	Adult	3.93 10^{12}
Mo-93	2.02 10^{-10}	1.01 10^{-10}	5.98 10^{-11}	Adult	9.90 10^{10}
Zr-93	8.25 10^{-13}	1.85 10^{-13}	2.46 10^{-14}	Adult	2.42 10^{13}
Nb-93m	0	0	0		nd
Nb-94	2.29 10^{-12}	2.08 10^{-12}	1.60 10^{-12}	Adult	8.74 10^{12}
Tc-99	1.02 10^{-6}	6.04 10^{-7}	9.32 10^{-7}	Adult	1.96 10^{7}
Ru-106	0	0	0		nd
Ag-108m	6.15 10^{-11}	5.67 10^{-11}	4.44 10^{-11}	Adult	3.25 10^{11}
Ag-110m	0	0	0		nd
Cd-109	0	0	0		nd
Sb-125	0	0	0		nd
Sn-119m	0	0	0		nd
Sn-123	0	0	0		nd
Sn-126	2.51 10^{-12}	2.36 10^{-12}	1.92 10^{-12}	Adult	7.98 10^{12}
Te-127m	0	0	0		nd
I-129	1.09 10^{-8}	9.82 10^{-9}	3.33 10^{-9}	Adult	1.83 10^{9}
Ba-133	1.56 10^{-15}	1.45 10^{-15}	1.13 10^{-15}	Adult	1.28 10^{16}
Cs-134	0	0	0		nd
Cs-135	1.05 10^{-13}	7.65 10^{-14}	3.47 10^{-14}	Adult	1.90 10^{14}
Cs-137	1.30 10^{-14}	1.12 10^{-14}	7.99 10^{-15}	Adult	1.54 10^{15}
Ce-144	0	0	0		nd

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Limiting age group	Scenario radiological capacity (MBq)$^{\$}$
Pm-147	0	0	0		nd
Sm-147	1.40 10^{-10}	9.22 10^{-11}	3.81 10^{-11}	Adult	1.43 10^{11}
Sm-151	1.25 10^{-14}	8.10 10^{-15}	3.59 10^{-15}	Adult	1.60 10^{15}
Eu-152	4.01 10^{-16}	3.61 10^{-16}	2.74 10^{-16}	Adult	4.98 10^{16}
Eu-154	0	0	0		nd
Eu-155	0	0	0		nd
Gd-153	0	0	0		nd
Pb-210	6.21 10^{-13}	4.74 10^{-13}	2.31 10^{-13}	Adult	3.22 10^{13}
Po-210	0	0	0		nd
Ra-226	3.45 10^{-10}	2.58 10^{-10}	1.26 10^{-10}	Adult	5.79 10^{10}
Ra-228	0	0	0		nd
Ac-227	7.71 10^{-12}	5.82 10^{-12}	2.56 10^{-12}	Adult	2.59 10^{12}
Th-228	0	0	0		nd
Th-229	1.79 10^{-9}	1.25 10^{-9}	4.42 10^{-10}	Adult	1.12 10^{10}
Th-230	1.04 10^{-9}	6.59 10^{-10}	2.39 10^{-10}	Adult	1.93 10^{10}
Th-232	1.18 10^{-9}	8.45 10^{-10}	3.42 10^{-10}	Adult	1.69 10^{10}
Pa-231	5.45 10^{-9}	3.36 10^{-9}	1.02 10^{-9}	Adult	3.67 10^{9}
U-232	3.77 10^{-9}	2.77 10^{-9}	1.38 10^{-9}	Adult	5.30 10^{9}
U-233	1.46 10^{-8}	1.05 10^{-8}	5.21 10^{-9}	Adult	1.37 10^{9}
U-234	7.42 10^{-9}	5.46 10^{-9}	2.61 10^{-9}	Adult	2.70 10^{9}
U-235	1.65 10^{-8}	1.23 10^{-8}	5.75 10^{-9}	Adult	1.21 10^{9}
U-236	5.87 10^{-9}	4.28 10^{-9}	2.08 10^{-9}	Adult	3.40 10^{9}
U-238	5.58 10^{-9}	4.02 10^{-9}	1.99 10^{-9}	Adult	3.59 10^{9}
Np-237	1.91 10^{-6}	1.10 10^{-6}	4.06 10^{-7}	Adult	1.05 10^{7}
Pu-238	4.11 10^{-10}	2.37 10^{-10}	8.09 10^{-11}	Adult	4.86 10^{10}
Pu-239	2.18 10^{-9}	1.26 10^{-9}	4.14 10^{-10}	Adult	9.17 10^{9}
Pu-240	2.15 10^{-9}	1.24 10^{-9}	4.08 10^{-10}	Adult	9.32 10^{9}
Pu-241	1.25 10^{-11}	7.53 10^{-12}	1.80 10^{-12}	Adult	1.60 10^{12}
Pu-242	2.01 10^{-9}	1.26 10^{-9}	3.95 10^{-10}	Adult	9.95 10^{9}
Pu-244	3.44 10^{-9}	2.16 10^{-9}	6.77 10^{-10}	Adult	5.82 10^{9}
Am-241	3.65 10^{-10}	2.19 10^{-10}	7.79 10^{-11}	Adult	5.48 10^{10}
Am-242m	9.64 10^{-10}	5.82 10^{-10}	1.90 10^{-10}	Adult	2.08 10^{10}
Am-243	8.25 10^{-10}	4.95 10^{-10}	1.67 10^{-10}	Adult	2.42 10^{10}
Cm-242	2.10 10^{-12}	1.68 10^{-12}	8.52 10^{-13}	Adult	9.52 10^{12}
Cm-243	3.47 10^{-12}	2.12 10^{-12}	8.59 10^{-13}	Adult	5.76 10^{12}
Cm-244	5.97 10^{-12}	3.68 10^{-12}	1.55 10^{-12}	Adult	3.35 10^{12}
Cm-245	6.19 10^{-10}	3.61 10^{-10}	1.28 10^{-10}	Adult	3.23 10^{10}
Cm-246	1.57 10^{-10}	9.26 10^{-11}	3.29 10^{-11}	Adult	1.27 10^{11}

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Limiting age group	Scenario radiological capacity (MBq)$
Cm-248	5.25 10^{-10}	3.11 10^{-10}	1.08 10^{-10}	Adult	3.81 10^{10}

$ “nd” indicates that a radiological capacity was not determined due to the low dose.

E.4.7. Exposure of coastal walker following site erosion

1110. The landfill site has been reclaimed from salt marsh and mudflats over many decades through the deposition of wastes, clinker and slag deposits from industries including gas works, lime works, chlorine works, soda works, blast furnaces and salt evaporating pans (Augean, 2014). These materials are not readily eroded in a low energy estuary environment. The deposited materials have created a land mass that is 2.5 m or more above the current tidal reach.

1111. Timing of the onset of erosion and the impact of sea level rise on the natural evolution of the restored landfill is uncertain. The start of erosion resulting in LLW exposure depends on cell location, the increase in global temperature, the rate of sea level rise and the future management of the estuary, barrage and coastal sea defences. For these reasons, it is uncertain as to whether and when, sea-level rise will result in erosion exposing LLW at the site.

1112. It is possible that local or national policies for maintaining shipping access and management of local flood defence schemes could change and impact the future evolution of the estuary. If dredging activities stopped there would be accumulation of sediments and development of salt marshes and mudflats in the estuary. The sediment deposits and sea level rise could lead to tidal erosion at the Port Clarence site from the seaward side. Sea-level rise could expose the north eastern side of the landfills to direct tidal action and the other sides to the action of waters within a modified estuary. There is also likely to be a delay before waste cells that contain the proposed LLW disposals become seaward facing due to existing completed cells (minimum of 200 m width) on the seaward side that do not contain LLW.

1113. The approach adopted here is to use very cautious assumptions, for this reason a radiological assessment is undertaken assuming that erosion occurs at the end of the period of authorisation.

1114. Once the landfill is directly in contact with coastal waters, erosion is assumed to occur. The rate (m y^{-1}) at which erosion could potentially occur has been reviewed by Bangor University using a number of approaches. The results of this review can be summarised as follows:

- vertical erosion of Port Clarence mudflat at 5.7 mm y^{-1} based on LIDAR observations, noting that areas that would not be expected to show changing elevation have greater variance over the same period (e.g. increased elevation of the training walls along the estuary over the same timescale giving reduced confidence that erosion is significant);

- vertical erosion rate of 0.01 m y^{-1} from a literature review of similar coastal/estuarine sites (95th percentile of 0.02 m y^{-1});
- a regression model for the River Tees estimates a lateral erosion rate of 0.21 m y^{-1};
- a global river bank database provides a mean lateral erosion rate of 0.51 m y^{-1} for similar sites and a maximum lateral erosion rate of 0.8 m y^{-1} for similar sites.

1115. The regression analysis taking account of local features has been used in the modelling work (0.21 m y^{-1}) in preference to the value from a literature review of vertical erosion or the global review of lateral erosion rate for similar sites.

1116. Radiation exposure of members of the public spending time at the site once erosion of the landfills has started could occur. Two exposure scenarios are considered; exposure through direct irradiation to a casual user who walks close to the exposed waste (e.g. on the estuary bank/along the coast); and, exposure from releases into the coastal waters (see Section E.4.8).

1117. The dose criterion used is a dose of 0.02 mSv y^{-1} for the public (this is equivalent to the risk guidance level of 10^{-6} y^{-1} for exposure of the public post closure, for situations that are expected to occur).

Potentially exposed group

1118. The intended end use of the site includes public access to scrub and grassland with paths. An assessment is therefore made of the doses to a member of the public who spends time walking over the restored site and it is assumed that this continues once erosion starts to impact the site even though erosion may restrict access to the site. Time spent close to and walking over the eroding materials is calculated assuming a daily walk of 1 hour, passing the exposed face once, assuming a face length of 1 km and walking at 5 km h^{-1} (about 73 h y^{-1}). The walker inadvertently ingests soil, inhales dust and receives an external exposure from exposed waste and it is cautiously assumed that all three age groups walk together. The habit data are summarised in Table 140.

Table 140 Habit data for exposure of coastal walker to eroded waste: applicable after the Period of Authorisation

Parameter	Value	Comment
Inhalation rate – adult (m^3 h^{-1})	1.21	Inhalation rates based on ICRP 66 (ICRP, 1994), see Table 73 for derivation
Inhalation rate – child (m^3 h^{-1})	0.87	
Inhalation rate – infant (m^3 h^{-1})	0.31	
Soil ingestion - adult (kg y^{-1})	3.65 10^{-4}	Derived from (NRPB, 2003b) Table 11 for time spent near waste
Soil ingestion - child (kg y^{-1})	7.31 10^{-4}	
Soil ingestion - infant (kg y^{-1})	3.65 10^{-3}	
Time on-site – public (h y^{-1})	73	Time taken to pass exposed waste.

E.4.7.1. Assessment calculations for coastal walker

1119. The coastal walker receives a dose (Sv y^{-1}) from external irradiation, inhalation and inadvertent ingestion at the time of erosion (*t*, taken to be 60 y after closure) as follows:

$$Dose_{walker} = \left(\frac{D_{irr,slab}^{Rn}}{8766}\right) T C_{Rn,waste}(t) + D_{inh}^{Rn} T B M_{inh} C_{Rn,waste}(t) + D_{ing}^{Rn} Q_{soil} C_{Rn,waste}(t)$$

where:

- $Dose_{walker}$ is the dose from external irradiation, inhalation and inadvertent ingestion (Sv y^{-1});
- M_{inh} is the dust loading of suspended eroded material inhaled by the walker (kg m^{-3});
- T is the time that the walker is exposed to the material (73.0 h y^{-1});
- B is the breathing rate (m^3 h^{-1});
- $D_{irr,slab}$, D_{inh} and D_{ing} are the dose coefficients for radionuclide *Rn* (Sv y^{-1} Bq^{-1} kg; Sv Bq^{-1}; and Sv Bq^{-1}, respectively);
- 8766 is the number of hours in a year (h y^{-1});
- $C_{Rn,waste}(t)$ is the activity concentration of radionuclide *Rn* (Bq kg^{-1}) in the waste at time of erosion, *t*:

$$C_{Rn,waste}(t) = \frac{A_{Rn}(t)}{V_{landfill}\rho_{waste}}$$

- $V_{landfill}$ is the volume of the landfill in which the activity is assumed to be concentrated (m^3);
- $Qsoil$ is the inadvertent ingestion rate of soil (g h^{-1}); and,
- ρ_{waste} is the density of the waste (kg m^{-3}).

Table 141 Parameters for the coastal walker exposure assessment

Parameter	Units	Value	Description
$V_{landfill}$	m^3	See Table 67	Volume of landfill (cells) in which activity is homogeneously distributed
M_{inh}	kg m^{-3}	1 10^{-7}	Dust load of contaminated waste inhaled by the coastal walker
ρ_{waste}	kg m^{-3}	1,530	Density of the waste
$D_{irr,slab}$, D_{inh} D_{ing}	Sv Bq^{-1}	See Table 227 and Table 225	Dose coefficients

E.4.7.2. Dose to beach user from exposure to external radiation and ingestion/inhalation of soil

1120. The dose to a beach walker after the start of erosion is given in Table 142.

Table 142 Doses to beach walkers after the start of tidal erosion

Radionuclide	Adult dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Child dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Infant dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Limiting age group	Scenario radiological capacity (MBq)
H-3	$6.91\ 10^{-14}$	$1.50\ 10^{-13}$	$1.38\ 10^{-12}$	Infant	$1.45\ 10^{13}$
C-14	$5.99\ 10^{-11}$	$1.43\ 10^{-10}$	$1.33\ 10^{-9}$	Infant	$1.50\ 10^{10}$
Cl-36	$9.73\ 10^{-11}$	$3.37\ 10^{-10}$	$5.26\ 10^{-9}$	Infant	$3.80\ 10^{9}$
Ca-41	$1.62\ 10^{-11}$	$8.03\ 10^{-11}$	$4.33\ 10^{-10}$	Infant	$4.62\ 10^{10}$
Mn-54	$2.86\ 10^{-31}$	$4.28\ 10^{-31}$	$2.21\ 10^{-30}$	Infant	$9.06\ 10^{30}$
Fe-55	$7.30\ 10^{-18}$	$4.66\ 10^{-17}$	$5.03\ 10^{-16}$	Infant	$3.97\ 10^{16}$
Co-60	$5.16\ 10^{-13}$	$1.13\ 10^{-12}$	$8.90\ 10^{-12}$	Infant	$2.25\ 10^{12}$
Ni-59	$6.13\ 10^{-12}$	$1.92\ 10^{-11}$	$2.84\ 10^{-10}$	Infant	$7.05\ 10^{10}$
Ni-63	$1.00\ 10^{-11}$	$3.24\ 10^{-11}$	$4.63\ 10^{-10}$	Infant	$4.32\ 10^{10}$
Zn-65	$5.08\ 10^{-37}$	$1.20\ 10^{-36}$	$1.23\ 10^{-35}$	Infant	$1.63\ 10^{36}$
Se-79	$2.55\ 10^{-10}$	$2.34\ 10^{-9}$	$2.33\ 10^{-8}$	Infant	$8.58\ 10^{8}$
Sr-90	$6.87\ 10^{-10}$	$2.66\ 10^{-9}$	$1.83\ 10^{-8}$	Infant	$1.09\ 10^{9}$
Mo-93	$2.60\ 10^{-10}$	$6.63\ 10^{-10}$	$5.69\ 10^{-9}$	Infant	$3.52\ 10^{9}$
Zr-93	$1.42\ 10^{-10}$	$1.11\ 10^{-10}$	$6.36\ 10^{-10}$	Infant	$3.15\ 10^{10}$
Nb-93m	$1.03\ 10^{-12}$	$3.69\ 10^{-12}$	$5.77\ 10^{-11}$	Infant	$3.46\ 10^{11}$
Nb-94	$8.42\ 10^{-10}$	$1.32\ 10^{-9}$	$8.86\ 10^{-9}$	Infant	$2.26\ 10^{9}$
Tc-99	$8.06\ 10^{-11}$	$2.42\ 10^{-10}$	$4.01\ 10^{-9}$	Infant	$4.98\ 10^{9}$
Ru-106	$1.86\ 10^{-27}$	$6.12\ 10^{-27}$	$9.07\ 10^{-26}$	Infant	$2.20\ 10^{26}$
Ag-108m	$7.82\ 10^{-10}$	$1.31\ 10^{-9}$	$9.00\ 10^{-9}$	Infant	$2.22\ 10^{9}$
Ag-110m	$5.27\ 10^{-36}$	$8.21\ 10^{-36}$	$5.11\ 10^{-35}$	Infant	$3.92\ 10^{35}$
Cd-109	$9.18\ 10^{-25}$	$3.02\ 10^{-24}$	$3.97\ 10^{-23}$	Infant	$5.04\ 10^{23}$
Sb-125	$8.19\ 10^{-17}$	$1.76\ 10^{-16}$	$1.84\ 10^{-15}$	Infant	$1.09\ 10^{16}$
Sn-119m	$1.02\ 10^{-33}$	$4.02\ 10^{-33}$	$6.47\ 10^{-32}$	Infant	$3.09\ 10^{32}$
Sn-123	$1.80\ 10^{-61}$	$6.96\ 10^{-61}$	$1.16\ 10^{-59}$	Infant	$1.72\ 10^{60}$
Sn-126	$1.23\ 10^{-9}$	$2.65\ 10^{-9}$	$2.78\ 10^{-8}$	Infant	$7.20\ 10^{8}$
Te-127m	$1.40\ 10^{-72}$	$5.89\ 10^{-72}$	$9.96\ 10^{-71}$	Infant	$2.01\ 10^{71}$
I-129	$9.23\ 10^{-9}$	$3.17\ 10^{-8}$	$1.83\ 10^{-7}$	Infant	$1.09\ 10^{8}$
Ba-133	$5.10\ 10^{-12}$	$1.77\ 10^{-11}$	$1.02\ 10^{-10}$	Infant	$1.96\ 10^{11}$
Cs-134	$3.97\ 10^{-18}$	$5.43\ 10^{-18}$	$2.52\ 10^{-17}$	Infant	$7.92\ 10^{17}$
Cs-135	$1.85\ 10^{-10}$	$3.00\ 10^{-10}$	$1.93\ 10^{-9}$	Infant	$1.04\ 10^{10}$
Cs-137	$3.47\ 10^{-10}$	$4.97\ 10^{-10}$	$2.60\ 10^{-9}$	Infant	$7.70\ 10^{9}$
Ce-144	$3.81\ 10^{-33}$	$1.37\ 10^{-32}$	$2.28\ 10^{-31}$	Infant	$8.76\ 10^{31}$
Pm-147	$4.20\ 10^{-18}$	$1.37\ 10^{-17}$	$2.07\ 10^{-16}$	Infant	$9.67\ 10^{16}$
Sm-147	$2.34\ 10^{-8}$	$2.66\ 10^{-8}$	$1.28\ 10^{-7}$	Infant	$1.56\ 10^{8}$
Sm-151	$1.02\ 10^{-11}$	$2.51\ 10^{-11}$	$3.39\ 10^{-10}$	Infant	$5.90\ 10^{10}$
Eu-152	$3.03\ 10^{-11}$	$4.65\ 10^{-11}$	$3.14\ 10^{-10}$	Infant	$6.38\ 10^{10}$
Eu-154	$6.05\ 10^{-12}$	$1.04\ 10^{-11}$	$8.44\ 10^{-11}$	Infant	$2.37\ 10^{11}$
Eu-155	$8.42\ 10^{-15}$	$2.25\ 10^{-14}$	$2.99\ 10^{-13}$	Infant	$6.69\ 10^{13}$
Gd-153	$1.50\ 10^{-38}$	$4.32\ 10^{-38}$	$5.51\ 10^{-37}$	Infant	$3.63\ 10^{37}$
Pb-210	$2.73\ 10^{-8}$	$1.18\ 10^{-7}$	$1.59\ 10^{-6}$	Infant	$1.26\ 10^{7}$
Po-210	$2.33\ 10^{-55}$	$9.46\ 10^{-55}$	$1.57\ 10^{-53}$	Infant	$1.27\ 10^{54}$
Ra-226	$2.16\ 10^{-7}$	$8.98\ 10^{-7}$	$1.09\ 10^{-5}$	Infant	$1.84\ 10^{6}$
Ra-228	$1.37\ 10^{-10}$	$6.04\ 10^{-10}$	$4.17\ 10^{-9}$	Infant	$4.80\ 10^{9}$
Ac-227	$1.84\ 10^{-7}$	$2.09\ 10^{-7}$	$6.53\ 10^{-7}$	Infant	$3.06\ 10^{7}$
Th-228	$3.58\ 10^{-17}$	$5.63\ 10^{-17}$	$3.55\ 10^{-16}$	Infant	$5.63\ 10^{16}$
Th-229	$5.63\ 10^{-7}$	$6.44\ 10^{-7}$	$2.25\ 10^{-6}$	Infant	$8.88\ 10^{6}$
Th-230	$2.24\ 10^{-7}$	$2.23\ 10^{-7}$	$7.29\ 10^{-7}$	Infant	$2.74\ 10^{7}$
Th-232	$4.31\ 10^{-7}$	$1.07\ 10^{-6}$	$6.25\ 10^{-6}$	Infant	$3.20\ 10^{6}$

Radionuclide	Adult dose (μSv y^{-1} MBq^{-1})	Child dose (μSv y^{-1} MBq^{-1})	Infant dose (μSv y^{-1} MBq^{-1})	Limiting age group	Scenario radiological capacity (MBq)
Pa-231	1.40 10^{-6}	1.57 10^{-6}	4.95 10^{-6}	Infant	4.04 10^{6}
U-232	1.11 10^{-7}	1.73 10^{-7}	9.44 10^{-7}	Infant	2.12 10^{7}
U-233	2.67 10^{-8}	3.41 10^{-8}	1.45 10^{-7}	Infant	1.38 10^{8}
U-234	2.31 10^{-8}	2.99 10^{-8}	1.23 10^{-7}	Infant	1.62 10^{8}
U-235	2.15 10^{-8}	2.85 10^{-8}	1.25 10^{-7}	Infant	1.60 10^{8}
U-236	2.14 10^{-8}	2.76 10^{-8}	1.22 10^{-7}	Infant	1.64 10^{8}
U-238	2.02 10^{-8}	2.71 10^{-8}	1.34 10^{-7}	Infant	1.50 10^{8}
Np-237	1.10 10^{-7}	9.14 10^{-8}	2.28 10^{-7}	Infant	8.79 10^{7}
Pu-238	1.50 10^{-7}	1.24 10^{-7}	2.68 10^{-7}	Infant	7.47 10^{7}
Pu-239	2.62 10^{-7}	2.19 10^{-7}	4.51 10^{-7}	Infant	4.44 10^{7}
Pu-240	2.60 10^{-7}	2.18 10^{-7}	4.49 10^{-7}	Infant	4.46 10^{7}
Pu-241	6.42 10^{-9}	5.57 10^{-9}	1.21 10^{-8}	Infant	1.66 10^{9}
Pu-242	2.41 10^{-7}	2.18 10^{-7}	4.30 10^{-7}	Infant	4.65 10^{7}
Pu-244	2.43 10^{-7}	2.20 10^{-7}	4.48 10^{-7}	Infant	4.46 10^{7}
Am-241	1.90 10^{-7}	1.65 10^{-7}	3.63 10^{-7}	Infant	5.51 10^{7}
Am-242m	2.65 10^{-7}	2.28 10^{-7}	4.83 10^{-7}	Infant	4.14 10^{7}
Am-243	2.09 10^{-7}	1.82 10^{-7}	3.98 10^{-7}	Infant	5.02 10^{7}
Cm-242	7.64 10^{-10}	6.35 10^{-10}	1.37 10^{-9}	Infant	1.46 10^{10}
Cm-243	3.66 10^{-8}	3.21 10^{-8}	8.48 10^{-8}	Infant	2.36 10^{8}
Cm-244	1.32 10^{-8}	1.18 10^{-8}	3.20 10^{-8}	Infant	6.24 10^{8}
Cm-245	2.20 10^{-7}	1.87 10^{-7}	4.04 10^{-7}	Infant	4.95 10^{7}
Cm-246	2.13 10^{-7}	1.80 10^{-7}	3.96 10^{-7}	Infant	5.05 10^{7}
Cm-248	7.88 10^{-7}	6.78 10^{-7}	1.50 10^{-6}	Infant	1.34 10^{7}

1121. This scenario limits the radiological capacity of 12 radionuclides (Se-79, Sm-151, Ra-228, Ac-227, U-232, Pu-238, Pu-241, Am-241, Am-242m, Cm-242, Cm-243 and Cm-244) and hence doses arising from disposing of the radiological capacity are 20 μSv y^{-1} for these 13 radionuclides. In growth to 20,000 years was also considered using this scenario and the radiological capacities combined to allow for potential ingrowth over that period. This further restricted the radiological capacity of Th-230 (2.03 10^{6} MBq). Table 18 presents the dose rate per MBq (μSv y^{-1} MBq^{-1}) to beach walkers at the time of erosion (60 years after site closure) for the combined scenarios.

1122. The doses to the walker at the time of erosion calculated using illustrative inventories are considered further in Appendix D.

E.4.8. Exposure following site erosion and release of leachate into sea

1123. As discussed in Section E.4.7, it is uncertain whether erosion of the landfill will occur and when it will happen should it occur. This scenario considers exposure from releases of LLW from the eroding site into the marine environment. It is assumed that erosion will occur from the seaward side of the landfill and that contamination will be leached from the landfill materials as they are eroded. It is also assumed that the leached contamination will predominantly enter the sea rather than a confined estuary. Doses relating to eroded landfill material on the beach are addressed in Section E.4.7 and are not addressed here.

1124. The rate at which material is assumed to be eroded is based on the review by Bangor University and the value derived from a regression model for the River Tees Estuary (0.21 m y^{-1}) is used here.

1125. The dose criterion used is a dose of 0.02 mSv y^{-1} for the public (this is equivalent to the risk guidance level of 10^{-6} y^{-1} for exposure of the public post closure, for situations that are expected to occur).

Potentially exposed group

1126. An assessment is made of the doses to a family (member of the public) who spends time on a beach or shore of the sea close to the site at some time in the future. It is assumed that the family fishes and collects seafood from the area, which they consume, receiving an ingestion dose. The family also receives external exposure from beaches and inhalation dose from sea spray. In addition, adults are assumed to receive external exposure from handling fishing equipment.

1127. Habits data for the family are presented in Table 143.

Table 143 Habit data for a fishing family exposed as a result of coastal erosion

Habit data	Adult	Child	Infant
Fish consumption (kg y^{-1})*	100	20	5
Crustacean consumption (kg y^{-1})*	20	5	0
Molluscs consumption (kg y^{-1})*	20	5	0
Occupancy on shore (h y^{-1})	2000	2000	2000
Inhalation rate (m^3 y^{-1})	8100	5600	1900

* 97.5th percentile from (Smith & Jones, 2003)

E.4.8.1. Assessment for coastal erosion dose

1128. Dose to the family from coastal erosion was calculated using PC CREAM 08. A local marine compartment was set up for Port Clarence using the default dimensions, volumetric exchange rate, sediment parameters and dispersion rate for a new local compartment. This was deemed appropriate as it is not possible to tell what shape the coastline or estuary may be following sea level rise and site erosion. The parameters are given in Table 144.

Table 144 Port Clarence Local Marine Compartment Parameters following site erosion

Parameter	Value
Volume (m^3)	$1\ 10^{9}$
Depth (m)	10
Coastline length (m)	$1\ 10^{4}$
Volumetric exchange rate (m^3/y)	$2\ 10^{10}$
Suspended sediment load (t m^{-3})	$1\ 10^{-5}$
Sedimentation rate (t m^2 y^{-1})	$2\ 10^{-4}$
Sediment density (t m^{-3})	2.6
Diffusion rate (m^2 y^{-1})	$3.15\ 10^{-2}$

1129. The DORIS module in PC CREAM was used to calculate activity concentrations in sea water, seabed sediment and seafood assuming a 1 Bq y^{-1} release to the local compartment. This was used as input to the ASSESSOR module of PC CREAM, in which the dose to the fishing family was calculated using habits data as shown in Table 143, also for a 1 Bq y^{-1} release.

1130. It is assumed that erosion starts 60 years after closure, and that the site is eroded at a rate of 0.21 m^3 y^{-1}. As the facility is approximately 900 m in length, it would take about 4,300 y for the whole facility to be eroded. It was assumed that activity is evenly released over this time period.

1131. The assessment considered a constant discharge over a period of 1, 5, 50, 500, 2000 and 4286 years. The approach does not allow for radioactive decay of the source over the release period and, therefore, will result in overestimates of the DPUR for radionuclides with a shorter half-life than the release period. The DPUR is different for the different release periods. We have cautiously selected the maximum DPUR from the six release periods.

1132. The activity of radionuclides and ingrown daughters 60 y after closure, assuming 1 MBq initial inventory, was calculated using the Bateman equations. Any radionuclide or daughter for which the activity remaining was less than 10^{-10} Bq was excluded from further assessment. For the remaining radionuclides, the activity was divided by the erosion period to obtain a yearly release rate for each radionuclide. Doses calculated in PC CREAM (for 1 Bq y^{-1}) were scaled to the calculated yearly release rate to obtain doses from a 1 MBq inventory.

E.4.8.2. Dose to fishing family following erosion of the site and release of leachate to sea

1133. The total dose to a fishing family from ingestion of seafood, external radiation and inhalation of sea spray once erosion of the landfill starts are given in Table 145, respectively. The cut-off of 10^{-13} produces values of zero dose for shorter half-life radionuclides. The highest dose per MBq disposed at Port Clarence following erosion is from Ra-226 (1 10^{-5} µSv y^{-1} MBq^{-1}), and the dose rate from wastes disposed of at Port Clarence will always be lower than this due to application of the sum of fractions approach. This scenario limits the radiological capacity of 5 radionuclides (Nb-94, Sn-126, Eu-152, Pb-210 and Ra-226).

Table 145 Doses to a fishing family after the start of tidal erosion

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Limiting age group	Scenario Radiological Capacity (MBq)*
H-3	3.60 10^{-16}	1.10 10^{-16}	9.77 10^{-18}	Adult	5.55 10^{16}
C-14	6.62 10^{-9}	2.18 10^{-9}	1.85 10^{-10}	Adult	3.02 10^{9}
Cl-36	7.00 10^{-14}	4.95 10^{-14}	3.79 10^{-14}	Adult	2.86 10^{14}
Ca-41	7.45 10^{-13}	6.21 10^{-13}	4.38 10^{-13}	Adult	2.68 10^{13}
Mn-54	0	0	0		nd
Fe-55	3.08 10^{-16}	2.57 10^{-16}	4.18 10^{-18}	Adult	6.49 10^{16}
Co-60	2.14 10^{-11}	2.10 10^{-11}	2.04 10^{-11}	Adult	9.34 10^{11}
Ni-59	2.67 10^{-10}	2.51 10^{-10}	2.41 10^{-10}	Adult	7.48 10^{10}
Ni-63	3.53 10^{-11}	1.60 10^{-11}	1.43 10^{-12}	Adult	5.66 10^{11}
Zn-65	0	0	0		nd
Se-79	9.42 10^{-9}	1.09 10^{-8}	9.87 10^{-10}	Child	1.84 10^{9}
Sr-90	2.13 10^{-11}	1.71 10^{-11}	1.42 10^{-11}	Adult	9.40 10^{11}
Mo-93	7.02 10^{-10}	6.68 10^{-10}	6.54 10^{-10}	Adult	2.85 10^{10}
Zr-93	4.45 10^{-10}	3.43 10^{-10}	3.25 10^{-10}	Adult	4.49 10^{10}
Nb-93m	7.70 10^{-12}	7.52 10^{-12}	7.39 10^{-12}	Adult	2.60 10^{12}

Radionuclide	Adult dose (µSv y^{-1} MBq^{-1})	Child dose (µSv y^{-1} MBq^{-1})	Infant dose (µSv y^{-1} MBq^{-1})	Limiting age group	Scenario Radiological Capacity (MBq)*
Nb-94	2.55 10^{-7}	2.52 10^{-7}	2.52 10^{-7}	Adult	7.83 10^{7}
Tc-99	3.02 10^{-10}	1.53 10^{-10}	1.29 10^{-12}	Adult	6.63 10^{10}
Ru-106	0	0	0		nd
Ag-108m	1.01 10^{-8}	6.11 10^{-9}	2.74 10^{-9}	Adult	1.99 10^{9}
Ag-110m	0	0	0		nd
Cd-109	1.48 10^{-22}	6.33 10^{-23}	4.87 10^{-24}	Adult	1.35 10^{23}
Sb-125	2.10 10^{-16}	1.32 10^{-16}	6.51 10^{-17}	Adult	9.54 10^{16}
Sn-119m	0	0	0		nd
Sn-123	0	0	0		nd
Sn-126	1.46 10^{-7}	7.72 10^{-8}	1.80 10^{-8}	Adult	1.37 10^{8}
Te-127m	0	0	0		nd
I-129	6.45 10^{-10}	2.68 10^{-10}	1.42 10^{-11}	Adult	3.10 10^{10}
Ba-133	3.37 10^{-11}	3.33 10^{-11}	3.32 10^{-11}	Adult	5.93 10^{11}
Cs-134	3.08 10^{-18}	2.39 10^{-18}	2.27 10^{-18}	Adult	6.50 10^{18}
Cs-135	5.72 10^{-11}	1.32 10^{-11}	4.82 10^{-12}	Adult	3.49 10^{11}
Cs-137	7.23 10^{-10}	6.48 10^{-10}	6.35 10^{-10}	Adult	2.77 10^{10}
Ce-144	0	0	0		nd
Pm-147	4.09 10^{-16}	1.33 10^{-16}	3.39 10^{-18}	Adult	4.89 10^{16}
Sm-147	3.12 10^{-9}	1.01 10^{-9}	1.85 10^{-11}	Adult	6.40 10^{9}
Sm-151	4.47 10^{-12}	2.82 10^{-12}	1.18 10^{-12}	Adult	4.47 10^{12}
Eu-152	2.99 10^{-9}	2.77 10^{-9}	2.68 10^{-9}	Adult	6.69 10^{9}
Eu-154	3.73 10^{-10}	3.68 10^{-10}	3.66 10^{-10}	Adult	5.36 10^{10}
Eu-155	2.29 10^{-13}	2.21 10^{-13}	2.16 10^{-13}	Adult	8.75 10^{13}
Gd-153	0	0	0		nd
Pb-210	2.55 10^{-6}	1.35 10^{-6}	1.33 10^{-7}	Adult	7.84 10^{6}
Po-210	0	0	0		nd
Ra-226	1.44 10^{-5}	7.63 10^{-6}	7.66 10^{-7}	Adult	1.39 10^{6}
Ra-228	1.48 10^{-10}	1.98 10^{-10}	1.64 10^{-11}	Child	1.01 10^{11}
Ac-227	1.17 10^{-8}	1.05 10^{-8}	5.32 10^{-9}	Adult	1.71 10^{9}
Th-228	2.11 10^{-18}	1.86 10^{-18}	1.39 10^{-18}	Adult	9.48 10^{18}
Th-229	7.15 10^{-8}	6.18 10^{-8}	5.81 10^{-8}	Adult	2.80 10^{8}
Th-230	4.08 10^{-7}	2.17 10^{-7}	2.59 10^{-8}	Adult	4.91 10^{7}
Th-232	5.80 10^{-7}	7.15 10^{-7}	2.06 10^{-7}	Child	2.80 10^{7}
Pa-231	1.53 10^{-7}	1.37 10^{-7}	8.60 10^{-8}	Adult	1.31 10^{8}
U-232	5.31 10^{-9}	3.96 10^{-9}	2.49 10^{-9}	Adult	3.76 10^{9}
U-233	8.94 10^{-10}	5.42 10^{-10}	3.39 10^{-10}	Adult	2.24 10^{10}
U-234	6.29 10^{-10}	2.66 10^{-10}	1.79 10^{-11}	Adult	3.18 10^{10}
U-235	9.86 10^{-10}	6.85 10^{-10}	4.68 10^{-10}	Adult	2.03 10^{10}
U-236	4.47 10^{-10}	1.70 10^{-10}	5.91 10^{-12}	Adult	4.48 10^{10}
U-238	5.43 10^{-10}	2.73 10^{-10}	1.14 10^{-10}	Adult	3.69 10^{10}
Np-237	1.34 10^{-8}	3.71 10^{-9}	5.15 10^{-10}	Adult	1.50 10^{9}
Pu-238	4.71 10^{-8}	1.22 10^{-8}	7.23 10^{-11}	Adult	4.25 10^{8}
Pu-239	9.04 10^{-8}	2.43 10^{-8}	1.38 10^{-10}	Adult	2.21 10^{8}
Pu-240	8.99 10^{-8}	2.43 10^{-8}	3.03 10^{-10}	Adult	2.22 10^{8}
Pu-241	1.38 10^{-9}	4.56 10^{-10}	1.10 10^{-10}	Adult	1.45 10^{10}
Pu-242	8.69 10^{-8}	2.36 10^{-8}	2.70 10^{-10}	Adult	2.30 10^{8}
Pu-244	1.25 10^{-7}	6.04 10^{-8}	3.69 10^{-8}	Adult	1.60 10^{8}
Am-241	3.98 10^{-8}	1.33 10^{-8}	3.30 10^{-9}	Adult	5.03 10^{8}
Am-242m	6.16 10^{-8}	1.92 10^{-8}	3.57 10^{-9}	Adult	3.25 10^{8}
Am-243	8.46 10^{-8}	5.34 10^{-8}	4.20 10^{-8}	Adult	2.36 10^{8}
Cm-242	2.40 10^{-10}	6.25 10^{-11}	3.69 10^{-13}	Adult	8.32 10^{10}
Cm-243	1.06 10^{-8}	4.89 10^{-9}	2.81 10^{-9}	Adult	1.88 10^{9}

Radionuclide	Adult dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Child dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Infant dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Limiting age group	Scenario Radiological Capacity (MBq)*
Cm-244	$2.58\ 10^{-9}$	$7.47\ 10^{-10}$	$2.56\ 10^{-12}$	Adult	$7.76\ 10^{9}$
Cm-245	$8.87\ 10^{-8}$	$3.71\ 10^{-8}$	$1.78\ 10^{-8}$	Adult	$2.25\ 10^{8}$
Cm-246	$6.45\ 10^{-8}$	$1.71\ 10^{-8}$	$2.80\ 10^{-10}$	Adult	$3.10\ 10^{8}$
Cm-248	$2.40\ 10^{-7}$	$6.53\ 10^{-8}$	$2.46\ 10^{-10}$	Adult	$8.33\ 10^{7}$

* Where dose is effectively zero the radiological capacity is infinite, marked here as nd (not determined).

1134. The doses calculated using illustrative inventories are considered further in Appendix D.

E.5. Human intrusion scenarios {R7}

1135. After the end of active management control of the site, it is assumed that use of the site eventually becomes unrestricted and that either intentional or unintentional intrusion through the landfill cap may occur, leading to members of potential exposure groups receiving radiation doses as a consequence of access to waste. In reality, it is likely that knowledge about the site would be retained and planning controls would continue to apply for decades. Redevelopment of the site in an absence of knowledge about its contents is not likely for a long time after the end of the period of authorisation.

1136. A review of both intentional and unintentional intrusion scenarios, and on-site or near-site occupancy scenarios, identified in generic guidance or in previous publicly available ESCs [(IAEA, 2004), (UK Environment Agencies, 2009), (Environment Agency, 2012), (Environment Agency, 2022), (Eden NE, 2023)] has identified four potential intrusion scenarios and six potentially exposed groups likely to be of relevance to Port Clarence. Environment Agency feedback recommended consideration of two additional intrusion scenarios (a scavenger and material recovery). The identified cases are believed to represent the most likely and relevant modes of human intrusion (i.e. they possess the potential to directly excavate the disposed wastes or damage the engineered cap).

1137. The active management phase is assumed to last for 60 years after closure. After this the following human intrusion scenarios and exposed groups are considered in the ESC:

- Borehole drilling: dose to worker;
- Trial pit excavation: dose to worker;
- Scavenger on eroding site: dose to worker;
- Material recovery on eroding site: dose to worker;
- Excavation for housing or road:
    - Dose to worker during excavation;
    - Dose to resident on the site;
    - Radon exposure of resident; and

- Small holder excavating on the site: dose to smallholder.

1138. Dose to a laboratory analyst working with borehole or trial pit samples has not been included in the assessment. Doses to this exposed group in the ENRMF ESC (Eden NE, 2023) were lower than for other exposed groups for all radionuclides, so it was deemed unnecessary to assess this exposed group for Port Clarence.

1139. In Table 146 descriptions of these human intrusion cases based on LLWR assessments (Hicks & Baldwin, 2011) are presented.

Table 146 Human intrusion events

Event/scenario	Summary
Borehole drilling	Could be undertaken as part of geotechnical investigations. The cap and profile materials above the waste would reduce the potential for intrusion into the waste, although boreholes will fully penetrate waste, if drilled into waste cell. Laboratory analysis of contaminated soil samples is also considered within the assessment. Those involved in the intrusion (i.e. drill operatives and laboratory analyst) are assumed to be exposed to the hazard.
Trial pit excavation	Could be undertaken as part of geotechnical investigations. Has the potential to disturb waste, if undertaken into a waste cell. Trial pit excavators are assumed to be exposed to the hazard.
Residential occupant (intact cap)	A housing development is positioned over the landfill. Buildings constructed using ‘floating’ foundations will not penetrate the cap.
Excavation for housing/road	Construction activities for housing developments would include shallow excavations and cap disturbance to prepare the site and install roads and services. Foundations for domestic and light buildings, typically 1 or 2 m deep have the potential to penetrate the engineered cap, particularly, if domestic buildings include cellars. There is also the possibility of building directly upon a waste/spoil mix (i.e. the cap has been destroyed as part of the intrusion event). Those involved in the excavation work would be exposed to the hazard, as would (in the long term) site occupants. Both are considered within the (radon) human intrusion assessment. Subsequent occupation of the site is assumed to be residential, not small holding.
Scavenger	An informal scavenger may comprise individuals or small groups of people scavenging items using hand tools. This could involve a dig into the side of an eroding bank with hand tools or simple scavenging from tide washed land. The exposure pathways would include: external doses from being close to exposed waste (both whilst excavating and at home, if any objects are taken home), inhalation of contaminated dusts and inadvertent ingestion of contaminated material.

Event/scenario	Summary
Material recovery	Small groups of local people or contractors may excavate the waste using hand tools once the site starts to erode, portable mechanical equipment or small diggers. A worker may be exposed to radioactivity as a result of inhalation of contaminated dust particles, ingestion of contaminated materials and external irradiation from exposed waste. This scenario considers recovered material that may be suitable for use as hardcore/ballast (e.g. for construction).
Smallholding	Construction/agricultural activities could result in contaminated material left at the surface. A smallholding is more cautious than a farm, as it allows crops to be grown on a more concentrated activity source.

1140. The impact assessment undertaken on behalf of the LLWR (LLWR Ltd, 2011c) suggests that house occupancy and a smallholding on-site are likely to offer the highest doses to exposed persons, followed by the borehole driller/housing construction worker. Although there are marked differences between the disposal facilities and the waste inventories, these potentially exposed groups are also likely to represent the limiting intrusion cases for Port Clarence in this assessment.

1141. Exposure to the borehole driller and the excavation worker is considered as a result of external irradiation, inhalation of dust and inadvertent ingestion of dust. Removal of material from the site by an informal scavenger or larger amounts by a material recovery worker considers the same pathways but includes exposure to material removed to an off-site location.

1142. Radiation doses to the resident and smallholder are considered to arise as a result of external irradiation, inhalation of dust and radon gas, inadvertent ingestion of dust and the ingestion of home produced food. The assumptions concerning the resident and smallholder scenarios differ in several ways, including: the quantity of excavated waste and the habit data.

1143. The dose implications of excavation of waste materials that consist of different sized objects are also considered by assessing the dose to a worker or site occupant. Further details are given in Section E.6.

1144. A site re-engineering/remediation scenario was included in the SNIFFER methodology to cover the situation where a site operator has no records of radioactive waste disposals or their location and excavates waste during final site restoration works. In the case of the Port Clarence site, which comprises a hazardous waste landfill alongside a non-hazardous waste landfill, records would be maintained as a condition of the LLW Permit. Any remediation work would be done with the knowledge that there was radioactive material on the site and it can be assumed that appropriate precautions against exposure would be adopted. Site rules also prevent any disposal of radioactive waste within 2 m of the landfill perimeter and basal liners and within 1 m of the top of the cell.

1145. Future removal of a part of a site as part of a major road construction project has been considered in some assessments (IAEA, 2003) and although this is considered to be extremely unlikely for the Port Clarence location, the dose to a road constructor is considered (Section E.5.4) and the dose to a resident on spoil would be covered by the site resident (Section E.5.8).

1146. The dose guidance level (human intrusion) is 3 mSv y^{-1} to around 20 mSv y^{-1}, depending on the duration of exposure, and this is applied to all intrusion scenarios for both the public and workers. In Table 147 the conceptual models and relevant exposure pathways considered in this ESC for each of the human intrusion cases are summarised. The radiological impact of each of these intrusion cases has been estimated using the approaches described in Sections E.5.2 to E.5.10.

Table 147 Summary of human intrusion cases and exposure pathways

Event/scenario	Exposure pathway	Description
Borehole drilling: operative	Inhalation of contaminated dust	Dust generated by borehole intrusion into waste includes radioactive material. Operative inhales dust during drilling activities.
	Ingestion of contaminated material	Operative ingests contaminated material during drilling activities.
	External irradiation	Contaminated material is left on the ground during drilling activities. A worker in close proximity to this material is exposed to external irradiation and dust on skin.
Trial pit excavation	Inhalation of contaminated dust	Dust generated by trial pit intrusion into waste includes radioactive material. Operative inhales dust during excavation activities.
	Ingestion of contaminated material	Operative ingests contaminated material during excavation activities.
	External irradiation	Contaminated material is left on the ground during excavation activities. A worker in close proximity to this material is exposed to external irradiation and dust on skin.
Excavation for housing/road: excavator	Inhalation of contaminated dust	Excavations into waste generate dust including radioactive material. Worker inhales dust during excavation activities.
	Ingestion of contaminated material	Operative ingests contaminated material during excavation activities.
	External irradiation	Contaminated material is left on the ground during excavation activities. A worker in close proximity to this material is exposed to external irradiation and dust on skin.
Residential occupant (intact cap)	Gas (including radon) inhalation	The house occupant is exposed to gases emanating from contaminated material beneath the house.
	External irradiation	The house is built above the intact cap. As a result, a site occupant is exposed to external irradiation while indoors and outside. The concrete floor of the house provides some shielding from gamma radiation.

Event/scenario	Exposure pathway	Description
Scavenger	Inhalation of contaminated dust	At the time the site is being revealed by coastal erosion, a scavenger collects material from the site. While on site, the scavenger inhales contaminated dust.
	Ingestion of contaminated material	Scavenger ingests contaminated material during these activities.
	External irradiation	Contaminated material is present on the ground, a scavenger in close proximity to this material is exposed to external irradiation and dust on skin. The scavenger is exposed to external irradiation while in proximity to wastes revealed by erosion.
	Retrieved object	The scavenger is periodically exposed to external irradiation from items recovered from the site and kept at home.
Material recovery	Inhalation of contaminated dust	At the time the site is being revealed by coastal erosion, materials are targeted for organised recovery. While on site, a worker inhales contaminated dust.
	Ingestion of contaminated material	Operative ingests contaminated material during these activities.
	External irradiation	Contaminated material is uncovered and left on the ground during recovery activities. A worker in close proximity to this material is exposed to external irradiation and dust on skin.
	Recovered materials	Material is used in construction of the workers house (external irradiation) and landscaping (external irradiation and inhalation/ingestion).
Excavation for housing/road: long-term residential occupant	Inhalation of contaminated dust	Contaminated material is left on the ground at the site after construction of a housing development. Wind action generates contaminated dust and a site occupant is exposed to the dust while outside.
	Ingestion of contaminated material	While outside (e.g. gardening), a site occupant ingests contaminated material (e.g. through hand-to-mouth contact and licking of the lips). Ingestion of contaminated vegetables grown on the site is also considered.
	External irradiation	The house is built on contaminated ground and contaminated material is present in garden soil. As a result, a site occupant is exposed to external irradiation while indoors and outside. The concrete floor of the house provides some shielding from gamma radiation.
	Gas (including Radon) inhalation	The house occupant is exposed to gases emanating from contaminated material beneath the house.

Event/scenario	Exposure pathway	Description
Smallholding	Inhalation of contaminated dust	Contaminated material is left on the ground at the site after site excavation. Wind action generates contaminated dust and a site occupant is exposed to the dust while outside.
	Ingestion of contaminated material	The smallholder ingests contaminated foodstuffs as a result of growing crops and keeping animals on the site. The smallholder also inadvertently ingests contaminated soil while working outside.
	External irradiation	The house is built on contaminated ground and contaminated material is present in garden soil. As a result, a site occupant is exposed to external irradiation while indoors and outside. The concrete floor of the house provides some shielding from gamma radiation.
	Gas (including Radon) inhalation	The house occupant is exposed to gases emanating from contaminated material beneath the house.

E.5.1. Presentation of results of dose assessments

1147. The radiological capacity (MBq) for individual radionuclides present in the LLW is obtained from the results of the assessments carried out and reported in the ESC and depends on the radiological characteristics of the radionuclide. The radiological capacity is calculated on the basis that the LLW only contains this one radionuclide and disposal of that amount of radioactivity would produce a dose or risk equal to the limiting criteria applicable to the scenario. Each scenario therefore generates a scenario radiological capacity for an individual radionuclide. The sum of fractions is applied to each scenario radiological capacity in turn.

1148. The results of the assessments of human intrusion that could impact the radiological capacity are presented as effective doses per MBq disposed (mSv y^{-1} MBq $^{-1}$ or µSv y^{-1} MBq $^{-1}$). The results presented in Sections E.5.2 to E.5.10 also show the scenario radiological capacity (MBq) for each radionuclide. Actual waste disposal will be controlled using a sum of fractions approach (see paragraphs 56 and 511).

1149. Estimates of radiological impact based on 'illustrative inventories' for waste streams that might be typical of those contributing to the total impact from disposals at the facility have been produced. These estimates are presented in Appendix D.

E.5.2. Borehole drilling – Drill Operative

E.5.2.1. Estimating activity concentration in waste for exposure calculations

1150. The initial radioactive inventory evolves with time as radionuclides decay and as they are slowly released from the waste cell (i.e. seepage through the sealing layer and the barrier). Consequently, the activity at time *t*, $A_{Rn}(t)$, is given (after site closure) in SNIFFER (SNIFFER, 2006):

$$A_{Rn}(t) = e^{-\left(\lambda_{Rn}+\lambda_{waste,after}^{Rn}\right)(t-t_{op})} A_{Rn,initial} e^{-\left(\lambda_{Rn}+\lambda_{waste,before}^{Rn}\right)t_{op}}$$

$$\lambda_{waste,before}^{Rn} = \frac{q_{out}}{V_{landfill}\left(\varphi_{waste}\varepsilon + \rho_{waste}K_{d,waste}^{Rn}\right)}$$

$$\lambda_{waste,after}^{Rn} = \frac{q_{barrier}}{V_{landfill}\left(\varphi_{waste}\varepsilon + \rho_{waste}K_{d,waste}^{Rn}\right)}$$

where:

- A_{Rn} is the activity in a waste cell after site closure (Bq);
- q_{out} is the volume of water flowing through the liner before closure (m^3 y^{-1});
- $V_{landfill}$ is the volume of the waste (m^3);
- φ_{waste} is the porosity of the waste;
- ε is the degree of saturation of the waste;
- ρ_{waste} is the bulk density of the waste (kg m^{-3});
- $K_{d,waste}^{Rn}$ is the distribution coefficient for radionuclide *Rn* in the waste (m^3 kg^{-1}) ;
- λ_{Rn} is the decay constant of radionuclide *Rn* (y^{-1});
- t_{op} is the time that the landfill is operational (taken to be 0 years);
- $A_{Rn,initial}$ is the initial inventory of radionuclide *Rn;* and,
- $q_{barrier}$ is the volume of water flowing out of the landfill into the geological barrier after closure (m^3 y^{-1}).

1151. The waste density and porosity are given in Table 130. The time that the landfill is operational is assumed to be zero years so that no depletion of the inventory in the landfill during the operational period is allowed for. This will produce an overestimate of the inventory in the landfill site at the time of intrusion.

1152. Seepage through a geomembrane sealing layer is dominated by flow through defects (holes) in the liner, SNIFFER (SNIFFER, 2006). The flow is given by an empirical formula:

$$q_{out} = c \cdot a_{Defect}^{0.1} \cdot h^{0.9} \cdot K_{Barrier}^{0.74} \cdot 3.16E + 07$$

where:

- q_{out} is the flow out of the compartment (m^3 s^{-1});
- c is a constant depending on the contact between the liner and the material below;
- a_{Defect} is the area of the defects (m^2);
- h is the head of leachate (m);
- $K_{barrier}$ is the hydraulic conductivity of the barrier (m s^{-1}); and,

- 3.16E+07 is the number of seconds in a year (s y^{-1}).

1153. Assumptions regarding the liner are given in Table 130. During the landfill's operational period, $q_{barrier}$ is set equal to q_{out}.

1154. After closure of the landfill, $q_{barrier}$ is set to be:

$$min(q_{inf}, a_{landfill}K_{barrier})$$

where:

- $q_{barrier}$ is the flow rate through the barrier (m^3 s^{-1});
- $a_{landfill}$ is the surface area of the landfill (m^2); and,
- q_{inf} is the infiltration volume into the landfill, given by:

$$q_{inf} = P_{eff} \cdot a_{landfill}$$

and,

$$P_{eff} = (P_{total} - AE - runoff)\left[1 - E_0\left(1 - \frac{t}{t_f}\right)\right] for\ t \leq t_f$$

where:

- P_{eff} is the rate of water infiltration through the cap of the landfill (m y^{-1});
- P_{total} is the total precipitation (m y^{-1});
- AE is the amount of precipitation lost to evapotranspiration (m y^{-1});
- $runoff$ is the amount of precipitation lost by runoff (m y^{-1});
- E_0 is the initial cap efficiency;
- t is the time after closure (y); and,
- t_f is the time of cap failure (y).

E.5.2.2. Assessment calculations for Drill Operative

External irradiation, inhalation and ingestion

1155. The drill operative receives a dose (Sv y^{-1}) from external irradiation, inhalation and ingestion (SNIFFER, 2006):

$$Dose_{excavator} = \left(\frac{D_{irr,slab}^{Rn}}{8766}\right)TC_{Rn,waste}(t) + D_{inh}^{Rn}TBM_{inh}C_{Rn,waste}(t)$$

$$+ D_{ing}^{Rn}TM_{ing}C_{Rn,waste}(t)$$

$$C_{Rn,waste}(t) = \frac{A_{Rn}(t)}{V_{landfill}\rho_{waste}}$$

where:

- $Dose_{excavator}$ is the dose to the drill operative from external irradiation, inhalation and ingestion (Sv y^{-1});
- M_{inh} is the dust loading of contaminated waste inhaled by the excavator (kg m^{-3});
- M_{ing} is the rate of ingestion of dust from the material (kg h^{-1});
- T is the time that the excavator is exposed to the material (h y^{-1});
- B is the breathing rate (m^3 h^{-1});
- $D_{irr,slab}^{Rn}$, D_{inh}^{Rn} and D_{ing}^{Rn} are the dose coefficients for radionuclide *Rn* (Sv y^{-1} Bq^{-1} kg; Sv Bq^{-1}; and Sv Bq^{-1}, respectively), see Table 225 and Table 227;
- 8766 is the number of hours in a year (h y^{-1});
- $C_{Rn,waste}(t)$ is the activity concentration of radionuclide *Rn* (Bq kg^{-1}) in the waste at time of excavation, *t*:
- $V_{landfill}$ is the volume of the landfill in which the activity is assumed to be concentrated (m^3); and,
- ρ_{waste} is the density of the waste (kg m^{-3}).

Hands and face

1156. While the exposure to external irradiation is assumed to arise from proximity to a semi-infinite slab of contaminated material, there is also a possibility of a dose arising from direct contact with contaminated waste dust on the hands and face.

1157. For the hands, the dose (Sv y^{-1}) is given by:

$$Dose_{skin,hands} = \left(\frac{C_{Rn,waste}(t) d_{hands} \rho_{waste}}{10^4}\right)\left(D_{gamma7}^{Rn} + D_{beta40}^{Rn}\right) W_{skin} T \frac{Area_{hands}}{Area_{body}}$$

where:

- $Dose_{skin,hands}$ is the dose to the hands of the drill operative (Sv y^{-1});
- D_{gamma7}^{Rn} is the skin equivalent dose rate for radionuclide *Rn* to the basal layer of the skin epidermis for gamma irradiation (Sv h^{-1} Bq^{-1} cm^2), see Table 227;
- D_{beta40}^{Rn} is the skin equivalent dose rate for radionuclide *Rn* to the basal layer of the skin epidermis for beta irradiation of the hand, skin thickness 400 µm (40 mg cm^{-2}), (Sv h^{-1} Bq^{-1} cm^2), see Table 227;
- 10^4 converts Bq m^{-2} to Bq cm^{-2};
- d_{hands} is the thickness of the contaminated layer on the hands (m);
- W_{skin} is the tissue weighting factor for skin;
- $Area_{hands}$ is the area of skin in contact with contaminated material (cm^2); and,

- $Area_{body}$ is the total UV exposed skin area of the adult body (cm²).

1158. For the face, the dose (Sv y⁻¹) is given by:

$$Dose_{skin,face} = \left(\frac{C_{Rn,waste}(t)d_{face}\rho_{waste}}{10^4}\right)\left(D_{gamma7}^{Rn} + D_{beta4}^{Rn}\right)W_{skin}T\frac{Area_{face}}{Area_{body}}$$

where; the meaning of the symbols is a direct substitution of *face* for *hands* and beta doses to the face assume a skin depth of 40 µm.

1159. Whilst acknowledging that the ICRP reference anatomical recommendations in ICRP 89 and averaging area and depth discussed in ICRP 103, to derive dose limits for skin (paragraph B 207), that both suggest using a skin depth of 70 µm. Our approach in the ESC is the same as that used in SNIFFER and applies dose conversion factors for skin depths of 40 µm (beta exposure of face), 70 µm (gamma exposure) and 400 µm (beta exposure of hands).

1160. The availability of dose conversion datasets for all the radionuclides considered in the ESC is limited. Whilst data sheets for 35 of the radionuclides considered at Port Clarence are available to 70 µm (Delacroix, et al., 2002), the data presented in RP65 provides better coverage (European Commission, 1993). The methodology adopted in SNIFFER considers beta doses to the face and hands where skin depth is assumed to be 40 µm and 400 µm, respectively, and draws on the RP65 dataset. For comparable radionuclides, the 40 µm dose coefficients for beta emitters are more cautious that those produced for a skin depth of 70 µm. The beta dose at 70 µm depth is less than the beta dose at 40 µm depth because the beta radiation has travelled through a greater thickness of skin and hence the attenuation is greater. This is illustrated in Table 81 of reference (Oatway, et al., 2011), which gives calculated dose rates at skin depths of 40 µm, 70 µm and 350 µm depths for a number of beta-rich particles. Oatway et al. also state that 'skin dose rates from beta rich-particles are not strongly dependent on skin depth; the dose rates calculated for a skin depth of 40 µm are about 16% higher than the 70 µm dose rates…'. Use of data for a skin depth of 40 µm as a surrogate for the dose rate at a skin depth of 70 µm is therefore cautious for beta-rich particles and it is assumed it is also cautious for dust.

1161. Note that Borehole driller assessment calculation is cautious as no account is taken of non-contaminated cap material that is also be excavated and becomes mixed with the radioactive material, resulting in dilution.

Table 148 Parameters used for the borehole excavation scenario

Parameter	Units	Value*	Description
M_{inh}	kg m⁻³	6 10⁻⁷	Dust load of contaminated waste inhaled by the excavator, value taken from (Hicks & Baldwin, 2011)
M_{ing}	kg h⁻¹	1.25 10⁻⁵	Rate of ingestion of dust from excavated material, values from (US EPA, 2014)
T	h y⁻¹	16	Time the excavator is exposed to excavated material (per event)
B	m³ h⁻¹	1.69	Worker breathing rate based on ICRP 66 (ICRP, 1994), see Table 73 for derivation
$V_{landfill}$	m³	See Table 67	Volume of landfill (cells) in which activity is homogeneously distributed

Parameter	Units	Value*	Description
ρ_{waste}	kg m^{-3}	See Table 160	Waste density
d_{hands}	M	1.0 10^{-4}	Thickness of the contaminated layer on the hands
W_{skin}		1 10^{-2}	Tissue weighting factor for skin
$Area_{hands}$	cm^2	2 10^2	Area of skin in contact with contaminated dust
$Area_{body}$	cm^2	3 10^3	Area of skin exposed to UK
d_{face}	M	5.0 10^{-5}	Thickness of the contaminated layer on the face
$Area_{face}$	cm^2	1 10^2	Area of skin in contact with contaminated dust
$V_{excavate}$	m^3	0.5	Volume of excavated material per event

Values taken from (Augean, 2009a), unless otherwise stated.

1162. The calculations for a borehole drill operative assume that a single drilling engineer is involved in 5 borehole excavations (Hicks & Baldwin, 2011), i.e. the potential dose arising from 5 intrusion events is calculated.

E.5.2.3. Dose to Borehole Drill Operative on-site 60 years after closure

1163. In Table 149 the dose rates to borehole drill operatives (mSv y^{-1} MBq^{-1}) involved in excavating waste at Port Clarence 60 years after capping are presented. The 60 years after capping is immediately at the end of the period of authorisation.

1164. The largest dose rates per MBq disposal are for Ra-226, Pa-231, Th-232, U-232 and Cm-248. These radionuclides will correspondingly have the smallest radiological capacities under this scenario. No Ra-226 emplacement depth restrictions are assumed in the calculation of the doses to the borehole drill operative.

Table 149 Dose to Borehole Drill Operative excavating at the site

Radionuclide	Dose to Borehole drill operative (60y) (mSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)
H-3	4.32 10^{-16}	6.94 10^{15}
C-14	3.70 10^{-12}	8.10 10^{11}
Cl-36	4.68 10^{-11}	6.41 10^{10}
Ca-41	4.66 10^{-14}	6.44 10^{13}
Mn-54	2.10 10^{-30}	1.43 10^{30}
Fe-55	2.34 10^{-20}	1.28 10^{20}
Co-60	3.39 10^{-12}	8.84 10^{11}
Ni-59	8.69 10^{-14}	3.45 10^{13}
Ni-63	3.35 10^{-13}	8.94 10^{12}
Zn-65	1.85 10^{-36}	1.62 10^{36}
Se-79	4.67 10^{-12}	6.42 10^{11}
Sr-90	6.79 10^{-11}	4.42 10^{10}
Mo-93	9.31 10^{-13}	3.22 10^{12}
Zr-93	1.27 10^{-12}	2.37 10^{12}
Nb-93m	7.20 10^{-15}	4.17 10^{14}
Nb-94	5.28 10^{-9}	5.68 10^{8}
Tc-99	1.16 10^{-11}	2.60 10^{11}
Ru-106	2.46 10^{-27}	1.22 10^{27}

Radionuclide	Dose to Borehole drill operative (60y) (mSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)
Ag-108m	$4.74\ 10^{-9}$	$6.33\ 10^{8}$
Ag-110m	$3.74\ 10^{-35}$	$8.03\ 10^{34}$
Cd-109	$3.86\ 10^{-26}$	$7.77\ 10^{25}$
Sb-125	$3.84\ 10^{-16}$	$7.81\ 10^{15}$
Sn-119m	$4.42\ 10^{-35}$	$6.79\ 10^{34}$
Sn-123	$1.20\ 10^{-61}$	$2.50\ 10^{61}$
Sn-126	$6.59\ 10^{-9}$	$4.55\ 10^{8}$
Te-127m	$2.60\ 10^{-74}$	$1.15\ 10^{74}$
I-129	$3.44\ 10^{-11}$	$8.72\ 10^{10}$
Ba-133	$2.03\ 10^{-11}$	$1.48\ 10^{11}$
Cs-134	$9.36\ 10^{-18}$	$3.21\ 10^{17}$
Cs-135	$9.90\ 10^{-12}$	$3.03\ 10^{11}$
Cs-137	$4.76\ 10^{-10}$	$6.31\ 10^{9}$
Ce-144	$3.43\ 10^{-34}$	$8.75\ 10^{33}$
Pm-147	$7.14\ 10^{-19}$	$4.20\ 10^{18}$
Sm-147	$1.88\ 10^{-10}$	$1.59\ 10^{10}$
Sm-151	$4.44\ 10^{-13}$	$6.76\ 10^{12}$
Eu-152	$1.84\ 10^{-10}$	$1.63\ 10^{10}$
Eu-154	$3.41\ 10^{-11}$	$8.79\ 10^{10}$
Eu-155	$1.67\ 10^{-14}$	$1.79\ 10^{14}$
Gd-153	$4.69\ 10^{-38}$	$6.40\ 10^{37}$
Pb-210	$1.06\ 10^{-10}$	$2.82\ 10^{10}$
Po-210	$7.56\ 10^{-58}$	$3.97\ 10^{57}$
Ra-226	$1.70\ 10^{-8}$	$1.77\ 10^{8}$
Ra-228	$7.14\ 10^{-12}$	$4.20\ 10^{11}$
Ac-227	$1.78\ 10^{-9}$	$1.69\ 10^{9}$
Th-228	$2.29\ 10^{-18}$	$1.31\ 10^{18}$
Th-229	$5.81\ 10^{-9}$	$5.16\ 10^{8}$
Th-230	$2.34\ 10^{-9}$	$1.28\ 10^{9}$
Th-232	$1.20\ 10^{-8}$	$2.51\ 10^{8}$
Pa-231	$1.31\ 10^{-8}$	$2.30\ 10^{8}$
U-232	$8.45\ 10^{-9}$	$3.55\ 10^{8}$
U-233	$2.22\ 10^{-10}$	$1.35\ 10^{10}$
U-234	$1.86\ 10^{-10}$	$1.61\ 10^{10}$
U-235	$6.14\ 10^{-10}$	$4.89\ 10^{9}$
U-236	$1.71\ 10^{-10}$	$1.75\ 10^{10}$
U-238	$4.47\ 10^{-10}$	$6.71\ 10^{9}$
Np-237	$1.59\ 10^{-9}$	$1.89\ 10^{9}$
Pu-238	$1.30\ 10^{-9}$	$2.31\ 10^{9}$
Pu-239	$2.27\ 10^{-9}$	$1.32\ 10^{9}$
Pu-240	$2.26\ 10^{-9}$	$1.33\ 10^{9}$
Pu-241	$5.64\ 10^{-11}$	$5.32\ 10^{10}$
Pu-242	$2.09\ 10^{-9}$	$1.44\ 10^{9}$
Pu-244	$3.40\ 10^{-9}$	$8.82\ 10^{8}$
Am-241	$1.67\ 10^{-9}$	$1.79\ 10^{9}$
Am-242m	$2.35\ 10^{-9}$	$1.28\ 10^{9}$
Am-243	$2.33\ 10^{-9}$	$1.29\ 10^{9}$
Cm-242	$6.62\ 10^{-12}$	$4.53\ 10^{11}$
Cm-243	$3.92\ 10^{-10}$	$7.65\ 10^{9}$
Cm-244	$1.14\ 10^{-10}$	$2.63\ 10^{10}$
Cm-245	$2.12\ 10^{-9}$	$1.42\ 10^{9}$
Cm-246	$1.85\ 10^{-9}$	$1.62\ 10^{9}$

Radionuclide	Dose to Borehole drill operative (60y) (mSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)
Cm-248	1.18 10^{-8}	2.54 10^{8}

1165. The doses calculated using illustrative inventories are considered further in Appendix D.

E.5.3. Trial pit excavation

E.5.3.1. Assessment Calculations for Trial Pit Excavator

1166. The exposure pathways for the trial pit excavator are the same as for the borehole excavator: for details, see Section E.5.2. The differences between the two scenarios manifest themselves in the duration of intrusion, depth of intrusion and the quantity of material recovered. These parameters are summarised in Table 150. All other parameters remain the same. The calculation is cautious in the same sense as the borehole excavation scenario – see Section E.5.2.

Table 150 Parameters for trial pit excavation

Parameter	Units	Value	Description
T	h y^{-1}	1	Time the excavator is exposed to excavated material (per event)
$V_{excavate}$	m^3	10	Volume of excavated material per event
$N_{intrusion}$		20	Number of intrusions (assumed to take place in the same landfill area)

Values taken from (Hicks & Baldwin, 2011)

1167. This scenario has also been used to consider both the consignment tonnage limit and the specific activity limits applied in the CfA. In the first set of calculations a consignment is assumed to have a specific activity of 200 Bq g^{-1}, weigh 10 t and comprise 10 packages. It is also assumed that excavator is exposed to this single group of packages for 20 hours. The calculations were then repeated for the specific activities proposed for the permit for each radionuclide. Further details are given in Section E.6.5. No Ra-226 emplacement depth restrictions are assumed in the calculation of the doses to the trial pit excavator.

E.5.3.2. Dose to Trial Pit Excavator on-site 60 years after closure

1168. The largest dose rates per MBq disposal for the trial pit excavator under this scenario are from Ra-226, Pa-231, Th-232, Cm-248 and U-232 (see Table 151). Note that the specific doses calculated for this scenario are smaller than those calculated for the borehole drill operative scenario. This is because the borehole drilling is of longer duration than the trial pit excavation and the borehole drill operative is therefore exposed to contaminated material for longer even though the trial pit excavator considers more waste. The radiological capacity calculations do not therefore consider the trial pit scenario, which results in a lower dose to workers than the borehole drill operative scenario.

1169. The calculated doses to a trial pit excavator who is exposed to a single 10 t consignment containing waste at the limiting activity concentrations (see Table 38) are shown in the last column of Table 151. The largest dose from a consignment containing a maximum specific activity is 0.73 mSv y^{-1} for Pu-244, followed closely by Cm-248 and Nb-94. Hence, the restriction on the activity concentration in a consignment will protect the trial pit excavator for all radionuclides.

Table 151 Dose to Trial pit excavator at the site

Radionuclide	Dose to trial pit excavator (60y) (mSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)	Dose to Trial pit excavator – 10 t waste at 200 Bq g^{-1} (mSv y^{-1})	Dose to Trial pit excavator – 10 t waste at limiting concentration (mSv y^{-1})
H-3	$1.08\ 10^{-16}$	$2.78\ 10^{16}$	$9.36\ 10^{-8}$	$2.34\ 10^{-6}$
C-14	$9.26\ 10^{-13}$	$3.24\ 10^{12}$	$7.79\ 10^{-4}$	$1.95\ 10^{-2}$
Cl-36	$1.17\ 10^{-11}$	$2.56\ 10^{11}$	$9.82\ 10^{-3}$	$2.46\ 10^{-1}$
Ca-41	$1.16\ 10^{-14}$	$2.58\ 10^{14}$	$1.02\ 10^{-5}$	$2.56\ 10^{-4}$
Mn-54	$5.26\ 10^{-31}$	$5.70\ 10^{30}$	$4.41\ 10^{-22}$	$1.10\ 10^{-20}$
Fe-55	$5.86\ 10^{-21}$	$5.12\ 10^{20}$	$5.14\ 10^{-12}$	$1.29\ 10^{-10}$
Co-60	$8.48\ 10^{-13}$	$3.54\ 10^{12}$	$7.12\ 10^{-4}$	$7.12\ 10^{-4}$
Ni-59	$2.17\ 10^{-14}$	$1.38\ 10^{14}$	$1.86\ 10^{-5}$	$4.65\ 10^{-4}$
Ni-63	$8.38\ 10^{-14}$	$3.58\ 10^{13}$	$7.07\ 10^{-5}$	$1.77\ 10^{-3}$
Zn-65	$4.63\ 10^{-37}$	$6.48\ 10^{36}$	$3.89\ 10^{-28}$	$9.72\ 10^{-27}$
Se-79	$1.17\ 10^{-12}$	$2.57\ 10^{12}$	$9.88\ 10^{-4}$	$9.88\ 10^{-3}$
Sr-90	$1.70\ 10^{-11}$	$1.77\ 10^{11}$	$1.43\ 10^{-2}$	$1.43\ 10^{-2}$
Mo-93	$2.33\ 10^{-13}$	$1.29\ 10^{13}$	$2.02\ 10^{-4}$	$5.06\ 10^{-3}$
Zr-93	$3.16\ 10^{-13}$	$9.48\ 10^{12}$	$2.73\ 10^{-4}$	$6.82\ 10^{-3}$
Nb-93m	$1.80\ 10^{-15}$	$1.67\ 10^{15}$	$1.55\ 10^{-6}$	$3.89\ 10^{-5}$
Nb-94	$1.32\ 10^{-9}$	$2.27\ 10^{9}$	$1.11\ 10^{0}$	$5.54\ 10^{-1}$
Tc-99	$2.89\ 10^{-12}$	$1.04\ 10^{12}$	$2.43\ 10^{-3}$	$2.43\ 10^{-3}$
Ru-106	$6.14\ 10^{-28}$	$4.88\ 10^{27}$	$5.16\ 10^{-19}$	$1.29\ 10^{-17}$
Ag-108m	$1.19\ 10^{-9}$	$2.53\ 10^{9}$	$9.95\ 10^{-1}$	$4.98\ 10^{-1}$
Ag-110m	$9.34\ 10^{-36}$	$3.21\ 10^{35}$	$7.84\ 10^{-27}$	$7.84\ 10^{-26}$
Cd-109	$9.66\ 10^{-27}$	$3.11\ 10^{26}$	$8.14\ 10^{-18}$	$2.04\ 10^{-16}$
Sb-125	$9.61\ 10^{-17}$	$3.12\ 10^{16}$	$8.06\ 10^{-8}$	$2.02\ 10^{-6}$
Sn-119m	$1.10\ 10^{-35}$	$2.72\ 10^{35}$	$9.31\ 10^{-27}$	$2.33\ 10^{-25}$
Sn-123	$3.00\ 10^{-62}$	$1.00\ 10^{62}$	$2.51\ 10^{-53}$	$6.29\ 10^{-52}$
Sn-126	$1.65\ 10^{-9}$	$1.82\ 10^{9}$	$1.38\ 10^{0}$	$3.46\ 10^{-1}$
Te-127m	$6.51\ 10^{-75}$	$4.61\ 10^{74}$	$5.51\ 10^{-66}$	$1.38\ 10^{-64}$
I-129	$8.60\ 10^{-12}$	$3.49\ 10^{11}$	$7.47\ 10^{-3}$	$7.47\ 10^{-3}$
Ba-133	$5.08\ 10^{-12}$	$5.91\ 10^{11}$	$4.26\ 10^{-3}$	$1.07\ 10^{-1}$
Cs-134	$2.34\ 10^{-18}$	$1.28\ 10^{18}$	$1.96\ 10^{-9}$	$4.91\ 10^{-8}$
Cs-135	$2.48\ 10^{-12}$	$1.21\ 10^{12}$	$2.08\ 10^{-3}$	$5.21\ 10^{-2}$
Cs-137	$1.19\ 10^{-10}$	$2.52\ 10^{10}$	$9.98\ 10^{-2}$	$9.98\ 10^{-2}$
Ce-144	$8.57\ 10^{-35}$	$3.50\ 10^{34}$	$7.21\ 10^{-26}$	$1.80\ 10^{-24}$
Pm-147	$1.79\ 10^{-19}$	$1.68\ 10^{19}$	$1.50\ 10^{-10}$	$3.75\ 10^{-9}$
Sm-147	$4.71\ 10^{-11}$	$6.37\ 10^{10}$	$4.13\ 10^{-2}$	$4.13\ 10^{-2}$
Sm-151	$1.11\ 10^{-13}$	$2.70\ 10^{13}$	$9.37\ 10^{-5}$	$2.34\ 10^{-3}$
Eu-152	$4.59\ 10^{-11}$	$6.53\ 10^{10}$	$3.86\ 10^{-2}$	$3.86\ 10^{-1}$
Eu-154	$8.54\ 10^{-12}$	$3.51\ 10^{11}$	$7.16\ 10^{-3}$	$1.79\ 10^{-1}$

Radionuclide	Dose to trial pit excavator (60y) (mSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)	Dose to Trial pit excavator – 10 t waste at 200 Bq g^{-1} (mSv y^{-1})	Dose to Trial pit excavator – 10 t waste at limiting concentration (mSv y^{-1})
Eu-155	$4.19\ 10^{-15}$	$7.17\ 10^{14}$	$3.51\ 10^{-6}$	$8.78\ 10^{-5}$
Gd-153	$1.17\ 10^{-38}$	$2.56\ 10^{38}$	$9.83\ 10^{-30}$	$2.46\ 10^{-28}$
Pb-210	$2.66\ 10^{-11}$	$1.13\ 10^{11}$	$2.32\ 10^{-2}$	$5.81\ 10^{-3}$
Po-210	$1.89\ 10^{-58}$	$1.59\ 10^{58}$	$1.66\ 10^{-49}$	$1.66\ 10^{-48}$
Ra-226*	$4.24\ 10^{-9}$	$7.07\ 10^{8}$	$3.57\ 10^{0}$	$1.78\ 10^{-1}$
Ra-228	$1.78\ 10^{-12}$	$1.68\ 10^{12}$	$1.51\ 10^{-3}$	$1.51\ 10^{-3}$
Ac-227	$4.45\ 10^{-10}$	$6.74\ 10^{9}$	$3.89\ 10^{-1}$	$9.72\ 10^{-2}$
Th-228	$5.72\ 10^{-19}$	$5.25\ 10^{18}$	$4.83\ 10^{-10}$	$4.83\ 10^{-10}$
Th-229	$1.45\ 10^{-9}$	$2.07\ 10^{9}$	$1.27\ 10^{0}$	$1.27\ 10^{-1}$
Th-230	$5.85\ 10^{-10}$	$5.13\ 10^{9}$	$5.09\ 10^{-1}$	$2.55\ 10^{-1}$
Th-232	$2.99\ 10^{-9}$	$1.00\ 10^{9}$	$2.54\ 10^{0}$	$1.27\ 10^{-1}$
Pa-231	$3.27\ 10^{-9}$	$9.18\ 10^{8}$	$2.86\ 10^{0}$	$1.43\ 10^{-1}$
U-232	$2.11\ 10^{-9}$	$1.42\ 10^{9}$	$1.78\ 10^{0}$	$4.45\ 10^{-1}$
U-233	$5.56\ 10^{-11}$	$5.40\ 10^{10}$	$4.87\ 10^{-2}$	$4.87\ 10^{-2}$
U-234	$4.65\ 10^{-11}$	$6.46\ 10^{10}$	$4.08\ 10^{-2}$	$4.08\ 10^{-2}$
U-235	$1.54\ 10^{-10}$	$1.95\ 10^{10}$	$1.30\ 10^{-1}$	$1.30\ 10^{-1}$
U-236	$4.28\ 10^{-11}$	$7.00\ 10^{10}$	$3.76\ 10^{-2}$	$3.76\ 10^{-2}$
U-238	$1.12\ 10^{-10}$	$2.68\ 10^{10}$	$9.54\ 10^{-2}$	$9.54\ 10^{-2}$
Np-237	$3.97\ 10^{-10}$	$7.55\ 10^{9}$	$3.42\ 10^{-1}$	$3.42\ 10^{-1}$
Pu-238	$3.24\ 10^{-10}$	$9.26\ 10^{9}$	$2.84\ 10^{-1}$	$2.84\ 10^{-1}$
Pu-239	$5.67\ 10^{-10}$	$5.29\ 10^{9}$	$4.98\ 10^{-1}$	$2.49\ 10^{-1}$
Pu-240	$5.64\ 10^{-10}$	$5.32\ 10^{9}$	$4.95\ 10^{-1}$	$4.95\ 10^{-1}$
Pu-241	$1.41\ 10^{-11}$	$2.13\ 10^{11}$	$1.24\ 10^{-2}$	$3.09\ 10^{-1}$
Pu-242	$5.21\ 10^{-10}$	$5.75\ 10^{9}$	$4.58\ 10^{-1}$	$4.58\ 10^{-1}$
Pu-244	$8.51\ 10^{-10}$	$3.53\ 10^{9}$	$7.34\ 10^{-1}$	$7.34\ 10^{-1}$
Am-241	$4.18\ 10^{-10}$	$7.17\ 10^{9}$	$3.67\ 10^{-1}$	$1.83\ 10^{-1}$
Am-242m	$5.87\ 10^{-10}$	$5.11\ 10^{9}$	$5.14\ 10^{-1}$	$2.57\ 10^{-1}$
Am-243	$5.83\ 10^{-10}$	$5.15\ 10^{9}$	$5.07\ 10^{-1}$	$5.07\ 10^{-1}$
Cm-242	$1.66\ 10^{-12}$	$1.81\ 10^{12}$	$1.45\ 10^{-3}$	$1.45\ 10^{-2}$
Cm-243	$9.81\ 10^{-11}$	$3.06\ 10^{10}$	$8.54\ 10^{-2}$	$8.54\ 10^{-2}$
Cm-244	$2.85\ 10^{-11}$	$1.05\ 10^{11}$	$2.50\ 10^{-2}$	$2.50\ 10^{-2}$
Cm-245	$5.30\ 10^{-10}$	$5.66\ 10^{9}$	$4.63\ 10^{-1}$	$4.63\ 10^{-1}$
Cm-246	$4.64\ 10^{-10}$	$6.47\ 10^{9}$	$4.07\ 10^{-1}$	$4.07\ 10^{-1}$
Cm-248	$2.96\ 10^{-9}$	$1.01\ 10^{9}$	$2.55\ 10^{0}$	$6.37\ 10^{-1}$

* Assumes Ra-226 distributed with other LLW.

1170. This scenario is one of the scenarios used to determine the proposed radionuclide activity concentration limits for packaged wastes (see Section 7.4.1.2 and 0 for further details).

E.5.4. Informal Scavenger

1171. An informal scavenger may comprise individuals or small groups of people scavenging items using hand tools. This could involve a dig into the side of a bank with hand tools or simple scavenging from tide washed land. The exposure pathways would include: external doses from being close to exposed waste (both whilst excavating and at home, if any objects are taken home), inhalation of contaminated dusts and inadvertent ingestion of contaminated material.

E.5.4.1. Assessment Calculations for Informal Scavenger

1172. The exposure pathways for the Informal Scavenger are similar to the borehole excavator (for details, see Section E.5.2). The differences between the two scenarios manifest themselves in the duration of intrusion, the breathing rate and removal of objects that are taken home. The scavenger is assumed to come into contact with the objects removed from the site from time to time. The expression for external irradiation resulting from being in the vicinity of the item is a scaled form of the expression for irradiation dose from exposure to a semi-infinite slab of radioactively contaminated material, with the scaling factor f_{ext} accounting for reductions in dose associated with the finite geometry of the item (Hicks & Baldwin, 2011). These parameters are summarised in Table 156. All other parameters remain the same.

1173. The scavenger operative receives an additional dose (Sv y^{-1}) from external irradiation due to proximity to an object calculated as:

$$Dose_{object} = f_{ext}\left(\frac{D_{irr,slab}^{Rn}}{8766}\right)TC_{Rn,waste}(t)$$

where:

- $Dose_{object}$ is the dose to the scavenger from external irradiation by the object (Sv y^{-1});
- f_{ext} is the finite size scaling factor (dimensionless);
- T is the time that the scavenger is exposed to the material (h y^{-1});
- $D_{irr,slab}^{Rn}$ is the dose coefficients for radionuclide *Rn* (Sv y^{-1} Bq^{-1} kg), see Table 227;
- 8766 is the number of hours in a year (h y^{-1}); and,
- $C_{Rn,waste}(t)$ is the activity concentration of radionuclide *Rn* (Bq kg^{-1}) in the waste at time of excavation (*t*), assumes only waste excavated.

Table 152 Parameters for informal scavenger

Parameter	Units	Value	Description
T	h y^{-1}	50	Time the scavenger is exposed to excavated material
f_{ext}		0.002	Finite size irradiation scaling factor
B	m^3 h^{-1}	1.20	Light work breathing rate based on ICRP 66 (ICRP, 1994), 5.5 h light work (1.5 m^3/h) and 2.5 h sitting (0.54 m^3/h)

Values taken from (Hicks & Baldwin, 2011) unless stated otherwise

1174. This scenario has not been used to consider the specific activity limits applied in the CfA because the material recovery worker scenario produces lower values. No Ra-226 emplacement depth restrictions are assumed in the calculation of the doses to the scavenger.

E.5.4.2. Dose to Informal Scavenger on-site 60 years after closure

1175. The largest dose rates per MBq disposal for the informal scavenger under this scenario are from Ra-226, Th-232, Cm-248, U-232 and Pa-231. Note that the specific doses calculated for this scenario are smaller than those calculated for the borehole drill operative scenario (see Table 151). This is because the borehole drilling is of longer duration than the informal scavenger and with a higher breathing rate. The additional dose from objects in the home does not offset the smaller doses from the other pathways.

1176. The radiological capacity calculations do not therefore consider the informal scavenger scenario, which results in lower dose rates than the borehole drill operative scenario. This scenario has not been used to consider the specific activity limits applied in the CfA because the informal scavenger scenario produces lower values than borehole operative.

Table 153 Dose to Informal scavenger at the site

Radionuclide	Dose to informal scavenger (60y) (mSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)
H-3	$2.16\ 10^{-16}$	$1.39\ 10^{16}$
C-14	$3.00\ 10^{-12}$	$1.00\ 10^{12}$
Cl-36	$3.93\ 10^{-11}$	$7.64\ 10^{10}$
Ca-41	$1.23\ 10^{-14}$	$2.44\ 10^{14}$
Mn-54	$1.78\ 10^{-30}$	$1.69\ 10^{30}$
Fe-55	$6.91\ 10^{-21}$	$4.34\ 10^{20}$
Co-60	$2.86\ 10^{-12}$	$1.05\ 10^{12}$
Ni-59	$5.84\ 10^{-14}$	$5.14\ 10^{13}$
Ni-63	$2.63\ 10^{-13}$	$1.14\ 10^{13}$
Zn-65	$1.56\ 10^{-36}$	$1.92\ 10^{36}$
Se-79	$3.49\ 10^{-12}$	$8.60\ 10^{11}$
Sr-90	$5.60\ 10^{-11}$	$5.36\ 10^{10}$
Mo-93	$3.52\ 10^{-13}$	$8.51\ 10^{12}$
Zr-93	$7.30\ 10^{-13}$	$4.11\ 10^{12}$
Nb-93m	$3.82\ 10^{-15}$	$7.86\ 10^{14}$
Nb-94	$4.46\ 10^{-9}$	$6.73\ 10^{8}$
Tc-99	$9.55\ 10^{-12}$	$3.14\ 10^{11}$
Ru-106	$2.07\ 10^{-27}$	$1.45\ 10^{27}$
Ag-108m	$4.00\ 10^{-9}$	$7.49\ 10^{8}$
Ag-110m	$3.15\ 10^{-35}$	$9.51\ 10^{34}$
Cd-109	$3.09\ 10^{-26}$	$9.72\ 10^{25}$
Sb-125	$3.24\ 10^{-16}$	$9.25\ 10^{15}$
Sn-119m	$3.51\ 10^{-35}$	$8.56\ 10^{34}$
Sn-123	$1.01\ 10^{-61}$	$2.97\ 10^{61}$
Sn-126	$5.56\ 10^{-9}$	$5.39\ 10^{8}$
Te-127m	$1.93\ 10^{-74}$	$1.55\ 10^{74}$
I-129	$1.39\ 10^{-11}$	$2.16\ 10^{11}$
Ba-133	$1.71\ 10^{-11}$	$1.75\ 10^{11}$
Cs-134	$7.89\ 10^{-18}$	$3.80\ 10^{17}$

Radionuclide	Dose to informal scavenger (60y) (mSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)
Cs-135	$8.01\ 10^{-12}$	$3.74\ 10^{11}$
Cs-137	$4.01\ 10^{-10}$	$7.48\ 10^{9}$
Ce-144	$2.81\ 10^{-34}$	$1.07\ 10^{34}$
Pm-147	$5.92\ 10^{-19}$	$5.07\ 10^{18}$
Sm-147	$8.15\ 10^{-11}$	$3.68\ 10^{10}$
Sm-151	$3.48\ 10^{-13}$	$8.63\ 10^{12}$
Eu-152	$1.55\ 10^{-10}$	$1.93\ 10^{10}$
Eu-154	$2.88\ 10^{-11}$	$1.04\ 10^{11}$
Eu-155	$1.41\ 10^{-14}$	$2.13\ 10^{14}$
Gd-153	$3.95\ 10^{-38}$	$7.59\ 10^{37}$
Pb-210	$3.91\ 10^{-11}$	$7.66\ 10^{10}$
Po-210	$2.22\ 10^{-58}$	$1.35\ 10^{58}$
Ra-226	$1.39\ 10^{-8}$	$2.16\ 10^{8}$
Ra-228	$5.62\ 10^{-12}$	$5.33\ 10^{11}$
Ac-227	$8.57\ 10^{-10}$	$3.50\ 10^{9}$
Th-228	$1.81\ 10^{-18}$	$1.66\ 10^{18}$
Th-229	$2.94\ 10^{-9}$	$1.02\ 10^{9}$
Th-230	$1.20\ 10^{-9}$	$2.50\ 10^{9}$
Th-232	$8.70\ 10^{-9}$	$3.45\ 10^{8}$
Pa-231	$6.20\ 10^{-9}$	$4.84\ 10^{8}$
U-232	$6.77\ 10^{-9}$	$4.43\ 10^{8}$
U-233	$9.88\ 10^{-11}$	$3.04\ 10^{10}$
U-234	$8.05\ 10^{-11}$	$3.73\ 10^{10}$
U-235	$4.48\ 10^{-10}$	$6.70\ 10^{9}$
U-236	$7.41\ 10^{-11}$	$4.05\ 10^{10}$
U-238	$3.12\ 10^{-10}$	$9.62\ 10^{9}$
Np-237	$9.57\ 10^{-10}$	$3.13\ 10^{9}$
Pu-238	$5.70\ 10^{-10}$	$5.26\ 10^{9}$
Pu-239	$9.97\ 10^{-10}$	$3.01\ 10^{9}$
Pu-240	$9.92\ 10^{-10}$	$3.02\ 10^{9}$
Pu-241	$2.51\ 10^{-11}$	$1.20\ 10^{11}$
Pu-242	$9.16\ 10^{-10}$	$3.27\ 10^{9}$
Pu-244	$2.02\ 10^{-9}$	$1.48\ 10^{9}$
Am-241	$7.44\ 10^{-10}$	$4.03\ 10^{9}$
Am-242m	$1.05\ 10^{-9}$	$2.86\ 10^{9}$
Am-243	$1.24\ 10^{-9}$	$2.43\ 10^{9}$
Cm-242	$2.91\ 10^{-12}$	$1.03\ 10^{12}$
Cm-243	$2.03\ 10^{-10}$	$1.48\ 10^{10}$
Cm-244	$5.02\ 10^{-11}$	$5.98\ 10^{10}$
Cm-245	$1.02\ 10^{-9}$	$2.95\ 10^{9}$
Cm-246	$8.20\ 10^{-10}$	$3.66\ 10^{9}$
Cm-248	$7.22\ 10^{-9}$	$4.15\ 10^{8}$

E.5.5. Material recovery

E.5.5.1. Assessment Calculations for Material Recovery Worker

1177. The exposure pathways for the material recovery worker are the same as for the borehole excavator: for details, see Section E.5.2.

1178. Small groups of local people or contractors may excavate the waste using hand tools, portable mechanical equipment or small diggers. A worker may be exposed to radioactivity as a result of inhalation of contaminated dust particles, ingestion of contaminated materials and external irradiation from exposed waste. There are numerous reasons why exposed materials might be recovered from the site (e.g. metal recycling, rubble for use on tracks, hardcore for surfaces or under buildings). Many of the recycling uses are likely to involve dilution of the activity through mixing with uncontaminated materials. This scenario considers recovered material that may be suitable for use as hardcore/ballast (e.g. for construction), although this is also anticipated to be mixed with other materials prior to use, and the material recovery worker is assumed to be an occupant of a house where such material is used.

1179. Additional exposure pathways (adding to the borehole excavator pathways that are included) may occur within the house of the material recovery worker constructed over recovered waste (external irradiation) and from the ingestion and inhalation of dusts coming from recovered material associated with land surrounding the house. The smallholder (see Section E.5.10) and resident scenarios (see Sections E.5.8 and E.5.9) also consider a residential setting and include the cultivation of foodstuffs on contaminated soils, however recovered hardcore is not considered suitable for growing plants without substantial dilution and this pathway was not therefore included for the material recovery worker.

1180. Contaminated landfill material placed beneath the ground floor of the house is assumed to be covered by a layer of compacted sub-base ballast (5 cm) and topped with a layer of concrete (10 cm). The approach outlined by Hicks & Baldwin was used to derive a factor to account for the shielding provided by the concrete and sub-base ballast. A factor was also applied to account for only 5% of landfill waste being LLW. The recovered material inhaled or ingested, associated with land outside the residence is also assumed to be diluted to the same extent.

1181. Parameters modified or used for this scenario are summarised in Table 154. All other parameters remain the same. The calculation is cautious in the same sense as the borehole excavation scenario – see Section E.5.2 and the following additional pathways contribute to the total exposure.

1182. The material recovery worker receives an additional external irradiation dose (Sv y^{-1}) due to contaminated material beneath their house, calculated as:

$$Dose_{material} = f_{ext,in}\left(\frac{D_{irr,slab}^{Rn}}{8766}\right) T_{indoors}\, 0.05\, C_{Rn,waste}(t)$$

where:

- $Dose_{material}$ is the dose to the material recovery worker from external irradiation by material under the house (Sv y^{-1});
- $f_{ext,in}$ is the indoor irradiation scaling factor (dimensionless), the halving thickness of concrete is 6.1 cm, so for a 10 cm concrete layer over a 5 cm sub-base (of similar density to concrete) the scaling factor is 0.1819,

$$f_{ext,in} = \frac{1}{2^Y} \quad where \quad Y = (10+5)/6.1$$

- *0.05* is the proportion of LLW in the landfill (dimensionless);
- $T_{indoors}$ is the time that the worker is exposed at home indoors (h y^{-1});
- $D^{Rn}_{irr,slab}$ is the dose coefficient for external irradiation from a slab for radionuclide *Rn* (Sv y^{-1} Bq^{-1} kg), see Table 227;
- 8766 is the number of hours in a year (h y^{-1});
- $C_{Rn,waste}(t)$ is the activity concentration of radionuclide *Rn* (Bq kg^{-1}) in the waste at time of excavation (assumes only waste excavated), *t*:

1183. The material recovery worker receives an additional dose (Sv y^{-1}) from inhalation of soil from land contaminated with recovered material, calculated as:

$$Dose_{inhaled\ material} = D^{Rn}_{inh}\ T_{outdoors}\ B\ M_{inh}\ 0.05\ C_{Rn,waste}(t)$$

where:

- $Dose_{inhaled\ material}$ is the dose to the material recovery worker from inhalation of contaminated soil (Sv y^{-1});
- M_{inh} is the dust loading of contaminated waste inhaled by the excavator (kg m^{-3});
- B_{home} is the breathing rate at home doing light work outside (m^{3} h^{-1});
- *0.05* is the proportion of LLW in the landfill (dimensionless);
- $T_{outdoors}$ is the time that the worker is exposed to the material (h y^{-1});
- D^{Rn}_{inh} is the inhalation dose coefficient for radionuclide *Rn* (Sv y^{-1} Bq^{-1} kg), Table 225; and,
- $C_{Rn,waste}(t)$ is the activity concentration of radionuclide *Rn* (Bq kg^{-1}) in the waste at time of excavation (*t*), assumes only waste excavated.

1184. The material recovery worker receives an additional dose (Sv y^{-1}) from ingestion of soil from land contaminated with recovered material, calculated as:

$$Dose_{ingested\ material} = D^{Rn}_{ing}\ T_{outdoors}\ M_{ing}\ 0.05\ C_{Rn,waste}(t)$$

where:

- $Dose_{ingested\ material}$ is the dose to the material recovery worker from external irradiation by material under the house (Sv y^{-1});
- *0.05* is the proportion of LLW in the landfill (dimensionless);
- $T_{outdoors}$ is the time that the excavator is exposed to the material outdoors (h y^{-1});

- D_{ing}^{Rn} is the ingestion dose coefficient for radionuclide *Rn* (Sv y^{-1} Bq^{-1} kg), see Table 225;
- M_{ing} is the rate of ingestion of dust from the material (kg h^{-1}); and,
- $C_{Rn,waste}(t)$ is the activity concentration of radionuclide *Rn* (Bq kg^{-1}) in the waste at time of excavation (*t*), assumes only waste excavated.

Table 154 Parameters for a material recovery worker

Parameter	Units	Value	Description
T_{exc}	h y^{-1}	40	Time the material recovery worker is exposed to excavated material
$T_{indoors}$	h y^{-1}	5661.4	Time the material recovery worker is indoors at home, based on ICRP 66 (ICRP, 1994)
$T_{outdoors}$	h y^{-1}	730.5	Time the material recovery worker is outdoors at home, based on ICRP 66 (ICRP, 1994)
B_{home}	m^3 h^{-1}	1.20	Rate applied while outdoors at home: Light work breathing rate based on ICRP 66 (ICRP, 1994), 5.5 h light work (1.5 m^3/h) and 2.5 h sitting (0.54 m^3/h)
$f_{ext,in}$		0.1819	Indoor irradiation scaling factor for shielding from 10 cm concrete and 5 cm sub-base ballast

Values taken from (Hicks & Baldwin, 2011) unless stated otherwise

1185. No Ra-226 emplacement depth restrictions are assumed in the calculation of the doses to the material recovery worker.

E.5.5.2. Dose to Material Recovery Worker 60 years after site closure

1186. The largest dose rates per MBq disposal for the material recovery worker under this scenario are from Ra-226, Th-232, Cm-248, U-232 and Pa-231 (see Table 155). Note that the specific doses calculated under this scenario are greater than those calculated for the borehole drill operative scenario (see Table 149), where external irradiation is the dominant pathway contributing to total exposure. The shorter on-site exposure of material recovery worker is off-set by the longer exposure to material beneath the house, even with shielding and with material at a lower activity.

1187. This scenario has been used to consider the specific activity limits applied in the CfA because for a small number of radionuclides the material recovery worker scenario limits the activity concentrations in disposed material.

Table 155 Dose to Material Recovery Worker

Radionuclide	Dose to material recovery worker (60y) (mSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq^{-1})	Limiting concentration (Bq g^{-1})
H-3	3.35 10^{-16}	8.94 10^{15}	2.04 10^{9}
C-14	4.09 10^{-12}	7.34 10^{11}	1.67 10^{5}
Cl-36	5.32 10^{-11}	5.64 10^{10}	1.28 10^{4}
Ca-41	1.93 10^{-14}	1.55 10^{14}	3.54 10^{7}
Mn-54	2.41 10^{-30}	1.25 10^{30}	2.84 10^{23}
Fe-55	1.10 10^{-20}	2.74 10^{20}	6.24 10^{13}
Co-60	3.88 10^{-12}	7.73 10^{11}	1.76 10^{5}
Ni-59	8.12 10^{-14}	3.70 10^{13}	8.42 10^{6}
Ni-63	3.61 10^{-13}	8.31 10^{12}	1.89 10^{6}
Zn-65	2.12 10^{-36}	1.42 10^{36}	3.23 10^{29}
Se-79	4.78 10^{-12}	6.27 10^{11}	1.43 10^{5}
Sr-90	7.61 10^{-11}	3.94 10^{10}	8.99 10^{3}
Mo-93	5.17 10^{-13}	5.80 10^{12}	1.32 10^{6}
Zr-93	1.10 10^{-12}	2.72 10^{12}	6.20 10^{5}
Nb-93m	5.82 10^{-15}	5.15 10^{14}	1.17 10^{8}
Nb-94	6.04 10^{-9}	4.97 10^{8}	1.13 10^{2}
Tc-99	1.30 10^{-11}	2.31 10^{11}	5.26 10^{4}
Ru-106	2.81 10^{-27}	1.07 10^{27}	2.44 10^{20}
Ag-108m	5.42 10^{-9}	5.53 10^{8}	1.26 10^{2}
Ag-110m	4.27 10^{-35}	7.02 10^{34}	1.60 10^{28}
Cd-109	4.20 10^{-26}	7.13 10^{25}	1.63 10^{19}
Sb-125	4.39 10^{-16}	6.83 10^{15}	1.56 10^{9}
Sn-119m	4.79 10^{-35}	6.27 10^{34}	1.43 10^{28}
Sn-123	1.37 10^{-61}	2.19 10^{61}	5.00 10^{54}
Sn-126	7.53 10^{-9}	3.98 10^{8}	9.07 10^{1}
Te-127m	2.66 10^{-74}	1.13 10^{74}	2.57 10^{67}
I-129	2.01 10^{-11}	1.50 10^{11}	3.41 10^{4}
Ba-133	2.32 10^{-11}	1.29 10^{11}	2.95 10^{4}
Cs-134	1.07 10^{-17}	2.81 10^{17}	6.39 10^{10}
Cs-135	1.09 10^{-11}	2.75 10^{11}	6.27 10^{4}
Cs-137	5.43 10^{-10}	5.52 10^{9}	1.26 10^{3}
Ce-144	3.83 10^{-34}	7.84 10^{33}	1.79 10^{27}
Pm-147	8.05 10^{-19}	3.73 10^{18}	8.50 10^{11}
Sm-147	1.50 10^{-10}	1.99 10^{10}	4.55 10^{3}
Sm-151	4.82 10^{-13}	6.23 10^{12}	1.42 10^{6}
Eu-152	2.10 10^{-10}	1.43 10^{10}	3.25 10^{3}
Eu-154	3.90 10^{-11}	7.69 10^{10}	1.75 10^{4}
Eu-155	1.91 10^{-14}	1.57 10^{14}	3.57 10^{7}
Gd-153	5.36 10^{-38}	5.60 10^{37}	1.28 10^{31}
Pb-210	6.22 10^{-11}	4.82 10^{10}	1.10 10^{4}
Po-210	3.65 10^{-58}	8.23 10^{57}	1.88 10^{51}
Ra-226	1.89 10^{-8}	1.59 10^{8}	3.61 10^{1}
Ra-228	7.80 10^{-12}	3.85 10^{11}	8.76 10^{4}
Ac-227	1.51 10^{-9}	1.99 10^{9}	4.53 10^{2}
Th-228	2.51 10^{-18}	1.19 10^{18}	2.72 10^{11}
Th-229	5.04 10^{-9}	5.95 10^{8}	1.36 10^{2}
Th-230	2.04 10^{-9}	1.47 10^{9}	4.44 10^{2}
Th-232	1.25 10^{-8}	2.40 10^{8}	5.47 10^{1}
Pa-231	1.10 10^{-8}	2.73 10^{8}	2.98 10^{2}

Radionuclide	Dose to material recovery worker (60y) (mSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq^{-1})	Limiting concentration (Bq g^{-1})
U-232	9.36 10^{-9}	3.21 10^{8}	7.31 10^{1}
U-233	1.80 10^{-10}	1.67 10^{10}	4.52 10^{3}
U-234	1.48 10^{-10}	2.02 10^{10}	4.63 10^{3}
U-235	6.43 10^{-10}	4.67 10^{9}	1.07 10^{3}
U-236	1.37 10^{-10}	2.20 10^{10}	5.00 10^{3}
U-238	4.56 10^{-10}	6.58 10^{9}	1.50 10^{3}
Np-237	1.50 10^{-9}	2.00 10^{9}	4.55 10^{2}
Pu-238	1.05 10^{-9}	2.84 10^{9}	6.48 10^{2}
Pu-239	1.85 10^{-9}	1.63 10^{9}	3.70 10^{2}
Pu-240	1.84 10^{-9}	1.63 10^{9}	3.72 10^{2}
Pu-241	4.61 10^{-11}	6.51 10^{10}	3.50 10^{5}
Pu-242	1.70 10^{-9}	1.77 10^{9}	4.03 10^{2}
Pu-244	3.20 10^{-9}	9.39 10^{8}	2.15 10^{2}
Am-241	1.37 10^{-9}	2.19 10^{9}	5.00 10^{2}
Am-242m	1.92 10^{-9}	1.56 10^{9}	4.95 10^{2}
Am-243	2.07 10^{-9}	1.45 10^{9}	3.31 10^{2}
Cm-242	5.39 10^{-12}	5.57 10^{11}	2.52 10^{44}
Cm-243	3.44 10^{-10}	8.72 10^{9}	2.00 10^{3}
Cm-244	9.28 10^{-11}	3.23 10^{10}	7.75 10^{3}
Cm-245	1.79 10^{-9}	1.67 10^{9}	3.88 10^{2}
Cm-246	1.51 10^{-9}	1.98 10^{9}	4.52 10^{2}
Cm-248	1.13 10^{-8}	2.66 10^{8}	6.07 10^{1}

1188. This scenario is one of the scenarios used to determine the proposed radionuclide activity concentration limits for wastes (see Section 7.4.1.2 for further details).

E.5.6. Excavation for road

E.5.6.1. Assessment calculations for Road Excavator

1189. Scenario SCE7B considers road construction and was produced by the IAEA for an assessment of potential radiological impacts from near surface disposal facilities (IAEA, 2003). Whilst road construction may lead to the excavation of a larger amount of waste it may also lead to exposure from contaminated waste rather than spoil. However, the road construction worker is likely to spend much less time in contact with waste and spend a lot of that time in a vehicle.

1190. It is assumed that a road is constructed after institutional control is withdrawn (60 years after closure at Port Clarence). Exposure duration is based on an average construction speed of 10 km in six months (working 8 hour days for a 20 day month) in scenario SCE7B (IAEA, 2003). The exposure pathways include inadvertent inhalation, inhalation of dust and external exposure but exclude doses direct to the skin of workers. A road construction worker will be using machinery and it is reasonable to exclude the direct contact pathway compared to the borehole excavator who will be in closer contact with waste.

1191. The length and location of a new road through the site is very uncertain. It is extremely unlikely that the road will be aligned with the maximum distance across bordering waste cells or that it would traverse the highest part of the restored site. It is therefore assumed that the road will clip one corner of the site for a distance of 300 m with excavation to a depth of 9 m (IAEA, 2003). The recommended single carriageway width for new roads is 7.3 m (Highways England, 2020) and assuming a 3 m verge, and a slope of 1 in 7.7 (MJCA, 2019a) the dilution factor (*DIL*) for excavated waste would be 0.72 (close to the IAEA suggested value of 0.7).

1192. The concentration of activity in exposed materials is based on the proposed activity concentration limits for the waste consignments at the site (see Section 7.4) and assuming that LLW comprises 5% of waste deposited. The IAEA scenario also includes a short period (4 h) of exposure to higher concentration material (no dilution, activity concentration in waste as disposed but allowing for radioactive decay).

1193. The exposure pathways for the road excavator are the same as for the borehole excavator but excludes direct contact with the waste: for details, see Section E.5.2. The differences between the two scenarios manifest themselves in the duration of intrusion, inhalation rate (for light work), the dilution factor applied and initial activity concentration are the limiting concentrations (see Section 7.4). The main differences are summarised in Table 156. All other parameters remain the same.

Table 156 Parameters for road excavation

Parameter	Units	Value	Description
T	$h\ y^{-1}$	28.8	Time the excavator is exposed to excavated material
$V_{excavate}$	m^3	35000	Volume of excavated material
Q_{soil}	$kg\ h^{-1}$	$1.25\ 10^{-5}$	The inadvertent soil ingestion rate
B	$m^3\ h^{-1}$	1.20	Worker breathing rate
Dustload	$kg\ m^{-3}$	$6\ 10^{-7}$	The dust concentration in air
DIL		0.72	Dilution factor for excavated waste
Hotspot	$h\ y^{-1}$	4	Time exposed to waste as disposed

Values taken from (IAEA, 2003).

E.5.6.2. Dose to Excavator for Road on-site 60 years after closure

1194. The largest doses for the person excavating the road 60 years after closure are less than 1µ Sv and the largest doses are for Pu-244, Nb-94, Cm-248, Ag-108m and Cm-248 (Table 157). In most cases the dose rates to the borehole drill operator are greater than to the road excavator with the exception of Cl-36. The impact of Radium placement depth within Port Clarence on these intrusion doses and on radon release is discussed in the next section (see paragraph 1247). The waste acceptance criteria limit the overall consignment activity to 2,000 Bq g^{-1} and the doses shown below will therefore be lower.

1195. There are several practical reasons why a road would probably not be constructed through the site (surrounding areas may flood, there is an existing road adjacent to the northern edge of the site, it would be cheaper to go around the site than through it). It is our view that the road construction scenario remains highly unlikely.

Table 157 Dose to road excavator at the site

Radionuclide	Concentration limit (Bq g^{-1})	Dose from maximum concentration limit (mSv y^{-1})
H-3	5000	5.32 10^{-10}
C-14	5000	5.01 10^{-6}
Cl-36	5000	6.43 10^{-5}
Ca-41	5000	6.31 10^{-8}
Mn-54	5000	2.91 10^{-24}
Fe-55	5000	2.97 10^{-14}
Co-60	200	1.87 10^{-7}
Ni-59	5000	9.63 10^{-8}
Ni-63	5000	4.56 10^{-7}
Zn-65	5000	2.56 10^{-30}
Se-79	2000	2.53 10^{-6}
Sr-90	200	3.73 10^{-6}
Mo-93	5000	1.26 10^{-6}
Zr-93	5000	1.53 10^{-6}
Nb-93m	5000	8.84 10^{-9}
Nb-94	100	1.46 10^{-4}
Tc-99	200	6.30 10^{-7}
Ru-106	5000	3.39 10^{-21}
Ag-108m	100	1.31 10^{-4}
Ag-110m	2000	2.06 10^{-29}
Cd-109	5000	5.24 10^{-20}
Sb-125	5000	5.31 10^{-10}
Sn-119m	5000	5.87 10^{-29}
Sn-123	5000	1.66 10^{-55}
Sn-126	50	9.10 10^{-5}
Te-127m	5000	3.47 10^{-68}
I-129	200	1.89 10^{-6}
Ba-133	5000	2.80 10^{-5}
Cs-134	5000	1.29 10^{-11}
Cs-135	5000	1.35 10^{-5}
Cs-137	200	2.63 10^{-5}
Ce-144	5000	4.66 10^{-28}
Pm-147	5000	9.71 10^{-13}
Sm-147	200	7.58 10^{-6}
Sm-151	5000	5.94 10^{-7}
Eu-152	2000	1.02 10^{-4}
Eu-154	5000	4.72 10^{-5}
Eu-155	5000	2.31 10^{-8}
Gd-153	5000	6.47 10^{-32}
Pb-210	50	1.36 10^{-6}
Po-210	2000	3.91 10^{-52}
Ra-226	10	4.66 10^{-5}
Ra-228	200	3.82 10^{-7}
Ac-227	50	1.84 10^{-5}
Th-228	200	1.22 10^{-13}
Th-229	20	2.46 10^{-5}
Th-230	100	3.88 10^{-5}
Th-232	10	3.05 10^{-5}
Pa-231	10	1.12 10^{-4}

Radionuclide	Concentration limit (Bq g^{-1})	Dose from maximum concentration limit (mSv y^{-1})
U-232	50	1.13 10^{-4}
U-233	200	7.77 10^{-6}
U-234	200	7.47 10^{-6}
U-235	200	3.12 10^{-5}
U-236	200	6.91 10^{-6}
U-238	200	2.23 10^{-5}
Np-237	200	7.31 10^{-5}
Pu-238	200	5.15 10^{-5}
Pu-239	100	4.50 10^{-5}
Pu-240	200	8.96 10^{-5}
Pu-241	5000	3.46 10^{-6}
Pu-242	200	8.28 10^{-5}
Pu-244	200	1.55 10^{-4}
Am-241	100	3.34 10^{-5}
Am-242m	100	6.02 10^{-5}
Am-243	200	1.01 10^{-4}
Cm-242	2000	2.63 10^{-7}
Cm-243	200	1.67 10^{-5}
Cm-244	200	4.53 10^{-6}
Cm-245	200	1.27 10^{-4}
Cm-246	200	7.38 10^{-5}
Cm-248	50	1.37 10^{-4}

E.5.7. Site Resident – no cap damage

E.5.7.1. Assessment calculations for Site Residents (no cap damage)

1196. Members of the public living in a house built close to, or on, the site after closure is also considered. The house is assumed to be built 60 years after closure in such a way, e.g. on a concrete raft, that it does not damage the integrity of the cap. The situation where the cap is damaged or a house is built on excavated spoil is considered in Section E.5.9. External irradiation from the buried wastes and inhalation of radioactive gases released through the cap are considered. Habit data are presented in Table 158.

Table 158 Habit data for site resident family

Parameter	Units	Value	Description
B_a	m^3 h^{-1}	0.78	Inhalation rate - adult indoors
B_c	m^3 h^{-1}	0.56	Inhalation rate – child indoors
B_i	m^3 h^{-1}	0.19	Inhalation rate – infant indoors
$O_{in,a}$	h y^{-1}	7978.0	Indoor occupancy – adult (0.91 indoors)
$O_{in,c}$	h y^{-1}	7366.0	Indoor occupancy – child (0.84 indoors)
$O_{in,i}$	h y^{-1}	7978.0	Indoor occupancy – infant (0.91 indoors)

Note: Inhalation rates based on ICRP 66 (ICRP, 1994), see Table 73 for derivation.

1197. The calculations consider the release of H-3, C-14 and radon gases. The doses are summed with the doses from external irradiation that could occur through the intact cap. With the exception of radon exposure, the impact of these exposure pathways is expected to be low. Exposure to gas is only considered while the person is indoors since when outdoors there would be significant dilution in the atmosphere, leading to negligible doses in comparison.

Gas generation – H-3 and C-14

1198. The gas pathway is considered in the same way for tritium and C-14. The release rate of radioactive gas is given in paragraph 737 using the release fractions and initial activity values in Table 75.

1199. The release rate of gases from a landfill is expected to vary over time. A conservative assumption for the operational period assumed all C-14 and H-3 that was associated with organic material would be released over a ten year period. Gas generation within the landfill has been simulated using the GasSim model (Augean, 2010) which shows a rapid build-up in the rate of release after capping followed by an exponential decline. It was shown that 85% of the gas yield for carbon occurs within 60 years and it is assumed that the remainder is released at a slower rate. We have cautiously assumed this lower rate remains constant until the period of interest i.e. for a further 90 years. The average timescale for carbon-based gas generation has therefore been set to 600 for this scenario (90/0.15). For H-3, the default SNIFFER value of 50 is used.

1200. The effective doses arising from inhalation of generated gases are calculated for site residents post-closure (at *t* = 60 years after closure), assuming that a proportion of a resident's time is spent indoors (as detailed in Table 158). The dose (Sv y^{-1}) is calculated according to:

$$Dose_{gas,indoors} = D_{inh,j}^{Rn} \cdot B_j \cdot O_{in,j} \left[R_{Rn,gas}(t) \cdot \frac{a_H}{a} \cdot \left(\frac{1}{kV} \right) \right]$$

where:

- $Dose_{gas,indoors}$ is the dose to a site resident from gases (Sv y^{-1});
- $D_{inh,j}^{Rn}$ is the inhalation dose coefficient of radionuclide *Rn* for age group j (Sv Bq^{-1}), see Table 225;
- B_j is the inhalation rate for age group j (m^3 h^{-1});
- $O_{in,j}$ is the occupancy indoors for age group j (h y^{-1});
- $R_{Rn,gas}(t)$ is the release rate of radioactive gas at time *t* (Bq y^{-1});
- $\frac{a_H}{a}$ is the horizontal area of a dwelling divided by the area over which the radioactive gas is being released (i.e. the facility footprint);
- k is the turnover rate, accounting for gas release from the house by ventilation (y^{-1}); and,
- V is the volume of the house (m^3).

1201. The gas dispersion parameters used in this work are summarised in Table 159, the dimensions of the landfill are given in Table 67, the dose coefficients in Table 225 and habit data in Table 158.

Gas generation – Radon

1202. This section considers migration of radon gas from a waste cell into a building constructed on the intact cap.

1203. This case considers long-term occupation of the former landfill site, and thus long-term potential exposure to contaminated wastes. The flux of radon through soil ($F_{radon}(t)$) is described by the equation given in paragraph 746. The parameters in Table 78 were used for the building located on an intact cap with the exception of h_2 which was set to the intact cap depth (1.3 m) plus the depth of waste material above the LLW (1 m) i.e. a total of 2.3 m.

1204. The activity concentration of radon gas in the house, $C_{Rn222,house}$ (Bq m^{-3}) is then calculated according to (SNIFFER, 2006):

$$C_{Rn222,house} = F_{radon}(t) \cdot \frac{a_H}{AREA} \cdot \frac{1}{(\lambda_{house} \cdot v_{house})}$$

where:

- $C_{Rn222,house}$ is the activity concentration of radon gas (Bq m^{-3});
- a_H is the area of the house (m^2);
- $AREA$ is the surface area of that part of the landfill facility containing radioactive waste, 273,468 m^2;
- λ_{house} is the turnover rate of air in the house (y^{-1}); and
- v_{house} is the volume of the house (m^3).

1205. The values of the quantities used in this work are given in Table 159, except for the landfill area (see Table 67).

Table 159 Radon parameters

Parameter	Units	Value	Description	Source
λ_{house}	y^{-1}	2600	Air turnover rate in house	(Passive House Institute, 2012)
v_{house}	m^3	125	Volume of house	(HPA, 2007)
a_H	m^2	50	Area of house	(Quintessa Ltd, 2011)

1206. The resultant inhalation dose (Sv y^{-1}) to a resident of the house is then given by:

$$Dose_j = D_{inh,j} \cdot C_{Rn222,house} \cdot B_{inh,j} \cdot O_{indoor,j}$$

where:

- $Dose_j$ is the inhalation dose for age group *j* (Sv y^{-1});
- $D_{inh,j}$ is the inhalation dose coefficient for age group *j* (Sv Bq^{-1});

- $B_{inh,j}$ is the breathing rate for age group j (m^3 h^{-1}); and,
- $O_{indoor,j}$ is the indoor occupancy for age group j (h y^{-1}).

1207. The dose coefficient is presented in Table 79 and habit data in Table 158.

External irradiation

1208. The dose to a future site resident from external irradiation is also calculated through the intact cap assuming that a proportion of a resident's time is spent indoors (as set out in Table 158). The dose (Sv y^{-1}) is calculated according to:

$$Dose_{irr} = D_{irr,slab}^{Rn} \cdot \left(O_{out,j} + O_{in,j} sf\right) \cdot \left(\frac{A_{Rn,waste}(t)}{V_{waste}\rho_{waste}}\right) \cdot e^{-\mu^{Rn} \cdot x}$$

where:

- $Dose_{irr}$ is the dose external irradiation to a resident (Sv y^{-1});
- $D_{irr,slab}^{Rn}$ is the dose conversion factor for irradiation from radionuclide *Rn* (see Table 227), based on the receptor being 1 m from the ground, and the contamination is taken to be a semi-infinite slab (Sv y^{-1} Bq^{-1} kg);
- $O_{out,j}$ is the outdoor occupancy for age group j;
- $O_{in,j}$ is the indoor occupancy for age group j;
- sf is the shielding factor from the ground when indoors;
- $A_{Rn,waste}(t)$ is the activity of radionuclide *Rn* at time *t*;
- V_{waste} is the volume of waste (m^3);
- ρ_{waste} is the density of waste (kg m^{-3});
- μ^{Rn} is the linear attenuation coefficient for radionuclide *Rn* (see Table 227); and,
- x is the thickness of the cap and cover material (m).

1209. The values of these parameters employed in this work are summarised in Table 160 unless stated otherwise. The model uses the linear attenuation coefficient to account for shielding by clean material above the waste mass; the greater the depth of clean material, the greater the shielding. Note that since the linear attenuation coefficient is dependent on the density of the material, the mass attenuation coefficient (μ^{Rn} / the density of the material) is often reported for convenience. The linear attenuation coefficients used in the model are taken from (SNIFFER, 2006) and are the recommended values for soil given by (Hung, 2000).

Table 160 External irradiation parameters

Parameter	Units	Value	Description
$O_{out,a}$		0.09	Outdoor occupancy - adult
$O_{in,a}$		0.91	Indoor occupancy - adult
$O_{out,c}$		0.16	Outdoor occupancy - child
$O_{in,c}$		0.84	Indoor occupancy - child
$O_{out,i}$		0.09	Outdoor occupancy - infant
$O_{in,i}$		0.91	Indoor occupancy - infant
sf		0.1	Shielding factor
V_{waste}	m^3	$2.87\ 10^6$	Waste volume
ρ_{waste}	$kg\ m^{-3}$	1530	Waste density
x	M	2.3	Cap plus cover thickness

E.5.7.2. Dose to Site Resident – no cap damage

1210. Doses to a site resident from radon are sensitive to the depth of radium placement beneath the surface of the landfill. This is shown in Table 161 which give radon fluxes, indoor Rn-222 activity concentrations and inhalation doses at 60 years after closure arising from a nominal 1 MBq of Ra-226 in the landfill. These calculations assume that the released radon is in secular equilibrium with the parent radium.

1211. As the placement depth increases the estimated dose decreases and the radiological capacity increases. Hence, an emplacement strategy for Ra-226 wastes will have a significant effect on the radon doses.

Table 161 Radon inhalation doses for a dwelling built on a capped landfill – unit inventory

Depth below Cap (m)	Depth below ground level (m)	Rn-222 flux into house ($Bq\ y^{-1}$)	Indoor Rn-222 activity concentration ($Bq\ m^{-3}$)	Adult inhalation effective dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)
0.0	1.3	$1.62\ 10^{2}$	$9.39\ 10^{-8}$	$8.94\ 10^{-6}$
1.0	2.3	$1.21\ 10^{0}$	$7.01\ 10^{-10}$	$6.68\ 10^{-8}$
2.0	3.3	$9.13\ 10^{-3}$	$5.30\ 10^{-12}$	$5.05\ 10^{-10}$
3.0	4.3	$7.01\ 10^{-5}$	$4.07\ 10^{-14}$	$3.87\ 10^{-12}$
3.7	5.0	$2.34\ 10^{-6}$	$1.36\ 10^{-15}$	$1.30\ 10^{-13}$
4.0	5.3	$5.48\ 10^{-7}$	$3.18\ 10^{-16}$	$3.03\ 10^{-14}$
5.0	6.3	$4.40\ 10^{-9}$	$2.55\ 10^{-18}$	$2.43\ 10^{-16}$

1212. The doses to site residents (60 years after closure and with the cap intact) from gas released and through external irradiation are presented in Table 162, Table 163 and Table 164 for the adult, child and infant groups respectively. Note that these results include the effects of ingrowth after 60 years upon the calculated doses.

1213. The scenario radiological capacity is shown in the right hand column. The highest dose is to an infant from Ra-226 ($1.14\ 10^{-4}\ \mu Sv\ y^{-1}\ MBq^{-1}$) with no emplacement strategy; if an emplacement strategy is applied to wastes containing Ra-226 at >5 $Bq\ g^{-1}$ then the radiological capacity increases (deep placement is shown at bottom of table). The highest dose to an adult is $8.01\ 10^{-5}\ \mu Sv\ y^{-1}\ MBq^{-1}$ from Ra-226 with no emplacement strategy for waste containing >5 $Bq\ g^{-1}$. The next highest dose to an adult is from C-14 gas ($1.25\ 10^{-5}\ \mu Sv\ y^{-1}\ MBq^{-1}$). Similar patterns are seen for the dose to child and infant.

Table 162 Adult Site Resident Exposure

Radionuclide	Dose (µSv y^{-1} MBq^{-1})			Scenario radiological capacity (MBq)
	Gas	External	Total	
H-3	2.50 10^{-8}	2.54 10^{-12}	2.50 10^{-8}	1.20 10^{17}
C-14	1.25 10^{-5}	9.84 10^{-64}	1.25 10^{-5}	2.41 10^{14}
Cl-36	0	3.83 10^{-27}	3.83 10^{-27}	7.83 10^{35}
Ca-41	0	0	0	0
Mn-54	0	1.14 10^{-39}	1.14 10^{-39}	2.64 10^{48}
Fe-55	0	1.84 10^{-21}	1.84 10^{-21}	1.63 10^{30}
Co-60	0	6.59 10^{-20}	6.59 10^{-20}	4.55 10^{28}
Ni-59	0	9.83 10^{-10}	9.83 10^{-10}	3.05 10^{18}
Ni-63	0	5.88 10^{-9}	5.88 10^{-9}	5.11 10^{17}
Zn-65	0	9.96 10^{-45}	9.96 10^{-45}	3.01 10^{53}
Se-79	0	9.12 10^{-62}	9.12 10^{-62}	3.29 10^{70}
Sr-90	0	4.46 10^{-25}	4.46 10^{-25}	6.73 10^{33}
Mo-93	0	3.66 10^{-9}	3.66 10^{-9}	8.19 10^{17}
Zr-93	0	1.05 10^{-8}	1.05 10^{-8}	2.85 10^{17}
Nb-93m	0	5.02 10^{-11}	5.02 10^{-11}	5.97 10^{19}
Nb-94	0	1.58 10^{-18}	1.58 10^{-18}	1.90 10^{27}
Tc-99	0	7.58 10^{-46}	7.58 10^{-46}	3.96 10^{54}
Ru-106	0	9.70 10^{-38}	9.70 10^{-38}	3.09 10^{46}
Ag-108m	0	1.16 10^{-19}	1.16 10^{-19}	2.58 10^{28}
Ag-110m	0	4.34 10^{-44}	4.34 10^{-44}	6.91 10^{52}
Cd-109	0	4.24 10^{-63}	4.24 10^{-63}	7.07 10^{71}
Sb-125	0	3.14 10^{-27}	3.14 10^{-27}	9.55 10^{35}
Sn-119m	0	0	0	0
Sn-123	0	1.30 10^{-70}	1.30 10^{-70}	2.31 10^{79}
Sn-126	0	3.66 10^{-19}	3.66 10^{-19}	8.19 10^{27}
Te-127m	0	1.34 10^{-100}	1.34 10^{-100}	2.23 10^{109}
I-129	0	3.64 10^{-138}	3.64 10^{-138}	8.25 10^{146}
Ba-133	0	4.96 10^{-25}	4.96 10^{-25}	6.05 10^{33}
Cs-134	0	1.14 10^{-27}	1.14 10^{-27}	2.64 10^{36}
Cs-135	0	5.88 10^{-54}	5.88 10^{-54}	5.10 10^{62}
Cs-137	0	3.25 10^{-20}	3.25 10^{-20}	9.23 10^{28}
Ce-144	0	1.30 10^{-57}	1.30 10^{-57}	2.31 10^{66}
Pm-147	0	7.99 10^{-52}	7.99 10^{-52}	3.75 10^{60}
Sm-147	0	0	0	0
Sm-151	0	0	0	0
Eu-152	0	3.40 10^{-19}	3.40 10^{-19}	8.82 10^{27}
Eu-154	0	8.02 10^{-20}	8.02 10^{-20}	3.74 10^{28}
Eu-155	0	7.57 10^{-44}	7.57 10^{-44}	3.96 10^{52}

Radionuclide	Dose (μSv y^{-1} MBq^{-1})			Scenario radiological capacity (MBq)
	Gas	External	Total	
Gd-153	0	$2.11\ 10^{-69}$	$2.11\ 10^{-69}$	$1.42\ 10^{78}$
Pb-210	0	$3.33\ 10^{-21}$	$3.33\ 10^{-21}$	$9.01\ 10^{29}$
Po-210	0	$1.99\ 10^{-71}$	$1.99\ 10^{-71}$	$1.51\ 10^{80}$
Ra-226	$8.01\ 10^{-5}$	$4.86\ 10^{-16}$	$8.01\ 10^{-5}$	$3.74\ 10^{13}$
Ra-228	0	$6.19\ 10^{-18}$	$6.19\ 10^{-18}$	$4.85\ 10^{26}$
Ac-227	0	$7.11\ 10^{-21}$	$7.11\ 10^{-21}$	$4.22\ 10^{29}$
Th-228	0	$1.98\ 10^{-24}$	$1.98\ 10^{-24}$	$1.51\ 10^{33}$
Th-229	0	$1.64\ 10^{-17}$	$1.64\ 10^{-17}$	$1.83\ 10^{26}$
Th-230	0	$1.28\ 10^{-17}$	$1.28\ 10^{-17}$	$2.35\ 10^{26}$
Th-232	0	$8.57\ 10^{-15}$	$8.57\ 10^{-15}$	$3.50\ 10^{23}$
Pa-231	0	$4.09\ 10^{-20}$	$4.09\ 10^{-20}$	$7.34\ 10^{28}$
U-232	0	$7.56\ 10^{-15}$	$7.56\ 10^{-15}$	$3.97\ 10^{23}$
U-233	0	$9.32\ 10^{-20}$	$9.32\ 10^{-20}$	$3.22\ 10^{28}$
U-234	0	$4.16\ 10^{-41}$	$4.16\ 10^{-41}$	$7.21\ 10^{49}$
U-235	0	$2.48\ 10^{-28}$	$2.48\ 10^{-28}$	$1.21\ 10^{37}$
U-236	0	$2.54\ 10^{-23}$	$2.54\ 10^{-23}$	$1.18\ 10^{32}$
U-238	0	$1.39\ 10^{-19}$	$1.39\ 10^{-19}$	$2.16\ 10^{28}$
Np-237	0	$6.06\ 10^{-25}$	$6.06\ 10^{-25}$	$4.95\ 10^{33}$
Pu-238	0	$3.85\ 10^{-47}$	$3.85\ 10^{-47}$	$7.80\ 10^{55}$
Pu-239	0	$5.29\ 10^{-31}$	$5.29\ 10^{-31}$	$5.67\ 10^{39}$
Pu-240	0	$9.08\ 10^{-47}$	$9.08\ 10^{-47}$	$3.31\ 10^{55}$
Pu-241	0	$2.55\ 10^{-41}$	$2.55\ 10^{-41}$	$1.18\ 10^{50}$
Pu-242	0	$1.29\ 10^{-27}$	$1.29\ 10^{-27}$	$2.32\ 10^{36}$
Pu-244	0	$2.06\ 10^{-19}$	$2.06\ 10^{-19}$	$1.46\ 10^{28}$
Am-241	0	$1.12\ 10^{-29}$	$1.12\ 10^{-29}$	$2.68\ 10^{38}$
Am-242m	0	$8.33\ 10^{-20}$	$8.33\ 10^{-20}$	$3.60\ 10^{28}$
Am-243	0	$1.40\ 10^{-28}$	$1.40\ 10^{-28}$	$2.14\ 10^{37}$
Cm-242	0	$1.92\ 10^{-49}$	$1.92\ 10^{-49}$	$1.56\ 10^{58}$
Cm-243	0	$1.85\ 10^{-29}$	$1.85\ 10^{-29}$	$1.62\ 10^{38}$
Cm-244	0	$1.20\ 10^{-56}$	$1.20\ 10^{-56}$	$2.50\ 10^{65}$
Cm-245	0	$5.10\ 10^{-34}$	$5.10\ 10^{-34}$	$5.88\ 10^{42}$
Cm-246	0	$1.25\ 10^{-68}$	$1.25\ 10^{-68}$	$2.40\ 10^{77}$
Cm-248	0	$1.07\ 10^{-25}$	$1.07\ 10^{-25}$	$2.81\ 10^{34}$
Ra-226$^{\$}$	$1.30\ 10^{-10}$	0	$3.50\ 10^{-13}$	$8.58\ 10^{21}$

Note: $ Ra-226 containing >5 Bq g^{-1} buried 5m or greater below the restored site level

Table 163 Child Site Resident Exposure

Radionuclide	Dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)			Scenario radiological capacity (MBq)
	Gas	External	Total	
H-3	$2.43\ 10^{-8}$	$3.77\ 10^{-12}$	$2.43\ 10^{-8}$	$1.24\ 10^{11}$
C-14	$1.05\ 10^{-5}$	$1.46\ 10^{-63}$	$1.05\ 10^{-5}$	$2.84\ 10^{8}$
Cl-36	0	$5.69\ 10^{-27}$	$5.69\ 10^{-27}$	$5.28\ 10^{29}$
Ca-41	0	0	0	0
Mn-54	0	$1.69\ 10^{-39}$	$1.69\ 10^{-39}$	$1.77\ 10^{42}$
Fe-55	0	$2.81\ 10^{-21}$	$2.81\ 10^{-21}$	$1.07\ 10^{24}$
Co-60	0	$9.77\ 10^{-20}$	$9.77\ 10^{-20}$	$3.07\ 10^{22}$
Ni-59	0	$1.47\ 10^{-9}$	$1.47\ 10^{-9}$	$2.04\ 10^{12}$
Ni-63	0	$8.73\ 10^{-9}$	$8.73\ 10^{-9}$	$3.44\ 10^{11}$
Zn-65	0	$1.47\ 10^{-44}$	$1.47\ 10^{-44}$	$2.04\ 10^{47}$
Se-79	0	$1.36\ 10^{-61}$	$1.36\ 10^{-61}$	$2.21\ 10^{64}$
Sr-90	0	$6.57\ 10^{-25}$	$6.57\ 10^{-25}$	$4.56\ 10^{27}$
Mo-93	0	$1.19\ 10^{-8}$	$1.19\ 10^{-8}$	$2.53\ 10^{11}$
Zr-93	0	$1.57\ 10^{-8}$	$1.57\ 10^{-8}$	$1.92\ 10^{11}$
Nb-93m	0	$1.62\ 10^{-10}$	$1.62\ 10^{-10}$	$1.85\ 10^{13}$
Nb-94	0	$2.35\ 10^{-18}$	$2.35\ 10^{-18}$	$1.28\ 10^{21}$
Tc-99	0	$1.13\ 10^{-45}$	$1.13\ 10^{-45}$	$2.65\ 10^{48}$
Ru-106	0	$1.45\ 10^{-37}$	$1.45\ 10^{-37}$	$2.07\ 10^{40}$
Ag-108m	0	$1.73\ 10^{-19}$	$1.73\ 10^{-19}$	$1.73\ 10^{22}$
Ag-110m	0	$6.46\ 10^{-44}$	$6.46\ 10^{-44}$	$4.64\ 10^{46}$
Cd-109	0	$7.19\ 10^{-63}$	$7.19\ 10^{-63}$	$4.18\ 10^{65}$
Sb-125	0	$4.72\ 10^{-27}$	$4.72\ 10^{-27}$	$6.36\ 10^{29}$
Sn-119m	0	0	0	0
Sn-123	0	$1.93\ 10^{-70}$	$1.93\ 10^{-70}$	$1.55\ 10^{73}$
Sn-126	0	$5.47\ 10^{-19}$	$5.47\ 10^{-19}$	$5.48\ 10^{21}$
Te-127m	0	$2.29\ 10^{-100}$	$2.29\ 10^{-100}$	$1.31\ 10^{103}$
I-129	0	$6.14\ 10^{-138}$	$6.14\ 10^{-138}$	$4.88\ 10^{140}$
Ba-133	0	$7.50\ 10^{-25}$	$7.50\ 10^{-25}$	$4.00\ 10^{27}$
Cs-134	0	$1.70\ 10^{-27}$	$1.70\ 10^{-27}$	$1.77\ 10^{30}$
Cs-135	0	$8.73\ 10^{-54}$	$8.73\ 10^{-54}$	$3.44\ 10^{56}$
Cs-137	0	$4.85\ 10^{-20}$	$4.85\ 10^{-20}$	$6.19\ 10^{22}$
Ce-144	0	$1.98\ 10^{-57}$	$1.98\ 10^{-57}$	$1.52\ 10^{60}$
Pm-147	0	$1.19\ 10^{-51}$	$1.19\ 10^{-51}$	$2.53\ 10^{54}$
Sm-147	0	0	0	0
Sm-151	0	0	0	0
Eu-152	0	$5.07\ 10^{-19}$	$5.07\ 10^{-19}$	$5.92\ 10^{21}$
Eu-154	0	$1.19\ 10^{-19}$	$1.19\ 10^{-19}$	$2.51\ 10^{22}$
Eu-155	0	$1.17\ 10^{-43}$	$1.17\ 10^{-43}$	$2.55\ 10^{46}$

Radionuclide	Dose (µSv y^{-1} MBq^{-1})			Scenario radiological capacity (MBq)
	Gas	External	Total	
Gd-153	0	$3.33\ 10^{-69}$	$3.33\ 10^{-69}$	$9.02\ 10^{71}$
Pb-210	0	$4.95\ 10^{-21}$	$4.95\ 10^{-21}$	$6.06\ 10^{23}$
Po-210	0	$2.96\ 10^{-71}$	$2.96\ 10^{-71}$	$1.01\ 10^{74}$
Ra-226	$1.02\ 10^{-4}$	$7.20\ 10^{-16}$	$1.02\ 10^{-4}$	$2.95\ 10^{7}$
Ra-228	0	$9.16\ 10^{-18}$	$9.16\ 10^{-18}$	$3.27\ 10^{20}$
Ac-227	0	$1.07\ 10^{-20}$	$1.07\ 10^{-20}$	$2.80\ 10^{23}$
Th-228	0	$2.93\ 10^{-24}$	$2.93\ 10^{-24}$	$1.02\ 10^{27}$
Th-229	0	$2.47\ 10^{-17}$	$2.47\ 10^{-17}$	$1.22\ 10^{20}$
Th-230	0	$1.90\ 10^{-17}$	$1.90\ 10^{-17}$	$1.58\ 10^{20}$
Th-232	0	$1.27\ 10^{-14}$	$1.27\ 10^{-14}$	$2.37\ 10^{17}$
Pa-231	0	$6.15\ 10^{-20}$	$6.15\ 10^{-20}$	$4.88\ 10^{22}$
U-232	0	$1.12\ 10^{-14}$	$1.12\ 10^{-14}$	$2.69\ 10^{17}$
U-233	0	$1.40\ 10^{-19}$	$1.40\ 10^{-19}$	$2.14\ 10^{22}$
U-234	0	$6.66\ 10^{-41}$	$6.66\ 10^{-41}$	$4.51\ 10^{43}$
U-235	0	$3.76\ 10^{-28}$	$3.76\ 10^{-28}$	$7.99\ 10^{30}$
U-236	0	$3.75\ 10^{-23}$	$3.75\ 10^{-23}$	$7.99\ 10^{25}$
U-238	0	$2.06\ 10^{-19}$	$2.06\ 10^{-19}$	$1.46\ 10^{22}$
Np-237	0	$9.16\ 10^{-25}$	$9.16\ 10^{-25}$	$3.28\ 10^{27}$
Pu-238	0	$9.03\ 10^{-47}$	$9.03\ 10^{-47}$	$3.32\ 10^{49}$
Pu-239	0	$8.72\ 10^{-31}$	$8.72\ 10^{-31}$	$3.44\ 10^{33}$
Pu-240	0	$1.73\ 10^{-46}$	$1.73\ 10^{-46}$	$1.73\ 10^{49}$
Pu-241	0	$3.84\ 10^{-41}$	$3.84\ 10^{-41}$	$7.82\ 10^{43}$
Pu-242	0	$1.91\ 10^{-27}$	$1.91\ 10^{-27}$	$1.57\ 10^{30}$
Pu-244	0	$3.07\ 10^{-19}$	$3.07\ 10^{-19}$	$9.77\ 10^{21}$
Am-241	0	$1.69\ 10^{-29}$	$1.69\ 10^{-29}$	$1.77\ 10^{32}$
Am-242m	0	$1.26\ 10^{-19}$	$1.26\ 10^{-19}$	$2.38\ 10^{22}$
Am-243	0	$2.14\ 10^{-28}$	$2.14\ 10^{-28}$	$1.40\ 10^{31}$
Cm-242	0	$4.53\ 10^{-49}$	$4.53\ 10^{-49}$	$6.63\ 10^{51}$
Cm-243	0	$2.80\ 10^{-29}$	$2.80\ 10^{-29}$	$1.07\ 10^{32}$
Cm-244	0	$2.75\ 10^{-56}$	$2.75\ 10^{-56}$	$1.09\ 10^{59}$
Cm-245	0	$7.80\ 10^{-34}$	$7.80\ 10^{-34}$	$3.85\ 10^{36}$
Cm-246	0	$2.00\ 10^{-68}$	$2.00\ 10^{-68}$	$1.50\ 10^{71}$
Cm-248	0	$1.60\ 10^{-25}$	$1.60\ 10^{-25}$	$1.88\ 10^{28}$
Ra-226$	$1.66\ 10^{-10}$	$1.14\ 10^{-29}$	$1.66\ 10^{-10}$	$1.81\ 10^{13}$

Note: $ Ra-226 containing >5 Bq g^{-1} buried 5m or greater below the restored site level

Table 164 Infant Site Resident Exposure

Radionuclide	Dose (µSv y^{-1} MBq^{-1})			Scenario radiological capacity (MBq)
	Gas	External	Total	
H-3	2.35 10^{-8}	3.12 10^{-12}	2.35 10^{-8}	1.28 10^{11}
C-14	8.90 10^{-6}	1.21 10^{-63}	8.90 10^{-6}	3.37 10^{8}
Cl-36	0	4.70 10^{-27}	4.70 10^{-27}	6.38 10^{29}
Ca-41	0	0	0	0
Mn-54	0	1.41 10^{-39}	1.41 10^{-39}	2.13 10^{42}
Fe-55	0	2.37 10^{-21}	2.37 10^{-21}	1.26 10^{24}
Co-60	0	8.07 10^{-20}	8.07 10^{-20}	3.72 10^{22}
Ni-59	0	1.23 10^{-9}	1.23 10^{-9}	2.44 10^{12}
Ni-63	0	7.23 10^{-9}	7.23 10^{-9}	4.15 10^{11}
Zn-65	0	1.22 10^{-44}	1.22 10^{-44}	2.46 10^{47}
Se-79	0	1.12 10^{-61}	1.12 10^{-61}	2.68 10^{64}
Sr-90	0	5.41 10^{-25}	5.41 10^{-25}	5.54 10^{27}
Mo-93	0	1.12 10^{-8}	1.12 10^{-8}	2.67 10^{11}
Zr-93	0	1.30 10^{-8}	1.30 10^{-8}	2.32 10^{11}
Nb-93m	0	1.54 10^{-10}	1.54 10^{-10}	1.95 10^{13}
Nb-94	0	1.96 10^{-18}	1.96 10^{-18}	1.53 10^{21}
Tc-99	0	9.30 10^{-46}	9.30 10^{-46}	3.23 10^{48}
Ru-106	0	1.20 10^{-37}	1.20 10^{-37}	2.50 10^{40}
Ag-108m	0	1.45 10^{-19}	1.45 10^{-19}	2.08 10^{22}
Ag-110m	0	5.36 10^{-44}	5.36 10^{-44}	5.60 10^{46}
Cd-109	0	6.40 10^{-63}	6.40 10^{-63}	4.69 10^{65}
Sb-125	0	3.94 10^{-27}	3.94 10^{-27}	7.62 10^{29}
Sn-119m	0	0	0	0
Sn-123	0	1.59 10^{-70}	1.59 10^{-70}	1.89 10^{73}
Sn-126	0	4.56 10^{-19}	4.56 10^{-19}	6.58 10^{21}
Te-127m	0	2.20 10^{-100}	2.20 10^{-100}	1.37 10^{103}
I-129	0	5.95 10^{-138}	5.95 10^{-138}	5.04 10^{140}
Ba-133	0	6.29 10^{-25}	6.29 10^{-25}	4.77 10^{27}
Cs-134	0	1.41 10^{-27}	1.41 10^{-27}	2.12 10^{30}
Cs-135	0	7.20 10^{-54}	7.20 10^{-54}	4.17 10^{56}
Cs-137	0	4.05 10^{-20}	4.05 10^{-20}	7.41 10^{22}
Ce-144	0	1.67 10^{-57}	1.67 10^{-57}	1.79 10^{60}
Pm-147	0	9.82 10^{-52}	9.82 10^{-52}	3.06 10^{54}
Sm-147	0	0	0	0
Sm-151	0	0	0	0
Eu-152	0	4.18 10^{-19}	4.18 10^{-19}	7.17 10^{21}
Eu-154	0	9.86 10^{-20}	9.86 10^{-20}	3.04 10^{22}
Eu-155	0	1.01 10^{-43}	1.01 10^{-43}	2.98 10^{46}

Radionuclide	Dose ($\mu Sv\ y^{-1}\ MBq^{-1}$)			Scenario radiological capacity (MBq)
	Gas	External	Total	
Gd-153	0	$2.92\ 10^{-69}$	$2.92\ 10^{-69}$	$1.03\ 10^{72}$
Pb-210	0	$4.09\ 10^{-21}$	$4.09\ 10^{-21}$	$7.33\ 10^{23}$
Po-210	0	$2.47\ 10^{-71}$	$2.47\ 10^{-71}$	$1.22\ 10^{74}$
Ra-226	$1.14\ 10^{-4}$	$5.92\ 10^{-16}$	$1.14\ 10^{-4}$	$2.64\ 10^{7}$
Ra-228	0	$7.50\ 10^{-18}$	$7.50\ 10^{-18}$	$4.00\ 10^{20}$
Ac-227	0	$8.93\ 10^{-21}$	$8.93\ 10^{-21}$	$3.36\ 10^{23}$
Th-228	0	$2.39\ 10^{-24}$	$2.39\ 10^{-24}$	$1.26\ 10^{27}$
Th-229	0	$2.06\ 10^{-17}$	$2.06\ 10^{-17}$	$1.46\ 10^{20}$
Th-230	0	$1.56\ 10^{-17}$	$1.56\ 10^{-17}$	$1.92\ 10^{20}$
Th-232	0	$1.04\ 10^{-14}$	$1.04\ 10^{-14}$	$2.89\ 10^{17}$
Pa-231	0	$5.13\ 10^{-20}$	$5.13\ 10^{-20}$	$5.84\ 10^{22}$
U-232	0	$9.06\ 10^{-15}$	$9.06\ 10^{-15}$	$3.31\ 10^{17}$
U-233	0	$1.17\ 10^{-19}$	$1.17\ 10^{-19}$	$2.56\ 10^{22}$
U-234	0	$5.72\ 10^{-41}$	$5.72\ 10^{-41}$	$5.25\ 10^{43}$
U-235	0	$3.13\ 10^{-28}$	$3.13\ 10^{-28}$	$9.57\ 10^{30}$
U-236	0	$3.07\ 10^{-23}$	$3.07\ 10^{-23}$	$9.76\ 10^{25}$
U-238	0	$1.70\ 10^{-19}$	$1.70\ 10^{-19}$	$1.77\ 10^{22}$
Np-237	0	$7.65\ 10^{-25}$	$7.65\ 10^{-25}$	$3.92\ 10^{27}$
Pu-238	0	$8.52\ 10^{-47}$	$8.52\ 10^{-47}$	$3.52\ 10^{49}$
Pu-239	0	$7.55\ 10^{-31}$	$7.55\ 10^{-31}$	$3.97\ 10^{33}$
Pu-240	0	$1.58\ 10^{-46}$	$1.58\ 10^{-46}$	$1.90\ 10^{49}$
Pu-241	0	$3.20\ 10^{-41}$	$3.20\ 10^{-41}$	$9.37\ 10^{43}$
Pu-242	0	$1.58\ 10^{-27}$	$1.58\ 10^{-27}$	$1.90\ 10^{30}$
Pu-244	0	$2.54\ 10^{-19}$	$2.54\ 10^{-19}$	$1.18\ 10^{22}$
Am-241	0	$1.42\ 10^{-29}$	$1.42\ 10^{-29}$	$2.12\ 10^{32}$
Am-242m	0	$1.06\ 10^{-19}$	$1.06\ 10^{-19}$	$2.84\ 10^{22}$
Am-243	0	$1.80\ 10^{-28}$	$1.80\ 10^{-28}$	$1.67\ 10^{31}$
Cm-242	0	$4.28\ 10^{-49}$	$4.28\ 10^{-49}$	$7.02\ 10^{51}$
Cm-243	0	$2.34\ 10^{-29}$	$2.34\ 10^{-29}$	$1.28\ 10^{32}$
Cm-244	0	$2.60\ 10^{-56}$	$2.60\ 10^{-56}$	$1.16\ 10^{59}$
Cm-245	0	$6.58\ 10^{-34}$	$6.58\ 10^{-34}$	$4.56\ 10^{36}$
Cm-246	0	$1.69\ 10^{-68}$	$1.69\ 10^{-68}$	$1.78\ 10^{71}$
Cm-248	0	$1.32\ 10^{-25}$	$1.32\ 10^{-25}$	$2.27\ 10^{28}$
Ra-226$	$1.85\ 10^{-10}$	$9.40\ 10^{-30}$	$1.85\ 10^{-10}$	$1.62\ 10^{13}$

Note: $ Ra-226 containing >5 Bq g^{-1} buried 5m or greater below the restored site level

E.5.8. Excavation for housing – Residential Occupant

1214. Construction activities for housing developments would include shallow excavations and cap disturbance to prepare the site and install roads and services. Foundations for domestic and light buildings, typically 1 or 2 m deep, may penetrate the 1.3 m thick capping layer but will not reach the LLW since it is not placed within the top 1 m of waste within the cell. At sites where the load bearing capacity of underlying ground is low, such as made-ground, land in-fill or soft clay, foundations are likely to be cast as a raft (thick concrete slab with steel reinforcement).

1215. In this assessment we assume that the ground has sufficient load bearing capacity for conventional foundations and that construction that might intersect waste at depths greater than 1-2 m below the surface does occur, for example excavation for cellars, an underground car park or underground tanks (for petrol or farm slurry). Excavated material could be used as backfill and in landscaping. Those involved in the excavation would be exposed to the hazard and, in the long term, site occupants could be exposed to contaminated materials that remain in the surface environment.

1216. Contaminated material may be left at the surface, although it is more likely that such materials would be disposed of given the nature of material in the landfill. The non-radioactive waste disposed of at Port Clarence largely comprises treated residues (grey coloured) and asbestos. This material is not biodegradable and will essentially remain the same over geological timescales. This would discourage extensive excavation and it is therefore unlikely that contaminated soil will be left on the surface of the site.

1217. The radioactive and non-radioactive waste includes numerous other materials some of which are unlikely to degrade with time and this would discourage extensive excavation. It is therefore unlikely that extensive excavation will take place and highly unlikely contaminated soil will be left on the surface of the site. Furthermore, the ability of such material to support plant growth is inconceivable without significant dilution of the waste by clean soil.

1218. Occupancy of a smallholding is addressed in Section E.5.10.

E.5.8.1. Estimating activity concentration in waste for exposure calculations

Dilution factors

1219. The excavated spoil will include a mixture of radioactive waste, hazardous waste, soil and cover material, resulting in ‘dilution’ of the radioactive waste with other material. Characteristics that have been used to determine the dilution factor applied to radioactive waste in excavated spoil in other studies include:

- Depth and area of landfill displaced (volume excavated);
- Capping layer depth and waste emplacement cover depth (depth to contaminated waste);
- Proportion of radioactive waste in the landfilled materials;
- Mixing with clean soil is described in different ways:
    - loading of clean soil with excavated spoil;

- depth of waste spread on a given land area;
- depth of clean soil cover or depth of mixing with clean soil; and,

- Fraction of inhabited/utilised area that is contaminated.

1220. The term “dilution factor” is not applied consistently in the studies reviewed and may have incorporated one or more of the factors listed above. It can be used to determine a spoil activity concentration based on the following equation:

$$C_{spoil} = \frac{INV_y}{V_L \cdot \rho_{waste}} \cdot DIL$$

where:

- C_{spoil} is the spoil activity concentration (Bq kg^{-1});
- INV_y is the inventory in the landfill in year y (Bq);
- V_L is the landfill volume (m^3);
- ρ_{waste} is the waste density (kg m^{-3}); and,
- DIL is the dilution factor.

1221. The type of construction will determine the depth and area of displaced material. We have assumed the excavation will be 5 m deep (Hicks & Baldwin, 2011), producing a mixed spoil comprising 1.3 m capping materials, 1.0 m cover and 2.7 m waste. The mixed spoil therefore comprises 54% waste. It is assumed for the ESC that radioactive waste input to the landfill will be on average limited to approximately 5% of total future tonnage inputs to Port Clarence, the rest comprising other wastes and emplacement cover material.

1222. A factor of 0.05 is therefore used for larger excavations (a housing development or small holding) where an average composition is more likely to be displaced and hence the excavated spoil is assumed to contain 2.7% radioactive waste. For relatively small excavations it is conceivable that the displaced waste material will comprise only radioactive waste and this was covered in the assessment of doses to the trial pit excavation worker.

1223. It is clear that clean soil will need to be mixed with the excavated spoil in order to provide a growing medium that will sustain plant growth. A review of dilution factors used in other ESCs is given in ENRMF ESC (Eden NE, 2015a). A growing medium was therefore assumed to contain a maximum of 10% spoil.

1224. This assessment considers the following potentially exposed groups:

- A housing development (60 years after closure) with residents growing their own vegetables to supplement retail purchases.

1225. The assumptions for the excavations for a housing estate are taken from the ENRMF ESC (Eden NE, 2023):

- For the housing development, the excavated area is 400 m^2, removing 2000 m^3 of spoil. It is assumed that the excavated waste contains 5% radioactive material (site average) and is mixed with clean soil (at a rate of 10% spoil) for the garden. Combining the spoil dilution, site average radioactive waste content and mixing with clean soil, an overall dilution factor of 0.0027 is applied (DIL). This is conservative as it does not use assumptions concerning a patchy distribution/partially contaminated area. It is assumed that excavated waste is spread directly under the house and in this case the dilution factor omits the clean soil factor (DIL = 0.027).

1226. A factor, limiting the area assumed to be contaminated to a fraction of that available, has not been applied in this assessment. This is an uncertain factor and could have a far greater impact than any of the factors applied above, in particular where land is used either for a smallholding or is farmed commercially. Available assessments and example calculations have used factors as low as 1.0 10^{-4}.

1227. The long-term occupants of the housing estate are an adult, child and infant living at a residential site built on top of Port Clarence facility. While it is reasonable for a residential occupant to grow some crops (assumed to be green vegetables and root vegetables) in a garden or allotment, it is assumed for the purposes of this assessment that they will not keep livestock or cultivate grain. It is further assumed that only half of this produce consumed comes from their garden, this is reasonable for a household resident where most food is purchased.

Activity concentration in soil

1228. Following excavation, radioactively contaminated waste and the covering layer are mixed, forming a partially-contaminated soil layer. The activity concentration of radionuclide *Rn* in the soil, $C_{Rn,soil,excavate}$ (Bq kg^{-1}) after the excavation event is given by:

$$C_{Rn,soil,excavate} = \frac{A_{Rn}(t)\,.\,Dil}{V_{landfill} \cdot \rho_{landfill}}$$

1229. Where Dil is a dilution factor given by the ratio of the volume of contaminated landfill waste to the volume of other material that is mixed in to form the soil multiplied by any further mixing with uncontaminated surface soil. A value of 0.0027 is used for LLW in the garden as discussed above (see paragraph 1225) and a factor of 0.027 for exposure inside the house.

E.5.8.2. Assessment calculations for Residential Occupant

1230. Doses can result from:

- ingestion of foodstuff grown on contaminated soil;
- ingestion or inhalation of dust from the soil; and,
- external irradiation from contaminated soil.

Ingestion of crops

1231. The dose (Sv y^{-1}) from ingesting crops grown on contaminated soil is given by (Augean, 2009a):

$$Dose_{ing,crops} = \sum_{crop} \{Q_{crop} \cdot [C_{Rn,soil}(t) \cdot UF_{Rn,crop}]\} \cdot D_{Rn,ing}$$

where:

- $Dose_{ing,crops}$ is the dose from ingesting crops grown on contaminated soil (Sv y^{-1});
- Q_{crop} is the crop consumption rate (kg y-1);
- $C_{Rn,soil}(t)$ is the activity concentration of radionuclide Rn at time t (Bq kg^{-1});
- $UF_{Rn,crop}$ is the soil to crop transfer factors for radionuclide Rn (Bq kg^{-1} fresh weight of crop per Bq kg^{-1} of soil); and,
- $D_{Rn,ing}$ is the dose coefficient for ingestion of radionuclide Rn (Sv Bq^{-1}).

1232. Parameter values are summarised in Table 165, dose coefficients for ingestion are given in Table 225 and soil to crop transfer factors are given in Table 230.

Table 165 Parameters used in the long-term occupant scenario[1]

Parameter	Substance	Units	Value	
Consumption rate (adult)	Green vegetables[2]	kg y^{-1}	Mean	17.5
			97.5th	40
	Root vegetables[2]	kg y^{-1}	Mean	30
			97.5th	65
	Soil	kg y^{-1}	0.0083	
Consumption rate (child)	Green vegetables[2]	kg y^{-1}	Mean	7.5
			97.5th	17.5
	Root vegetables[2]	kg y^{-1}	Mean	25
			97.5th	42.5
	Soil	kg y^{-1}	0.018	
Consumption rate (infant)	Green vegetables[2]	kg y^{-1}	Mean	2.5
			97.5th	7.5
	Root vegetables[2]	kg y^{-1}	Mean	7.5
			97.5th	22.5
	Soil	kg y^{-1}	0.044	
Occupancy indoors		y y^{-1}	Adult	0.91
			Child	0.84
			Infant	0.91
Occupancy outdoors		y y^{-1}	Adult	0.09
			Child	0.16
			Infant	0.09
Shielding factor indoors			0.1	
Occupancy dust		h y^{-1}	Adult	788
			Child	1400
			Infant	788
Dustload		kg m^{-3}	1 10^{-7}	
Breathing rate indoors[3]		m^3 h^{-1}	Adult	0.78
			Child	0.56
			Infant	0.19
Breathing rate outdoors[3]		m^3 h^{-1}	Adult	1.21
			Child	0.87
			Infant	0.31
Dilution factor	Soil in garden		0.0027	
Dilution factor	Soil under house		0.027	

1) Values from (Augean, 2009a), unless otherwise stated
2) Taken from NRPB W41 (Smith & Jones, 2003), consumption rates are half of values reported to allow for shop purchases
3) Inhalation rates based on ICRP 66 (ICRP, 1994), see Table 167 and Table 73 for derivation

External irradiation

1233. The dose (Sv y^{-1}) from external irradiation while living and working on contaminated soil is given by (Augean, 2009a):

$$Dose_{irr,soil} = (Clean \cdot O_{out,j} + O_{in,j} \cdot SF) \cdot C_{Rn,soil}(t) \cdot D_{Rn,irr,slab}$$

where:

- $Dose_{irr,soil}$ is the dose from external irradiation (Sv y^{-1});
- $O_{out,j}$ is the fraction of time spent outside by age group j, exposed to contaminated soil (y y^{-1});
- $O_{in,j}$ is the fraction of time spent inside by age group j (y y^{-1});
- $Clean$ is the dilution with clean soil in garden;
- SF is the shielding factor from the ground while indoors;
- $C_{Rn,soil}(t)$ is the activity concentration of radionuclide *Rn* at time *t* (Bq kg^{-1}) in spoil; and,
- $D_{Rn,irr,slab}$ is the dose conversion factor for irradiation from radionuclide *Rn* (Sv y^{-1} Bq^{-1} kg), based on the receptor being 1 m from the ground and assuming a semi-infinite slab of contamination.

1234. Parameter values are summarised in Table 165. Note that the foodstuff consumption rates taken from NRPB W36 (Oatway & Mobbs, 2003) correspond to a residential occupant who cultivates a quantity of root and green vegetables that supplements, but does not form the bulk, of their vegetable intake. A higher rate of consumption would be more appropriate to a smallholder or subsistence cultivator of crops.

1235. Dose conversion factors for irradiation are given in Table 227.

Ingestion of contaminated soil

1236. The dose (Sv y^{-1}) from ingestion of contaminated soil is given by (Augean, 2009a):

$$Dose_{ing,soil} = Q_{soil} \cdot C_{Rn,soil}(t) \cdot D_{Rn,ing}$$

where:

- $Dose_{ing,soil}$ is the dose from ingestion of contaminated soil (Sv y^{-1});
- Q_{soil} is the soil consumption rate (kg y^{-1});
- $C_{Rn,soil}(t)$ is the activity concentration of radionuclide *Rn* at time *t* (Bq kg^{-1}); and,
- $D_{Rn,inh}$ is the dose coefficient for ingestion of radionuclide *Rn* (Sv Bq^{-1}).

Parameter values are summarised in Table 165 and dose coefficients for ingestion are given in Table 225.

Inhalation of contaminated soil

1237. The dose (Sv y^{-1}) from inhalation of contaminated soil is given by (Augean, 2009a):

$$Dose_{inh,soil} = B \cdot O_{dust} \cdot C_{Rn,soil}(t) \cdot Dustload \cdot D_{Rn,inh}$$

where:

- $Dose_{inh,soil}$ is the dose from inhalation of contaminated soil (Sv y^{-1});
- B is the breathing rate (m^3 y^{-1});
- O_{dust} is the fraction of time spent exposed to dust from the soil (y y^{-1});
- $C_{Rn,soil}(t)$ is the activity concentration of radionuclide *Rn* at time *t* (Bq kg^{-1});
- $Dustload$ is the dust concentration in air (kg m^{-3}); and,
- $D_{Rn,inh}$ is the dose coefficient for inhalation of radionuclide *Rn* (Sv Bq^{-1}).

Parameter values are summarised in Table 165 and dose coefficients for inhalation are given in Table 225.

Inhalation of gases

1238. The assessment calculations presented for the residential housing scenario include a contribution based on gas migration from underlying waste (see Section E.5.7) and in the case of radon from excavated waste remaining directly under the house. The average timescales for release of gas for H-3 and C-14 used were 50 y and 100 y, respectively.

1239. The radon model for spoil uses the original model from which the version in SNIFFER is derived (see Section E.5.10.2). The soil depth is assumed to be 0.10 m for the resident.

E.5.8.3. Dose to Residential Occupant on-site 60 years after closure

1240. In Table 166 the dose rates to adult, child and infant residents respectively on the site following construction of houses 60 years after site capping are presented. The largest contributions to dose arise from Ra-226 with no emplacement strategy for wastes containing >5 Bq g^{-1}, C-14, Tc-99 Th-232, Pa-231 and U-232. The impact of Radium placement depth within Port Clarence on radon release is discussed in paragraph 1247.

Table 166 Doses to site residents after 60 years

Radionuclide	Dose to adult ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose to child ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose to infant ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario radiological capacity (MBq)	Limiting age group
H-3	$2.52\ 10^{-8}$	$2.44\ 10^{-8}$	$2.36\ 10^{-8}$	$1.19\ 10^{11}$	Adult
C-14	$1.25\ 10^{-5}$	$1.06\ 10^{-5}$	$8.91\ 10^{-6}$	$2.40\ 10^{8}$	Adult
Cl-36	$3.03\ 10^{-7}$	$3.54\ 10^{-7}$	$5.85\ 10^{-7}$	$5.13\ 10^{9}$	Infant
Ca-41	$6.14\ 10^{-9}$	$8.86\ 10^{-9}$	$4.81\ 10^{-9}$	$3.39\ 10^{11}$	Child
Mn-54	$1.15\ 10^{-28}$	$1.70\ 10^{-28}$	$1.42\ 10^{-28}$	$1.76\ 10^{31}$	Child
Fe-55	$1.30\ 10^{-18}$	$4.84\ 10^{-18}$	$1.83\ 10^{-17}$	$1.64\ 10^{20}$	Infant
Co-60	$1.83\ 10^{-10}$	$2.72\ 10^{-10}$	$2.26\ 10^{-10}$	$1.10\ 10^{13}$	Child
Ni-59	$1.25\ 10^{-10}$	$1.27\ 10^{-10}$	$2.01\ 10^{-10}$	$1.49\ 10^{13}$	Infant
Ni-63	$2.08\ 10^{-10}$	$2.30\ 10^{-10}$	$3.42\ 10^{-10}$	$8.78\ 10^{12}$	Infant
Zn-65	$1.28\ 10^{-34}$	$1.70\ 10^{-34}$	$1.50\ 10^{-34}$	$1.76\ 10^{37}$	Child
Se-79	$1.88\ 10^{-7}$	$5.17\ 10^{-7}$	$5.18\ 10^{-7}$	$5.79\ 10^{9}$	Infant
Sr-90	$5.88\ 10^{-8}$	$7.66\ 10^{-8}$	$5.63\ 10^{-8}$	$3.92\ 10^{10}$	Child
Mo-93	$1.17\ 10^{-8}$	$8.87\ 10^{-9}$	$7.87\ 10^{-9}$	$2.56\ 10^{11}$	Adult
Zr-93	$8.15\ 10^{-11}$	$6.41\ 10^{-11}$	$6.55\ 10^{-11}$	$3.68\ 10^{13}$	Adult
Nb-93m	$1.81\ 10^{-12}$	$2.88\ 10^{-12}$	$6.09\ 10^{-12}$	$4.93\ 10^{14}$	Infant
Nb-94	$2.83\ 10^{-7}$	$4.22\ 10^{-7}$	$3.51\ 10^{-7}$	$7.12\ 10^{9}$	Child
Tc-99	$4.14\ 10^{-7}$	$4.81\ 10^{-7}$	$8.87\ 10^{-7}$	$3.38\ 10^{9}$	Infant
Ru-106	$1.36\ 10^{-25}$	$2.01\ 10^{-25}$	$1.73\ 10^{-25}$	$1.49\ 10^{28}$	Child
Ag-108m	$2.54\ 10^{-7}$	$3.79\ 10^{-7}$	$3.16\ 10^{-7}$	$7.91\ 10^{9}$	Child
Ag-110m	$2.00\ 10^{-33}$	$2.98\ 10^{-33}$	$2.47\ 10^{-33}$	$1.01\ 10^{36}$	Child
Cd-109	$2.57\ 10^{-22}$	$2.44\ 10^{-22}$	$3.22\ 10^{-22}$	$9.31\ 10^{24}$	Infant
Sb-125	$2.06\ 10^{-14}$	$3.09\ 10^{-14}$	$2.58\ 10^{-14}$	$9.72\ 10^{16}$	Child
Sn-119m	$7.04\ 10^{-32}$	$9.06\ 10^{-32}$	$1.50\ 10^{-31}$	$2.00\ 10^{34}$	Infant
Sn-123	$1.82\ 10^{-59}$	$2.43\ 10^{-59}$	$3.39\ 10^{-59}$	$8.86\ 10^{61}$	Infant
Sn-126	$3.85\ 10^{-7}$	$5.66\ 10^{-7}$	$4.99\ 10^{-7}$	$5.30\ 10^{9}$	Child
Te-127m	$4.91\ 10^{-71}$	$6.76\ 10^{-71}$	$1.21\ 10^{-70}$	$2.48\ 10^{73}$	Infant
I-129	$9.08\ 10^{-8}$	$1.04\ 10^{-7}$	$6.83\ 10^{-8}$	$2.90\ 10^{10}$	Child
Ba-133	$1.09\ 10^{-9}$	$1.64\ 10^{-9}$	$1.38\ 10^{-9}$	$1.82\ 10^{12}$	Child

Radionuclide	Dose to adult (µSv y^{-1} MBq^{-1})	Dose to child (µSv y^{-1} MBq^{-1})	Dose to infant (µSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)	Limiting age group
Cs-134	$5.21\ 10^{-16}$	$7.56\ 10^{-16}$	$6.27\ 10^{-16}$	$3.97\ 10^{18}$	Child
Cs-135	$1.70\ 10^{-9}$	$1.36\ 10^{-9}$	$1.09\ 10^{-9}$	$1.77\ 10^{12}$	Adult
Cs-137	$2.74\ 10^{-8}$	$3.88\ 10^{-8}$	$3.23\ 10^{-8}$	$7.73\ 10^{10}$	Child
Ce-144	$1.99\ 10^{-32}$	$3.02\ 10^{-32}$	$3.51\ 10^{-32}$	$8.55\ 10^{34}$	Infant
Pm-147	$5.08\ 10^{-17}$	$7.41\ 10^{-17}$	$8.40\ 10^{-17}$	$3.57\ 10^{19}$	Infant
Sm-147	$7.14\ 10^{-9}$	$6.26\ 10^{-9}$	$9.30\ 10^{-9}$	$3.23\ 10^{11}$	Infant
Sm-151	$2.89\ 10^{-11}$	$4.13\ 10^{-11}$	$5.11\ 10^{-11}$	$5.87\ 10^{13}$	Infant
Eu-152	$9.85\ 10^{-9}$	$1.47\ 10^{-8}$	$1.21\ 10^{-8}$	$2.05\ 10^{11}$	Child
Eu-154	$1.83\ 10^{-9}$	$2.72\ 10^{-9}$	$2.25\ 10^{-9}$	$1.10\ 10^{12}$	Child
Eu-155	$9.04\ 10^{-13}$	$1.40\ 10^{-12}$	$1.22\ 10^{-12}$	$2.14\ 10^{15}$	Child
Gd-153	$2.51\ 10^{-36}$	$3.96\ 10^{-36}$	$3.49\ 10^{-36}$	$7.58\ 10^{38}$	Child
Pb-210	$9.43\ 10^{-8}$	$1.23\ 10^{-7}$	$2.02\ 10^{-7}$	$1.49\ 10^{10}$	Infant
Po-210	$1.80\ 10^{-55}$	$2.76\ 10^{-55}$	$8.78\ 10^{-55}$	$3.42\ 10^{57}$	Infant
Ra-226	$8.26\ 10^{-5}$	$1.06\ 10^{-4}$	$1.18\ 10^{-4}$	$2.54\ 10^{7}$	Infant
Ra-228	$8.10\ 10^{-10}$	$1.98\ 10^{-9}$	$1.70\ 10^{-9}$	$1.52\ 10^{12}$	Child
Ac-227	$2.73\ 10^{-8}$	$3.73\ 10^{-8}$	$4.50\ 10^{-8}$	$6.67\ 10^{10}$	Infant
Th-228	$1.08\ 10^{-16}$	$1.61\ 10^{-16}$	$1.40\ 10^{-16}$	$1.86\ 10^{19}$	Child
Th-229	$7.55\ 10^{-8}$	$1.20\ 10^{-7}$	$1.44\ 10^{-7}$	$2.08\ 10^{10}$	Infant
Th-230	$7.56\ 10^{-8}$	$1.11\ 10^{-7}$	$1.33\ 10^{-7}$	$2.25\ 10^{10}$	Infant
Th-232	$4.85\ 10^{-7}$	$7.72\ 10^{-7}$	$7.79\ 10^{-7}$	$3.85\ 10^{9}$	Infant
Pa-231	$2.01\ 10^{-6}$	$1.60\ 10^{-6}$	$1.26\ 10^{-6}$	$1.50\ 10^{9}$	Adult
U-232	$4.40\ 10^{-7}$	$6.44\ 10^{-7}$	$5.50\ 10^{-7}$	$4.66\ 10^{9}$	Child
U-233	$7.22\ 10^{-9}$	$7.60\ 10^{-9}$	$9.64\ 10^{-9}$	$3.11\ 10^{11}$	Infant
U-234	$6.52\ 10^{-9}$	$6.59\ 10^{-9}$	$8.20\ 10^{-9}$	$3.66\ 10^{11}$	Infant
U-235	$3.23\ 10^{-8}$	$4.41\ 10^{-8}$	$3.97\ 10^{-8}$	$6.80\ 10^{10}$	Child
U-236	$6.23\ 10^{-9}$	$6.20\ 10^{-9}$	$8.15\ 10^{-9}$	$3.68\ 10^{11}$	Infant
U-238	$2.18\ 10^{-8}$	$2.94\ 10^{-8}$	$2.79\ 10^{-8}$	$1.02\ 10^{11}$	Child
Np-237	$6.47\ 10^{-8}$	$7.29\ 10^{-8}$	$6.64\ 10^{-8}$	$4.11\ 10^{10}$	Child
Pu-238	$5.22\ 10^{-9}$	$7.13\ 10^{-9}$	$8.78\ 10^{-9}$	$3.42\ 10^{11}$	Infant
Pu-239	$9.13\ 10^{-9}$	$1.26\ 10^{-8}$	$1.48\ 10^{-8}$	$2.03\ 10^{11}$	Infant
Pu-240	$9.08\ 10^{-9}$	$1.25\ 10^{-8}$	$1.47\ 10^{-8}$	$2.04\ 10^{11}$	Infant

Radionuclide	Dose to adult ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose to child ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose to infant ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario radiological capacity (MBq)	Limiting age group
Pu-241	$2.77\ 10^{-10}$	$3.91\ 10^{-10}$	$4.60\ 10^{-10}$	$6.53\ 10^{12}$	Infant
Pu-242	$8.48\ 10^{-9}$	$1.25\ 10^{-8}$	$1.41\ 10^{-8}$	$2.12\ 10^{11}$	Infant
Pu-244	$7.82\ 10^{-8}$	$1.17\ 10^{-7}$	$1.01\ 10^{-7}$	$2.57\ 10^{10}$	Child
Am-241	$8.30\ 10^{-9}$	$1.17\ 10^{-8}$	$1.39\ 10^{-8}$	$2.16\ 10^{11}$	Infant
Am-242m	$1.22\ 10^{-8}$	$1.71\ 10^{-8}$	$1.92\ 10^{-8}$	$1.56\ 10^{11}$	Infant
Am-243	$3.57\ 10^{-8}$	$5.34\ 10^{-8}$	$4.92\ 10^{-8}$	$5.62\ 10^{10}$	Child
Cm-242	$2.66\ 10^{-11}$	$3.64\ 10^{-11}$	$4.48\ 10^{-11}$	$6.69\ 10^{13}$	Infant
Cm-243	$5.59\ 10^{-9}$	$8.14\ 10^{-9}$	$8.08\ 10^{-9}$	$3.69\ 10^{11}$	Child
Cm-244	$5.44\ 10^{-10}$	$7.33\ 10^{-10}$	$1.11\ 10^{-9}$	$2.71\ 10^{12}$	Infant
Cm-245	$2.05\ 10^{-8}$	$2.90\ 10^{-8}$	$2.85\ 10^{-8}$	$1.04\ 10^{11}$	Child
Cm-246	$9.61\ 10^{-9}$	$1.22\ 10^{-8}$	$1.46\ 10^{-8}$	$2.06\ 10^{11}$	Infant
Cm-248	$3.01\ 10^{-7}$	$4.38\ 10^{-7}$	$3.76\ 10^{-7}$	$6.85\ 10^{9}$	Child
Ra-226[$]	$1.30\ 10^{-10}$	$1.66\ 10^{-10}$	$1.85\ 10^{-10}$	$1.62\ 10^{13}$	Infant

Note: $ Assumes Ra-226 containing >5 Bq g^{-1} distributed below 5 m depth.

1241. The doses calculated using illustrative inventories are considered further in Appendix D.

E.5.9. Excavation for Housing – radon exposure from a house on spoil

1242. This case considers building a house on a spoil/waste mix. This corresponds to a case in which the cap has either completely degraded, or has been destroyed in the intrusion event; thus the house has been built directly upon contaminated soil.

1243. This case assumes long-term occupation of the former landfill site, and thus long-term potential exposure to contaminated wastes.

Table 167 Breathing rates for residents indoors

Parameter	Units	Value	Comment
Breathing rate adult	$m^3\ h^{-1}$	0.78	8.5 h sleeping (0.45 m^3/h), 4.67 h light work (1.5 m^3/h) and 2.33 h sitting (0.54 m^3/h)
Breathing rate child	$m^3\ h^{-1}$	0.56	10 h sleeping (0.31 m^3/h), 5.33 h light work (1.12 m^3/h) and 2.67 h sitting (0.38 m^3/h)
Breathing rate infant	$m^3\ h^{-1}$	0.19	14 h sleeping (0.15 m^3/h), 3.33 h light work (0.35 m^3/h) and 1.67 h sitting (0.22 m^3/h)

Note: Inhalation rates for time spent indoors, based on ICRP 66 (ICRP, 1994).

E.5.9.1. Assessment calculation for radon exposure

1244. The radon model for spoil uses the original model from which the version in SNIFFER is derived. The flux of radon, $F_{radon}(t)$ (Bq m^{-2} y^{-1}), from bare waste is calculated according to (NEA, 1987):

$$F_{radon}(t) = \lambda_{Rn222} \cdot C_{Ra226} \cdot e^{-\lambda_{Ra-226}t} \cdot Dil \, . \rho_{soil} \cdot \tau \cdot h_{soil} \cdot \varepsilon$$

where:

- F_{radon} is the flux of radon from waste (Bq m^{-2} y^{-1});
- C_{Ra226} is the initial Ra-226 concentration in the waste (Bq kg^{-1});
- t is the time at which the flux is evaluated;
- Dil is the fraction of waste in soil;
- ρ_{waste} is the bulk density of the waste (kg m^{-3}) see Table 78;
- τ is the emanation factor, the fraction of the radon atoms produced which escape from the solid phase of the waste into the pore spaces;
- ε is the self-confinement factor; and,
- h_{soil} is the thickness of the soil (m).

1245. The self-confinement factor is calculated from:

$$\varepsilon = \frac{H_{soil}}{h_{soil}} \tanh \frac{h_{soil}}{H_{soil}}$$

where:

- H_{soil} is the effective diffusion relaxation length for the soil (m); and,
- h_{soil} is the thickness of the soil (m).

1246. The effective relaxation length for soil is 0.2 m and the thickness of soil for a house built on spoil is assumed to be 0.1 m.

E.5.9.2. Dose from radon when building on a waste/spoil mix

1247. In Table 168, the results of assessment calculations for radon gas and a dilution factor of 0.027 are presented for waste containing 5 Bq g^{-1} of Ra-226.

Table 168 Radon inhalation doses and radiological capacities for a dwelling built on a waste/spoil mix buried with other LLW at any depth

Case	Indoor Rn-222 activity concentration (Bq m^{-3} MBq^{-1})	Inhalation effective dose (mSv y^{-1} for 5 Bq g^{-1})	Scenario radiological capacity: radon dose (MBq)
Adult	8.42 10^{-7}	1.38	4.77 10^{7}
Child		1.75	3.75 10^{7}
Infant		1.97	3.34 10^{7}

1248. The calculations imply that the average activity concentration of Ra-226 in wastes that are excavated in this scenario, and that will meet the 3 mSv dose criterion, is about 7.6 Bq g^{-1}, based on the dose to an infant. An upper level of 5 Bq g^{-1} would ensure an average activity concentration in waste that was below this level. This restriction only applies to the activity concentration of Ra-226 in wastes that could be excavated. This scenario does not impose restrictions on the Ra-226 activity concentration of wastes that are buried deeper than the excavation depth. Waste emplacement strategies within waste cells can be employed to obviate the constraints imposed by this scenario. If it is cautiously assumed that the maximum depth of any human intrusion event leading to a dwelling built on spoil is 5 m, then ensuring that waste containing Ra-226 above 5 Bq g^{-1} is placed at depths greater than this will prevent it becoming mixed with spoil.

1249. The possibility of radon migration through the remaining cell-filling material must also be considered. Conceptually, this is the same calculation as considered in Section E.3.5 except modelling migration of radon through cell-filling material (i.e. soil, soil-like waste and other non-radium bearing wastes) instead of considering radon migration through an intact cap.

1250. Scoping calculations suggest, therefore, that consideration of waste emplacement strategies (i.e. placing radium bearing wastes at depths of greater than 5 m below the restored surface of the waste cells) may allow constraints upon the site's radium capacity to be set at a higher level.

1251. If wastes containing significant activity concentrations of Ra-226 were placed at depths of greater than 5 m, then this would result in radon migrating through cover material. As discussed earlier as cover depth increases the dose from radon declines. Radium will be placed at various depths from 5 m below the restored surface. The minimum depth which would apply to Radium wastes (and to any LLW) would be 2.3 m since LLW is not placed within the top 1 m of a cell and the cap is 1.3 m thick. A value of 5 Bq g^{-1}, corresponding to the activity concentration specified in the NORM exemption level (see paragraph 185), has been used to limit disposals in the upper layers of waste cells.

1252. The indoor Rn-222 activity concentration can be compared with the UKHSA radon action level of 200 Bq m^{-3} and the target level of 100 Bq m^{-3} for new dwellings (http://www.ukradon.org/information/level). The geometric mean radon level in the unitary authority of Middlesbrough is 15 Bq m^{-3}, with a highest recorded value, prior to 2002, of 41 Bq m^{-3} (Green, et al., 2002). These figures should be compared to a geometric mean radon level in England of 50 Bq m^{-3}, and a geometric mean radon level in Cleveland, the postcode area in which Port Clarence is located, of 20 Bq m^{-3}. If the quantities of radium emplaced in Port Clarence are equal to the radiological capacity given in Table 168 above, then this would result in an indoor Rn-222 activity concentration of approximately 50 to 70 Bq m^{-3} (below the UKHSA action level).

E.5.10. Excavation for a smallholding

E.5.10.1. Assessment calculations for the Smallholder

1253. Occupancy of a smallholding is considered as this is more cautious than a larger farm because it assumes more crops are grown on a relatively small area.

1254. The potentially exposed group is a smallholder (60 years after closure) living over the site who requires 1 to 3 hectares of land and produces meat, milk and a mixture of crops.

1255. The assumptions for the excavations for a smallholding are taken from the ENRMF ESC (Eden NE, 2023):

- For the smallholder, excavations to 5 m (100 m^2) have removed 500 m^3 of spoil for a new slurry tank. It is assumed that excavated waste contains 5% radioactive material and, following mixing with clean soil (at a rate of 10% spoil), the diluted spoil would be spread over an area of 1.6 ha which supports food production as detailed below. Combining the spoil dilution (1.3 m capping layer, 1.0 m cover, 2.7 m waste) during excavation, site average radioactive waste content and mixing with clean soil (0.1), an overall dilution factor of 0.0027 is applied (DIL). This is conservative as it does not use assumptions concerning a patchy distribution/partially contaminated area. It is assumed that excavated waste is spread directly under the house and in this case the dilution factor omits the clean soil factor (DIL = 0.027).

1256. The area of land assumed to be used for the smallholding (1.6 ha) is based on the crop yields in SNIFFER, critical group consumption rates (NDAWG, 2013) and sufficient crops to feed 3 adults (adult ingestion rates are greater than child and infant). The land also supports 2 cows using 0.57 forage ha, and 2 followers (at a rate of 1 ha for every

3 ha to cows) (Nix, 2010). On this basis the pasture required amounts to about 1.5 ha with a further 0.1 ha for growing crops.

1257. The smallholding case is conceptually similar to the long-term residential occupant described in Section E.5.8 but includes additional exposure pathways: it is assumed that the smallholder may grow green and root vegetables, farm some livestock (e.g. cows) and that they consume both the meat and milk from this livestock. In consequence, the mathematical model for the smallholder is based on that of the residential occupant, and the following equation that calculates the dose (Sv y^{-1}) arising from ingesting animal foodstuff (e.g. meat and milk) raised on contaminated land is given by Galson (Augean, 2009a):

$$Dose_{ing,animal} = \sum_{animal} \{Q_{animal} \cdot [q_{soil} \cdot C_{Rn,soil}(t) + q_{pasture} \cdot C_{Rn,soil}(t) \cdot UF_{Rn,grass}] \cdot TF_{Rn,animal}\} \cdot D_{Rn,ing}$$

where:

- $Dose_{ing,animal}$ is the dose arising from ingesting animal foodstuffs (Sv y^{-1});
- Q_{animal} is the consumption rate of animal foodstuff (kg y^{-1});
- q_{soil} is the soil consumption rate by the animal (kg d^{-1});
- $q_{pasture}$ is the pasture consumption rate by the animal (kg d^{-1});
- $UF_{Rn,grass}$ is the soil to grass transfer factor for radionuclide *Rn* (Bq kg^{-1} fresh weight of crop per Bq kg^{-1} of soil);
- $TF_{Rn,animal}$ is the animal product transfer factor for radionuclide *Rn* (d kg^{-1});
- $C_{Rn,soil}(t)$ is the activity concentration of radionuclide *Rn* at time *t* (Bq kg^{-1}); and,
- $D_{Rn,ing}$ is the dose coefficient for ingestion of radionuclide *Rn* (Sv Bq^{-1}).

1258. The smallholding calculation is carried out at 60 years after closure. Note that the overall dilution factor applied to LLW for soil used for the crops and livestock is 0.0027 as discussed above (see paragraph 1224). The house is assumed to be built on an intact part of the cap. External exposure inside the house is dominated by the contribution from the surrounding soil (with SF) rather than by the direct radiation through the floor. Soil to crop transfer factors are given in Table 230 and dose coefficients for ingestion are given in Table 225. Relevant parameters for the smallholding scenario are given in Table 169 and animal produce transfer factors are given in Table 231.

Table 169 Parameters for smallholding scenario

Parameter	Substance	Units	Value	
Consumption rate (adult)	Green vegetables[2]	kg y^{-1}	Mean	35
			97.5^{th}	80
	Root vegetables[2]	kg y^{-1}	Mean	60
			97.5^{th}	130
	Meat[2]	kg y^{-1}	Mean	23

Parameter	Substance	Units	Value	
			97.5th	70
	Milk[2]	kg y^{-1}	Mean	95
			97.5th	240
	Soil	kg y^{-1}	0.0083	
Consumption rate (child)	Green vegetables[2]	kg y^{-1}	Mean	15
			97.5th	35
	Root vegetables[2]	kg y^{-1}	Mean	50
			97.5th	95
	Meat[2]	kg y^{-1}	Mean	19
			97.5th	40
	Milk[2]	kg y^{-1}	Mean	110
			97.5th	240
	Soil	kg y^{-1}	0.018	
Consumption rate (infant)	Green vegetables[2]	kg y^{-1}	Mean	5
			97.5th	15
	Root vegetables[2]	kg y^{-1}	Mean	15
			97.5th	45
	Meat[2]	kg y^{-1}	Mean	3.8
			97.5th	13
	Milk[2]	kg y^{-1}	Mean	130
			97.5th	320
	Soil	kg y^{-1}	0.044	
Occupancy indoors		y y^{-1}	Adult	0.72
			Child	0.84
			Infant	0.91
Occupancy outdoors		y y^{-1}	Adult	0.28
			Child	0.16
			Infant	0.09
Shielding factor indoors			0.1	
Dustload		kg m^{-3}	1 10^{-7}	
Occupancy dust		h y^{-1}	Adult	2452.4
			Child	1400.0
			Infant	788.0
Breathing rate indoors[3]		m^3 h^{-1}	Adult	0.78
			Child	0.56
			Infant	0.19
Breathing rate outdoors[3]		m^3 h^{-1}	Adult	1.69
			Child	0.87
			Infant	0.31
Dilution factor	Soil on land		0.0027	
Dilution factor	Soil under house		0.027	
Animal consumption rate	Pasture	kg d^{-1}	55	
	Soils	kg d^{-1}	0.6	

1) Values from (Augean, 2009a), unless otherwise stated
2) Taken from NRPB W41 (Smith & Jones, 2003), consumption rates are half of values reported to allow for shop purchases
3) Inhalation rates based on ICRP 66 (ICRP, 1994), see Table 167 and Table 73 for derivation

1259. The assessment calculations presented for the smallholding scenario also include a gas contribution based on gas migration from underlying waste (see Section E.5.7) and in the case of radon from excavated waste remaining directly under the house. The average timescale for gas release of H-3 and C-14 was 50 and 100 years, respectively, these values are used to determine the fraction of the inventory released each year (Bq y^{-1}).

1260. The radon model for spoil uses the original model from which the version in SNIFFER is derived (see Section E.5.9.2).

E.5.10.2. Assessment calculation for radon exposure

1261. The flux of radon, $F_{radon}(t)$ (Bq m^{-2} y^{-1}), from bare waste is calculated according to (NEA, 1987):

$$F_{radon}(t) = \lambda_{Rn222} \cdot C_{Ra226} \cdot e^{-\lambda_{Ra-226}t} \cdot Dil \,.\, \rho_{soil} \cdot \tau \cdot h_{soil} \cdot \varepsilon$$

where:

- F_{radon} is the flux of radon from waste (Bq m^{-2} y^{-1});
- C_{Ra226} is the initial Ra-226 concentration in the waste (Bq kg^{-1});
- t is the time at which the flux is evaluated;
- Dil is the fraction of waste in soil;
- ρ_{waste} is the bulk density of the waste (kg m^{-3}) see Table 118;
- τ is the emanation factor, the fraction of the radon atoms produced which escape from the solid phase of the waste into the pore spaces;
- ε is the self-confinement factor; and,
- h_{soil} is the thickness of the soil (m).

1262. The self-confinement factor is calculated from:

$$\varepsilon = \frac{H_{soil}}{h_{soil}} \tanh \frac{h_{soil}}{H_{soil}}$$

where:

- H_{soil} is the effective diffusion relaxation length for the soil (m); and,
- h_{soil} is the thickness of the soil (m).

1263. The effective relaxation length for soil is 0.2 m and the thickness of soil is assumed to be 0.1 m.

E.5.10.3. Dose to Smallholder on-site 60 years after site closure

In Table 170 the dose rates to an adult, child and infant smallholder respectively on the site following construction of a slurry pit 60 years after site capping are presented. The largest dose rates per MBq arise from Ra-226 assuming no emplacement strategy for wastes containing >5 Bq g^{-1}, C-14, Cl-36, Tc-99, Th-232 and Pa-231. The sensitivity of the dose and hence the capacity to the time of intrusion is discussed in Section E.8.1.1.

Table 170 Doses to smallholder family 60 years after closure

Radionuclide	Dose to adult ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose to child ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Dose to infant ($\mu Sv\ y^{-1}\ MBq^{-1}$)	Scenario radiological capacity (MBq)	Limiting age group
H-3	$2.04\ 10^{-8}$	$2.49\ 10^{-8}$	$2.46\ 10^{-8}$	$1.20\ 10^{11}$	Child
C-14	$9.90\ 10^{-6}$	$1.06\ 10^{-5}$	$8.93\ 10^{-6}$	$2.84\ 10^{8}$	Child
Cl-36	$1.18\ 10^{-6}$	$2.06\ 10^{-6}$	$6.85\ 10^{-6}$	$4.38\ 10^{8}$	Infant
Ca-41	$1.85\ 10^{-8}$	$3.82\ 10^{-8}$	$3.72\ 10^{-8}$	$7.85\ 10^{10}$	Child
Mn-54	$2.24\ 10^{-28}$	$1.73\ 10^{-28}$	$1.46\ 10^{-28}$	$1.34\ 10^{31}$	Adult
Fe-55	$3.38\ 10^{-17}$	$6.74\ 10^{-17}$	$6.38\ 10^{-17}$	$4.45\ 10^{19}$	Child
Co-60	$3.56\ 10^{-10}$	$2.76\ 10^{-10}$	$2.30\ 10^{-10}$	$8.42\ 10^{12}$	Adult
Ni-59	$2.77\ 10^{-10}$	$3.15\ 10^{-10}$	$5.56\ 10^{-10}$	$5.39\ 10^{12}$	Infant
Ni-63	$4.58\ 10^{-10}$	$5.46\ 10^{-10}$	$9.21\ 10^{-10}$	$3.26\ 10^{12}$	Infant
Zn-65	$6.66\ 10^{-34}$	$5.98\ 10^{-34}$	$5.87\ 10^{-34}$	$4.51\ 10^{36}$	Adult
Se-79	$4.29\ 10^{-7}$	$1.47\ 10^{-6}$	$2.11\ 10^{-6}$	$1.42\ 10^{9}$	Infant
Sr-90	$1.28\ 10^{-7}$	$1.97\ 10^{-7}$	$1.86\ 10^{-7}$	$1.52\ 10^{10}$	Child
Mo-93	$1.98\ 10^{-7}$	$2.30\ 10^{-7}$	$4.62\ 10^{-7}$	$6.50\ 10^{9}$	Infant
Zr-93	$1.60\ 10^{-10}$	$8.17\ 10^{-11}$	$7.54\ 10^{-11}$	$1.88\ 10^{13}$	Adult
Nb-93m	$3.58\ 10^{-12}$	$5.50\ 10^{-12}$	$9.88\ 10^{-12}$	$3.04\ 10^{14}$	Infant
Nb-94	$5.50\ 10^{-7}$	$4.22\ 10^{-7}$	$3.51\ 10^{-7}$	$5.45\ 10^{9}$	Adult
Tc-99	$8.29\ 10^{-7}$	$1.04\ 10^{-6}$	$1.78\ 10^{-6}$	$1.69\ 10^{9}$	Infant
Ru-106	$2.69\ 10^{-25}$	$2.12\ 10^{-25}$	$1.84\ 10^{-25}$	$1.11\ 10^{28}$	Adult
Ag-108m	$4.94\ 10^{-7}$	$3.80\ 10^{-7}$	$3.17\ 10^{-7}$	$6.08\ 10^{9}$	Adult
Ag-110m	$3.89\ 10^{-33}$	$2.98\ 10^{-33}$	$2.47\ 10^{-33}$	$7.71\ 10^{35}$	Adult
Cd-109	$6.89\ 10^{-22}$	$7.16\ 10^{-22}$	$8.19\ 10^{-22}$	$3.66\ 10^{24}$	Infant
Sb-125	$4.00\ 10^{-14}$	$3.09\ 10^{-14}$	$2.59\ 10^{-14}$	$7.50\ 10^{16}$	Adult
Sn-119m	$1.51\ 10^{-31}$	$2.15\ 10^{-31}$	$4.27\ 10^{-31}$	$7.03\ 10^{33}$	Infant
Sn-123	$3.78\ 10^{-59}$	$4.57\ 10^{-59}$	$8.34\ 10^{-59}$	$3.60\ 10^{61}$	Infant
Sn-126	$7.56\ 10^{-7}$	$6.23\ 10^{-7}$	$6.14\ 10^{-7}$	$3.97\ 10^{9}$	Adult
Te-127m	$1.69\ 10^{-70}$	$2.48\ 10^{-70}$	$3.85\ 10^{-70}$	$7.80\ 10^{72}$	Infant
I-129	$2.44\ 10^{-7}$	$3.36\ 10^{-7}$	$2.86\ 10^{-7}$	$8.93\ 10^{9}$	Child
Ba-133	$2.14\ 10^{-9}$	$1.73\ 10^{-9}$	$1.51\ 10^{-9}$	$1.40\ 10^{12}$	Adult
Cs-134	$1.08\ 10^{-15}$	$8.07\ 10^{-16}$	$6.77\ 10^{-16}$	$2.77\ 10^{18}$	Adult
Cs-135	$7.39\ 10^{-9}$	$4.84\ 10^{-9}$	$5.03\ 10^{-9}$	$4.06\ 10^{11}$	Adult

Radionuclide	Dose to adult (µSv y^{-1} MBq^{-1})	Dose to child (µSv y^{-1} MBq^{-1})	Dose to infant (µSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)	Limiting age group
Cs-137	$5.99\ 10^{-8}$	$4.39\ 10^{-8}$	$3.75\ 10^{-8}$	$5.01\ 10^{10}$	Adult
Ce-144	$3.87\ 10^{-32}$	$3.38\ 10^{-32}$	$4.08\ 10^{-32}$	$7.35\ 10^{34}$	Infant
Pm-147	$1.02\ 10^{-16}$	$1.01\ 10^{-16}$	$1.19\ 10^{-16}$	$2.51\ 10^{19}$	Infant
Sm-147	$1.56\ 10^{-8}$	$1.21\ 10^{-8}$	$1.47\ 10^{-8}$	$1.92\ 10^{11}$	Adult
Sm-151	$5.71\ 10^{-11}$	$5.28\ 10^{-11}$	$6.68\ 10^{-11}$	$4.49\ 10^{13}$	Infant
Eu-152	$1.91\ 10^{-8}$	$1.47\ 10^{-8}$	$1.21\ 10^{-8}$	$1.57\ 10^{11}$	Adult
Eu-154	$3.56\ 10^{-9}$	$2.73\ 10^{-9}$	$2.26\ 10^{-9}$	$8.43\ 10^{11}$	Adult
Eu-155	$1.76\ 10^{-12}$	$1.42\ 10^{-12}$	$1.24\ 10^{-12}$	$1.71\ 10^{15}$	Adult
Gd-153	$4.88\ 10^{-36}$	$3.96\ 10^{-36}$	$3.50\ 10^{-36}$	$6.14\ 10^{38}$	Adult
Pb-210	$2.22\ 10^{-7}$	$3.32\ 10^{-7}$	$6.83\ 10^{-7}$	$4.39\ 10^{9}$	Infant
Po-210	$1.80\ 10^{-54}$	$2.51\ 10^{-54}$	$4.71\ 10^{-54}$	$6.37\ 10^{56}$	Infant
Ra-226	$6.87\ 10^{-5}$	$1.09\ 10^{-4}$	$1.23\ 10^{-4}$	$2.43\ 10^{7}$	Infant
Ra-228	$1.68\ 10^{-9}$	$4.09\ 10^{-9}$	$3.64\ 10^{-9}$	$7.34\ 10^{11}$	Child
Ac-227	$6.51\ 10^{-8}$	$5.03\ 10^{-8}$	$5.69\ 10^{-8}$	$4.61\ 10^{10}$	Adult
Th-228	$2.12\ 10^{-16}$	$1.63\ 10^{-16}$	$1.42\ 10^{-16}$	$1.41\ 10^{19}$	Adult
Th-229	$1.86\ 10^{-7}$	$1.35\ 10^{-7}$	$1.56\ 10^{-7}$	$1.61\ 10^{10}$	Adult
Th-230	$1.72\ 10^{-7}$	$2.06\ 10^{-7}$	$2.71\ 10^{-7}$	$1.11\ 10^{10}$	Infant
Th-232	$9.73\ 10^{-7}$	$8.31\ 10^{-7}$	$8.15\ 10^{-7}$	$3.08\ 10^{9}$	Adult
Pa-231	$4.09\ 10^{-6}$	$3.26\ 10^{-6}$	$2.29\ 10^{-6}$	$7.34\ 10^{8}$	Adult
U-232	$8.65\ 10^{-7}$	$6.93\ 10^{-7}$	$6.09\ 10^{-7}$	$3.47\ 10^{9}$	Adult
U-233	$1.65\ 10^{-8}$	$1.48\ 10^{-8}$	$1.75\ 10^{-8}$	$1.71\ 10^{11}$	Infant
U-234	$1.48\ 10^{-8}$	$1.34\ 10^{-8}$	$1.54\ 10^{-8}$	$1.94\ 10^{11}$	Infant
U-235	$6.49\ 10^{-8}$	$5.27\ 10^{-8}$	$4.83\ 10^{-8}$	$4.62\ 10^{10}$	Adult
U-236	$1.41\ 10^{-8}$	$1.26\ 10^{-8}$	$1.54\ 10^{-8}$	$1.95\ 10^{11}$	Infant
U-238	$4.43\ 10^{-8}$	$3.63\ 10^{-8}$	$3.59\ 10^{-8}$	$6.78\ 10^{10}$	Adult
Np-237	$1.35\ 10^{-7}$	$9.36\ 10^{-8}$	$8.29\ 10^{-8}$	$2.21\ 10^{10}$	Adult
Pu-238	$1.92\ 10^{-8}$	$7.64\ 10^{-9}$	$9.34\ 10^{-9}$	$1.56\ 10^{11}$	Adult
Pu-239	$3.36\ 10^{-8}$	$1.35\ 10^{-8}$	$1.57\ 10^{-8}$	$8.92\ 10^{10}$	Adult
Pu-240	$3.35\ 10^{-8}$	$1.34\ 10^{-8}$	$1.57\ 10^{-8}$	$8.97\ 10^{10}$	Adult
Pu-241	$1.07\ 10^{-9}$	$5.11\ 10^{-10}$	$5.30\ 10^{-10}$	$2.81\ 10^{12}$	Adult
Pu-242	$3.10\ 10^{-8}$	$1.34\ 10^{-8}$	$1.50\ 10^{-8}$	$9.67\ 10^{10}$	Adult
Pu-244	$1.67\ 10^{-7}$	$1.18\ 10^{-7}$	$1.02\ 10^{-7}$	$1.80\ 10^{10}$	Adult
Am-241	$3.19\ 10^{-8}$	$1.54\ 10^{-8}$	$1.61\ 10^{-8}$	$9.39\ 10^{10}$	Adult

Radionuclide	Dose to adult (μSv y^{-1} MBq^{-1})	Dose to child (μSv y^{-1} MBq^{-1})	Dose to infant (μSv y^{-1} MBq^{-1})	Scenario radiological capacity (MBq)	Limiting age group
Am-242m	$4.40\ 10^{-8}$	$2.10\ 10^{-8}$	$2.15\ 10^{-8}$	$6.83\ 10^{10}$	Adult
Am-243	$8.67\ 10^{-8}$	$5.74\ 10^{-8}$	$5.16\ 10^{-8}$	$3.46\ 10^{10}$	Adult
Cm-242	$9.81\ 10^{-11}$	$3.90\ 10^{-11}$	$4.77\ 10^{-11}$	$3.06\ 10^{13}$	Adult
Cm-243	$1.31\ 10^{-8}$	$8.42\ 10^{-9}$	$8.33\ 10^{-9}$	$2.29\ 10^{11}$	Adult
Cm-244	$1.86\ 10^{-9}$	$8.39\ 10^{-10}$	$1.20\ 10^{-9}$	$1.62\ 10^{12}$	Adult
Cm-245	$5.32\ 10^{-8}$	$3.07\ 10^{-8}$	$2.97\ 10^{-8}$	$5.64\ 10^{10}$	Adult
Cm-246	$3.16\ 10^{-8}$	$1.39\ 10^{-8}$	$1.57\ 10^{-8}$	$9.50\ 10^{10}$	Adult
Cm-248	$6.33\ 10^{-7}$	$4.44\ 10^{-7}$	$3.80\ 10^{-7}$	$4.74\ 10^{9}$	Adult
Ra-226$	$1.03\ 10^{-10}$	$1.66\ 10^{-10}$	$1.85\ 10^{-10}$	$1.62\ 10^{13}$	Infant

Note: $ Assumes Ra-226 containing >5 Bq g^{-1} distributed below 5 m depth.

1264. The critical group consumption rate is applied to the two foodstuffs with the greatest contribution to dose rate. This varies by radionuclide as shown below in Table 171 for adult consumption. There are several cases where animal products result in larger dose rates (e.g. Cl-36, Cs-134 and Cs-137).

Table 171 Contributing foodstuff doses in the diet of an adult smallholder

Radionuclide	Dose per MBq (µSv y^{-1} MBq^{-1})			
	Root vegetables	Green vegetables	Meat	Milk
H-3	$2.46\ 10^{-10}$	$6.63\ 10^{-11}$	$6.96\ 10^{-11}$	$2.50\ 10^{-10}$
C-14	$2.13\ 10^{-9}$	$1.24\ 10^{-9}$	$1.82\ 10^{-8}$	$5.19\ 10^{-9}$
Cl-36	$3.72\ 10^{-7}$	$1.00\ 10^{-7}$	$6.17\ 10^{-8}$	$6.43\ 10^{-7}$
Ca-41	$7.60\ 10^{-9}$	$2.04\ 10^{-9}$	$9.82\ 10^{-10}$	$7.88\ 10^{-9}$
Mn-54	$3.53\ 10^{-30}$	$1.06\ 10^{-30}$	$4.98\ 10^{-32}$	$1.40\ 10^{-32}$
Fe-55	$1.33\ 10^{-18}$	$1.79\ 10^{-19}$	$3.17\ 10^{-17}$	$1.08\ 10^{-19}$
Co-60	$2.24\ 10^{-12}$	$1.07\ 10^{-12}$	$1.45\ 10^{-14}$	$1.53\ 10^{-14}$
Ni-59	$1.51\ 10^{-10}$	$9.30\ 10^{-11}$	$1.52\ 10^{-11}$	$1.19\ 10^{-11}$
Ni-63	$2.38\ 10^{-10}$	$1.46\ 10^{-10}$	$2.39\ 10^{-11}$	$1.87\ 10^{-11}$
Zn-65	$7.79\ 10^{-36}$	$4.15\ 10^{-35}$	$4.14\ 10^{-34}$	$9.49\ 10^{-36}$
Se-79	$2.32\ 10^{-7}$	$1.43\ 10^{-7}$	$1.60\ 10^{-8}$	$3.77\ 10^{-8}$
Sr-90	$8.34\ 10^{-8}$	$2.71\ 10^{-8}$	$2.08\ 10^{-9}$	$8.59\ 10^{-9}$
Mo-93	$7.25\ 10^{-9}$	$3.37\ 10^{-9}$	$3.93\ 10^{-8}$	$1.48\ 10^{-7}$
Zr-93	$7.04\ 10^{-11}$	$2.17\ 10^{-11}$	$1.43\ 10^{-14}$	$1.77\ 10^{-13}$
Nb-93m	$2.48\ 10^{-12}$	$7.62\ 10^{-13}$	$3.12\ 10^{-17}$	$2.03\ 10^{-16}$
Nb-94	$4.61\ 10^{-10}$	$1.42\ 10^{-10}$	$5.81\ 10^{-15}$	$3.78\ 10^{-14}$
Tc-99	$5.12\ 10^{-7}$	$3.15\ 10^{-7}$	$4.99\ 10^{-10}$	$4.74\ 10^{-10}$
Ru-106	$1.14\ 10^{-27}$	$6.85\ 10^{-27}$	$6.15\ 10^{-27}$	$2.38\ 10^{-29}$
Ag-108m	$4.33\ 10^{-11}$	$8.07\ 10^{-13}$	$7.82\ 10^{-12}$	$1.36\ 10^{-10}$
Ag-110m	$2.29\ 10^{-37}$	$4.26\ 10^{-39}$	$4.13\ 10^{-38}$	$7.18\ 10^{-37}$
Cd-109	$1.11\ 10^{-22}$	$2.71\ 10^{-22}$	$2.90\ 10^{-22}$	$1.29\ 10^{-23}$
Sb-125	$3.66\ 10^{-18}$	$7.47\ 10^{-20}$	$2.19\ 10^{-17}$	$9.42\ 10^{-19}$
Sn-119m	$8.44\ 10^{-32}$	$5.20\ 10^{-32}$	$3.29\ 10^{-33}$	$7.16\ 10^{-33}$
Sn-123	$1.46\ 10^{-59}$	$8.98\ 10^{-60}$	$5.69\ 10^{-61}$	$1.24\ 10^{-60}$
Sn-126	$4.06\ 10^{-8}$	$2.50\ 10^{-8}$	$1.58\ 10^{-9}$	$3.44\ 10^{-9}$
Te-127m	$7.33\ 10^{-71}$	$9.87\ 10^{-72}$	$7.87\ 10^{-71}$	$5.19\ 10^{-72}$
I-129	$1.76\ 10^{-7}$	$1.54\ 10^{-9}$	$6.89\ 10^{-9}$	$5.80\ 10^{-8}$
Ba-133	$1.06\ 10^{-12}$	$3.10\ 10^{-13}$	$5.83\ 10^{-12}$	$2.29\ 10^{-11}$
Cs-134	$1.41\ 10^{-17}$	$4.40\ 10^{-18}$	$5.29\ 10^{-17}$	$3.79\ 10^{-17}$
Cs-135	$8.27\ 10^{-10}$	$2.58\ 10^{-10}$	$3.11\ 10^{-9}$	$2.23\ 10^{-9}$
Cs-137	$1.35\ 10^{-9}$	$4.23\ 10^{-10}$	$5.09\ 10^{-9}$	$3.65\ 10^{-9}$
Ce-144	$3.49\ 10^{-33}$	$1.07\ 10^{-33}$	$9.58\ 10^{-36}$	$3.96\ 10^{-35}$
Pm-147	$2.27\ 10^{-17}$	$2.18\ 10^{-18}$	$5.57\ 10^{-18}$	$3.02\ 10^{-20}$
Sm-147	$7.84\ 10^{-9}$	$4.82\ 10^{-9}$	$2.51\ 10^{-10}$	$4.07\ 10^{-11}$
Sm-151	$9.88\ 10^{-12}$	$6.08\ 10^{-12}$	$3.16\ 10^{-13}$	$5.12\ 10^{-14}$
Eu-152	$1.56\ 10^{-11}$	$9.58\ 10^{-12}$	$3.30\ 10^{-13}$	$1.45\ 10^{-13}$
Eu-154	$3.80\ 10^{-12}$	$2.34\ 10^{-12}$	$8.05\ 10^{-14}$	$3.54\ 10^{-14}$
Eu-155	$1.23\ 10^{-14}$	$7.60\ 10^{-15}$	$2.62\ 10^{-16}$	$1.15\ 10^{-16}$
Gd-153	$4.68\ 10^{-39}$	$4.80\ 10^{-39}$	$4.69\ 10^{-41}$	$2.91\ 10^{-40}$
Pb-210	$6.97\ 10^{-8}$	$1.14\ 10^{-7}$	$1.64\ 10^{-8}$	$1.84\ 10^{-8}$
Po-210	$2.39\ 10^{-55}$	$4.10\ 10^{-56}$	$1.43\ 10^{-54}$	$8.14\ 10^{-56}$
Ra-226*	$2.37\ 10^{-6}$	$9.48\ 10^{-7}$	$1.40\ 10^{-7}$	$1.29\ 10^{-7}$

Radionuclide	Dose per MBq ($\mu Sv\ y^{-1}\ MBq^{-1}$)			
	Root vegetables	Green vegetables	Meat	Milk
Ra-228	$6.74\ 10^{-10}$	$2.70\ 10^{-10}$	$3.98\ 10^{-11}$	$3.67\ 10^{-11}$
Ac-227	$1.43\ 10^{-8}$	$8.83\ 10^{-9}$	$2.66\ 10^{-10}$	$2.75\ 10^{-12}$
Th-228	$6.56\ 10^{-19}$	$1.32\ 10^{-19}$	$6.56\ 10^{-19}$	$1.94\ 10^{-20}$
Th-229	$7.80\ 10^{-9}$	$1.58\ 10^{-9}$	$7.81\ 10^{-9}$	$2.30\ 10^{-10}$
Th-230	$6.51\ 10^{-8}$	$2.55\ 10^{-8}$	$6.37\ 10^{-9}$	$3.48\ 10^{-9}$
Th-232	$1.36\ 10^{-8}$	$2.75\ 10^{-9}$	$1.36\ 10^{-8}$	$4.02\ 10^{-10}$
Pa-231	$2.35\ 10^{-6}$	$1.45\ 10^{-6}$	$2.93\ 10^{-9}$	$5.96\ 10^{-10}$
U-232	$3.48\ 10^{-8}$	$2.55\ 10^{-8}$	$1.26\ 10^{-9}$	$2.66\ 10^{-9}$
U-233	$6.90\ 10^{-9}$	$5.03\ 10^{-9}$	$2.92\ 10^{-10}$	$5.26\ 10^{-10}$
U-234	$6.58\ 10^{-9}$	$4.82\ 10^{-9}$	$2.40\ 10^{-10}$	$5.04\ 10^{-10}$
U-235	$9.24\ 10^{-9}$	$6.43\ 10^{-9}$	$2.32\ 10^{-10}$	$4.88\ 10^{-10}$
U-236	$6.32\ 10^{-9}$	$4.63\ 10^{-9}$	$2.28\ 10^{-10}$	$4.84\ 10^{-10}$
U-238	$6.50\ 10^{-9}$	$4.77\ 10^{-9}$	$2.35\ 10^{-10}$	$4.98\ 10^{-10}$
Np-237	$3.90\ 10^{-8}$	$1.47\ 10^{-8}$	$1.74\ 10^{-9}$	$3.62\ 10^{-11}$
Pu-238	$8.94\ 10^{-10}$	$2.62\ 10^{-11}$	$1.37\ 10^{-12}$	$1.27\ 10^{-10}$
Pu-239	$1.56\ 10^{-9}$	$4.46\ 10^{-11}$	$2.34\ 10^{-12}$	$2.22\ 10^{-10}$
Pu-240	$1.55\ 10^{-9}$	$4.44\ 10^{-11}$	$2.33\ 10^{-12}$	$2.21\ 10^{-10}$
Pu-241	$6.45\ 10^{-11}$	$3.45\ 10^{-12}$	$1.44\ 10^{-10}$	$4.00\ 10^{-13}$
Pu-242	$1.50\ 10^{-9}$	$4.29\ 10^{-11}$	$2.25\ 10^{-12}$	$2.14\ 10^{-10}$
Pu-244	$1.51\ 10^{-9}$	$4.34\ 10^{-11}$	$2.28\ 10^{-12}$	$2.16\ 10^{-10}$
Am-241	$1.95\ 10^{-9}$	$1.06\ 10^{-10}$	$4.48\ 10^{-9}$	$5.10\ 10^{-12}$
Am-242m	$2.39\ 10^{-9}$	$1.18\ 10^{-10}$	$4.43\ 10^{-9}$	$7.08\ 10^{-11}$
Am-243	$2.14\ 10^{-9}$	$1.16\ 10^{-10}$	$4.92\ 10^{-9}$	$5.99\ 10^{-12}$
Cm-242	$4.56\ 10^{-12}$	$1.31\ 10^{-13}$	$6.86\ 10^{-15}$	$6.51\ 10^{-13}$
Cm-243	$4.92\ 10^{-10}$	$2.49\ 10^{-10}$	$1.26\ 10^{-11}$	$2.15\ 10^{-12}$
Cm-244	$1.68\ 10^{-10}$	$8.32\ 10^{-11}$	$4.21\ 10^{-12}$	$1.20\ 10^{-12}$
Cm-245	$2.87\ 10^{-9}$	$1.44\ 10^{-9}$	$7.30\ 10^{-11}$	$1.53\ 10^{-11}$
Cm-246	$2.83\ 10^{-9}$	$1.43\ 10^{-9}$	$7.26\ 10^{-11}$	$1.13\ 10^{-11}$
Cm-248	$1.05\ 10^{-8}$	$5.31\ 10^{-9}$	$2.69\ 10^{-10}$	$4.16\ 10^{-11}$

* Emplaced at any depth with other LLW

1265. The doses calculated using illustrative inventories are considered further in Appendix D.

E.6. Heterogeneity of disposed waste

1266. The waste that is expected to be sent to Port Clarence for disposal may not be uniformly contaminated and therefore the radioactivity may be heterogeneously distributed throughout the package or consignment. A series of scenarios has been considered to look at the potential dose that could arise from different types of waste that may be sent to the site for disposal. These assessments are independent of whether disposal occurs to the hazardous or non-hazardous landfill. In this section the disposal of large items, discrete (smaller) items and particles are considered (see Table 172). The assessment calculates the dose received if the scenario were to occur.

Table 172 Summary of radiological assessment scenarios for different waste forms

Scenario	Exposed group
Exposure to heterogeneously contaminated large objects during or following excavation or erosion	Worker and Member of public
Exposure to discrete items following erosion	Member of public
Exposure to discrete items following excavation	Member of public
Exposure to particles following erosion	Member of public
Exposure to particles following excavation	Member of public

1267. The range of materials that has been assessed covers large contaminated items, such as concrete blocks with a heterogeneous activity distribution profile, down to small particles. For such heterogeneous wastes, the overall specific activity (activity concentration) may be less than a given value, e.g. 200 Bq g^{-1}, but the activity concentration within certain fractions of the waste may exceed this value, e.g. certain fractions may exceed 200 Bq g^{-1}.

1268. Radioactive particles are small discrete items that could be as small as a grain of sand but contain a high level of activity and could be incorporated in a particular radioactive waste stream or package. The possibility that future intrusion events could lead to unintentional recovery of, and exposure to, these particles is assessed.

E.6.1. Large contaminated items

1269. This section considers the implications of disposing of large contaminated items, such as concrete blocks, with a heterogeneous activity distribution profile. The approach taken is the same as that used for the ENRMF ESC (Eden NE, 2023).

1270. Concrete slabs or blocks from decommissioning buildings and rubble from demolition of buildings used for the storage or conditioning of radioactive wastes may become contaminated. Such contamination may be restricted to the surface layers of the concrete, but the depth of penetration will depend on the nature of the waste or conditioning process (e.g. wet or dry facilities), the period of time the facility was in use, the building material (and any surface treatment such as painting or other sealants) and the chemical properties of the radionuclide fingerprint.

1271. Characterisation of wastes is always subject to some uncertainty. Wastes can be sampled to obtain an overall averaged activity concentration. To determine activity distributions within heterogeneously contaminated wastes they can be sub-sampled or, for large items, cores can be extracted and the depth of contamination, or depth profiles of contamination, can be determined. However, this can be a laborious and expensive undertaking, and considerable uncertainty may remain if there is spatial as well as penetrative heterogeneity in the activity distribution. Best practice is to remove the contaminated surface layer of the building before demolition and dispose of it separately from the rest of the building material, so avoiding significant inhomogeneity in the waste.

1272. To consider the potential effects of a range of assumptions regarding the distribution of activity within wastes, this assessment considers heterogeneous large items and demolition rubble. The characteristics of the large items and rubble are typical of decommissioning wastes. This scenario is not used to constrain landfill capacity, nor the average activity concentration in the waste.

1273. A number of different typical wastes are considered, including: a hypothetical concrete block contaminated with Cs-137; concrete blocks from decommissioning (with different radionuclide fingerprints); and, rubble and crushed concrete from building demolition (with different radionuclide fingerprints).

Scenario selection

1274. There are four principal scenarios by which activity from disposed waste may reach the accessible environment.

- Dissolution in leachate and transport though groundwater.
- Excavation of wastes and subsequent use for cultivation.
- Drilling through waste and handling retrieved material.
- Exposure of waste and subsequent occupancy.

1275. Dissolution in leachate is addressed in Section E.4.4 and the conservative assumptions in that assessment, regarding leaching through the mass of the waste with no retardation due to waste packaging, will also bound the disposal of heterogeneous wastes. The leachate/groundwater scenario is thus not considered further here.

1276. Excavation of waste and subsequent use of the material for cultivation requires a number of assumptions. The waste must provide a suitable growing medium or physical soil improver. The waste must be of sufficient volume and surface area to provide a credible option for cultivation, or must be mixed in a volume of soil or other material to provide a suitable medium and sufficient volume for cultivation. Where waste is mixed to provide a growing medium it will be the averaged activity concentration that is of relevance, rather than the activity distribution profile within the waste matrix itself (see Sections E.5.8 and E.5.10). Hence the use of the waste for cultivation is not considered further here.

1277. Drilling through waste or exposure of waste (through natural processes of erosion or through deliberate human activity) could lead to higher dose impacts for surface contaminated items compared to uniformly contaminated items. These two scenarios (site investigator and site occupant) are considered further.

1278. A series of boreholes could be drilled across the site in order to characterise the area. One or more such boreholes may penetrate the contaminated items and be retrieved for laboratory analysis. The driller may also handle the retrieved core. Such handling can lead to both an organ dose (skin on the hand) and a whole-body effective dose. In addition, dust from the core may be inhaled and inadvertent ingestion may occur. The principal considerations in determining dose are time spent handling or in proximity to the core and, for determining the whole-body effective dose, the averaged distance from the core. It is assumed that drilling will occur only after the end of the period of authorisation. The assessment assumes that a geotechnical worker examines an intact core for 2 hours.

1279. Natural erosion of the landfill surface will depend on processes described earlier in the ESC (Section 2.10).

1280. Following exposure of the waste, occupancy of the area may lead to external exposure and inhalation of contaminated dust may occur. Inadvertent ingestion is considered less likely in this scenario but is included for completeness.

E.6.1.1. Waste characteristics

1281. Six large item waste streams are characterised and detailed below:

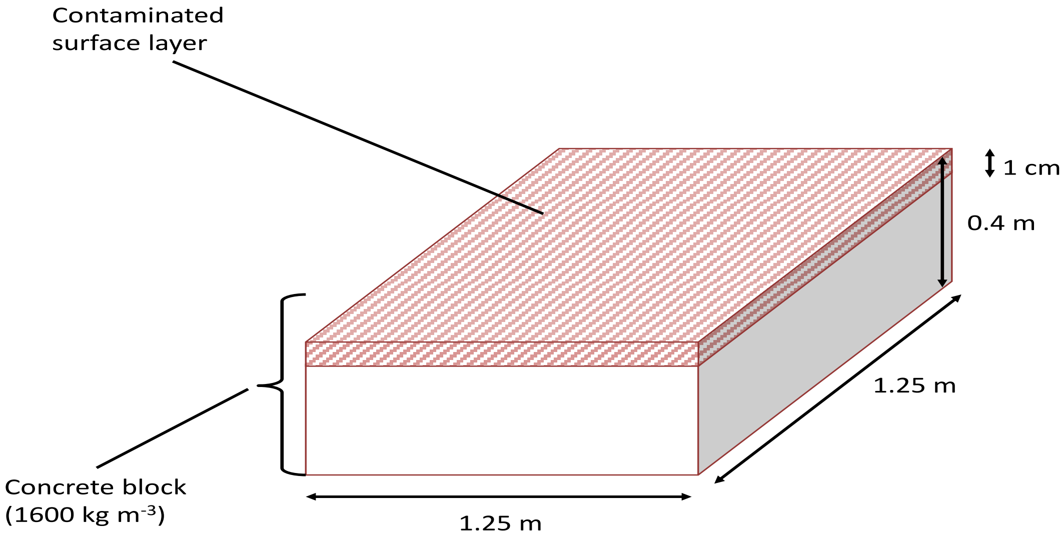
- concrete slabs from decommissioning a Fuel Element Debris (FED) storage silo;
- activated concrete shielding blocks;
- building rubble 1: concrete and rubble from building demolition;
- building rubble 2: crushed concrete, soil and rubble from building demolition;
- reinforced concrete from dismantling a research facility; and,
- a hypothetical concrete block contaminated with Cs-137.

1282. **Concrete demolition slabs** – Contaminated concrete slabs from a FED storage facility (Figure 23). The slabs are contaminated with H-3, Sr-90, Cs-137, Pu-239 and Am-241; which collectively account for 98% of all activity present. For simplicity, it is assumed that each named radionuclide accounts for 20% of the total measured activity. An average total activity concentration for the waste is 19 Bq g^{-1}. The concrete blocks are assumed to be 0.4 m deep, with all contamination on one surface only, to a depth of 1 cm. All radionuclides are assumed to have penetrated the concrete block equally to the same depth. The blocks are nominally assumed to measure 1.25 x 1.25 m surface area, but this assumption is relevant only insofar as the surface area is sufficient that a 10 cm diameter core may be drilled wholly through the block. The concrete is assumed to have a density of 1600 kg m^{-3}, the default density for which the external dose coefficients are derived.

1283. **Activated concrete shielding blocks** - Activated concrete shielding slabs from a research reactor. The slabs contain H-3 (as a contaminant) and the activation products Fe-55, Co-60, Ni-63 and Eu-152. These are present in equal proportions (i.e. they each account for 20% of the total activity) and are uniformly distributed to the same depth in the surface layer of the block. An average total activity concentration for the waste is 7 Bq g^{-1}. As before, the concrete blocks are 1.25 x 1.25 x 0.4 m, with all activity present in the surface 1 cm layer, and the concrete is also assumed to have a density of 1600 kg m^{-3}. All radionuclides are assumed to have penetrated the concrete block equally to the same depth.

1284. **Building rubble 1** - Concrete and rubble contaminated with tritium and C-14. The activity is present in the surface layer of the rubble, but the rubble is received as a mixed consignment. The average activity concentration is 136 Bq g^{-1} of which 99% is H-3. The rubble is assumed to have a density of 1600 kg m^{-3}.

Figure 23 Contaminated concrete block



1285. **Building rubble 2** - Concrete, soil and rubble from the demolition of a post-irradiation examination facility. The waste contains Co-60, Ni-63, Sr-90, Cs-137, Pu-241 and Am-241 in equal proportions. The activity is present in the surface layer of the rubble, but the rubble is received as a mixed consignment. The average activity concentration is 8 Bq g^{-1}. The rubble is assumed to have a density of 1600 kg m^{-3}.

1286. **Reinforced concrete** - Reinforced concrete blocks from dismantling a research facility. The blocks contain H-3 (11% of all activity), C-14 (1% of all activity) and Cs-137 (88% of all activity). The activity is present in the surface 1 cm layer of the block. An average total activity concentration for the waste is 153 Bq g^{-1}. As before, the concrete blocks are 1.25 x 1.25 x 0.4 m, and the concrete is assumed to have a density of 1600 kg m^{-3}. All radionuclides are assumed to have penetrated the concrete block equally to the same depth.

1287. **Hypothetical concrete block** - A large concrete block 0.4 m deep, contaminated with Cs-137 and with all contamination on one surface only. The blocks are nominally assumed to measure 1.25 x 1.25 m surface area, and to have a density of 1600 kg m^{-3}, the default density for which the external dose coefficients are derived. The average activity concentration is 200 Bq g^{-1} and all of the activity is present in the surface layer.

1288. The primary parameters that may be subject to uncertainty are the exposure time (hr y^{-1}), the time at which exposure occurs (following emplacement of the waste), distance from the waste, breathing and ingestion rates, depth of contamination, incident angle of the exposed waste and density of the waste. These aspects are considered in presenting the results of the dose calculations for the hypothetical concrete block. Sensitivity to assumed depth profiles for distribution of activity is explored in Section E.7.3.

1289. Consideration is also given to the impact of disposing of these wastes at the maximum activity concentrations using the same radionuclide fingerprints.

E.6.1.2. Assessment calculation for large contaminated items

Site occupant

1290. It is assumed that the surface layer of the disposal site is removed and the waste exposed. It is further assumed that a sufficient area is exposed such that the external dose rate can be approximated as a semi-infinite slab. It is also assumed that the site occupant breathes in, and inadvertently ingests, contaminated dust arising from drilling through the item.

1291. The dose (Sv y^{-1}) to a site occupant can then be calculated as:

$$Dose_{occupier} = (D_{irr}^{Rn} \cdot \mathrm{T} \cdot C_w(t)) + (D_{inh}^{Rn} \cdot \mathrm{T} \cdot \mathrm{B} \cdot \mathrm{M}_{inh} \cdot C_w(t)) + (D_{ing}^{Rn} \cdot \mathrm{T} \cdot \mathrm{M}_{ing} \cdot C_w(t))$$

where:

- $Dose_{occupier}$ is the dose to a site occupant (Sv y^{-1});
- D_{irr} is the external semi-infinite slab irradiation dose coefficient for radionuclide Rn (Sv y^{-1} per Bq kg^{-1}), see Table 228 where values are presented as mSv per Bq kg^{-1};
- M_{inh} is the dust load of contaminated waste inhaled by the site occupant (kg m^{-3});
- M_{ing} is the rate of ingestion of dust from the material (kg h^{-1});
- T is the time the person is exposed to the material (h);
- B is the breathing rate (m^3 h^{-1});
- D_{inh} and D_{ing} are the dose coefficients for radionuclide *Rn* (Sv Bq^{-1} and Sv Bq^{-1} respectively), see Table 225; and,
- $C_w(t)$ is the activity concentration of radionuclide *Rn* (Bq kg^{-1}) in the material at the time of intrusion, *t.*

1292. It is assumed that a person occupies the site for 1 hour per week (i.e. 52 hours per year). All activity in the contaminated waste is assumed to be in the surface 1 cm.

1293. The parameters for the site occupant are tabulated below (Table 173).

Table 173 Parameters for site occupant

Parameter	Units	Value	Description
M_{inh}	kg m^{-3}	1.0 10^{-7}	Dust load of contaminated waste (Hicks & Baldwin, 2011)
M_{ing}	kg h^{-1}	5.0 10^{-6}	Rate of ingestion of dust (Smith & Jones, 2003)
T	hr y^{-1}	52	Exposure time

B	$m^3\ h^{-1}$	1.21	Breathing rate

Note: Breathing rate based on ICRP 66 (ICRP, 1994), see Table 73 for derivation.

1294. It is assumed that the site occupant is exposed 60 years after closure (the end of the period of authorisation) as a result of an intrusion event. Scenarios determining the exposure of a coastal walker following erosion of the site assume that erosion occurs 60 years after closure. The same nominal value is used for the assessment of large contaminated items following coastal erosion and results are presented to show the impact of exposure at later times.

1295. Note, in this case the inadvertent rate of ingestion is lower than assumed for the site driller below. The adopted dust load is consistent with that used for long term occupants (e.g. site resident).

Site investigator (driller)

1296. It is assumed conservatively that intrusion occurs 60 years after closure. The dose to a site investigator assumes that a drill core has a diameter of 10 cm. The depth of the core is assumed to be sufficient to penetrate through the waste and the incident angle of penetration is such that the surface contaminated layer is removed. The core is then sectioned so as to expose the contaminated surface area.

1297. The dose ($Sv\ y^{-1}$) to a driller can then be calculated as:

$$Dose_{excavator} = \frac{(G_{irr}^{Rn} \cdot \mathrm{T} \cdot C_w(t))}{d^2} + \ (D_{inh}^{Rn} \cdot \mathrm{T} \cdot \mathrm{B} \cdot \mathrm{M}_{inh} \ \cdot C_w(t)) + (D_{ing}^{Rn} \cdot \mathrm{T} \cdot \mathrm{M}_{ing} \ \cdot C_w(t))$$

where parameters are as described in the previous equation except:

- G_{irr}^{Rn} is the point-source dose rate for radionuclide *Rn* at 1 m from a 1 MBq source ($mSv\ hour^{-1}\ MBq^{-1}$) see Table 228; and,
- *d* is the distance of the person from the source (m).

1298. It is assumed that a driller spends 2 hours examining a core and that all activity in the contaminated item is in the surface 1 cm. The whole-body effective dose is determined assuming that the worker is, on average, 1 m from the core. Dust in air from the core is assumed to be present at $6.0\ 10^{-7}$ kg m^{-3}. These and other assumptions are tabulated below (Table 174).

1299. It is assumed conservatively that intrusion occurs 60 years after site closure. The skin dose to the worker is also assessed at an average distance of 0.05 m to the core for the same 2 hour period. This is considered in order to provide confidence that there would not be an unacceptable impact. The closer distance used is arbitrary but we do not consider it appropriate that a worker would spend 2 hours holding a core.

Table 174 Parameters for a site investigator (driller)

Parameter	Units	Value	Description
D	m	1	Distance of the driller from the point source
M_{inh}	kg m^{-3}	6.0 10^{-7}	Dust load of contaminated waste (Hicks & Baldwin, 2011)
M_{ing}	kg hr^{-1}	1.25 10^{-5}	Rate of ingestion of dust (US EPA, 2017)
T	hr y^{-1}	2	Exposure time
B	m^3 hr^{-1}	1.69	Breathing rate

Note: Breathing rate based on ICRP 66 (ICRP, 1994), see Table 73 for derivation.

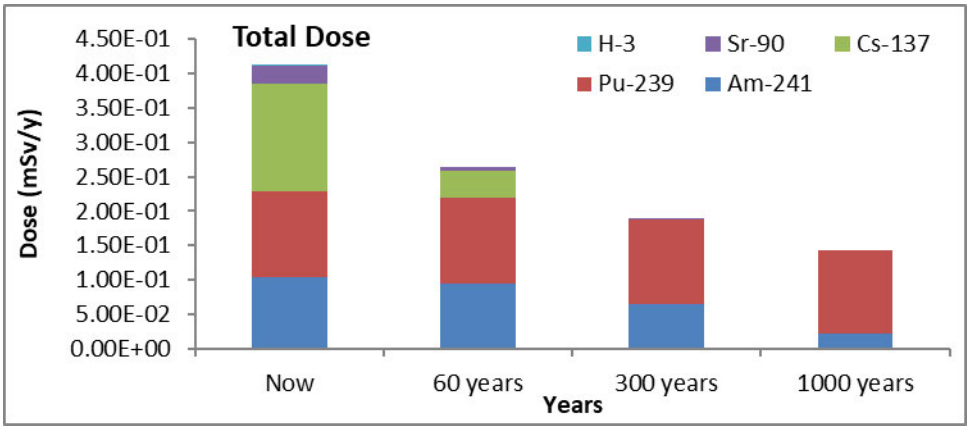
E.6.1.3. Dose from large contaminated waste items

1300. The doses to the site occupant and to the site investigator from each of the five characteristic waste types are presented in this section. Consideration of the sensitivity of the doses to certain input parameters is presented in Section E.8.1.

Concrete demolition slabs - dose to site occupant

1301. It is assumed that concrete demolition slabs (from a FED storage facility) are disposed of with an average activity of 19 Bq g^{-1} comprising H-3, Sr-90, Cs-137, Pu-239 and Am-241. If all of the activity is assumed to be in the surface 1 cm layer the total activity concentration in that layer is 760 Bq g^{-1}. The time dependence of the dose to a site occupant is shown in Figure 24. Although the reference time for a site occupant is 60 years after site closure, results are also given for 300 and 1000 years after site closure. The dose to a site occupant, at 60 years after closure, is 0.26 mSv y^{-1} (260 µSv y^{-1}), assuming 52 hours per year exposure and the dose at later times is lower. The dose is initially dominated by Cs-137 but at 60 years or later, the dose is dominated by the long-lived actinides, Pu-239 and Am-241 (see Figure 24). Exposure before 60 years is not credible as it is within the period of authorisation.

Figure 24 Time-dependent dose to site occupant from contaminated concrete demolition slabs



1302. The dose at 60 years is dominated by the inhalation contribution. The ingestion and inhalation dose components are dominated by Pu-239 and Am-241 (see Table 175).

The external dose component is dominated by Cs-137. The ingestion and inhalation dose components are dominated by Pu-239 and Am-241 (see Table 175). The dose at 150 years would be dominated by ingestion and inhalation of Pu-239 and Am-241.

Table 175 Pathway-dependent dose to site occupant from contaminated concrete demolition slabs at 60 years after closure

Radionuclide	Dose (mSv y^{-1}) at 60 years			
	External	Inhalation	Ingestion	Total
Am-241	$4.1\ 10^{-3}$	$8.3\ 10^{-2}$	$7.2\ 10^{-3}$	$9.5\ 10^{-2}$
Pu-239	$2.2\ 10^{-5}$	$1.1\ 10^{-1}$	$9.9\ 10^{-3}$	$1.2\ 10^{-1}$
Cs-137	$3.9\ 10^{-2}$	$9.4\ 10^{-6}$	$1.3\ 10^{-4}$	$3.9\ 10^{-2}$
Sr-90	$5.8\ 10^{-3}$	$3.6\ 10^{-5}$	$2.9\ 10^{-4}$	$6.1\ 10^{-3}$
H-3	$9.8\ 10^{-9}$	$8.5\ 10^{-9}$	$2.4\ 10^{-8}$	$4.3\ 10^{-8}$
Total	$4.9\ 10^{-2}$	$2.0\ 10^{-1}$	$1.7\ 10^{-2}$	$2.6\ 10^{-1}$

1303. For human intrusion situations, the dose at 60 years or later after closure should be compared to the human intrusion dose guidance values of 3 to 20 mSv (with the lower value being applicable for doses that may occur over extended periods). The doses are all below the lower guidance level. Considering exposure of the waste through natural processes, the risk guidance level is relevant. Extrapolating the dose out to 1000 years after closure (a more realistic date at which 'natural' erosion could expose the waste) gives a dose estimate of 0.14 mSv y^{-1}, dominated by the ingestion and inhalation of dust containing Pu-239. This dose is equivalent to an annual risk of around 7.0 10^{-6}. Given the grossly conservative nature of the assumption that the waste would be exposed in such a fashion that the contaminated surface 1 cm is uniformly exposed and the occupant drills into it for 1 hour per week, it is considered that this risk is broadly consistent with the risk guidance criterion of 10^{-6} for times after the period of authorisation.

1304. The dose estimate at 60 years to a site occupant from disposal of contaminated concrete demolition slabs at the maximum activity concentrations (an average activity of 1120 Bq g^{-1}) is 1.6 mSv y^{-1}.

Concrete demolition slabs - dose to Site Investigator

1305. The dose to a site geotechnical worker / investigator taking borehole samples at 60 years after closure is 6.5 10^{-2} mSv (65 µSv) per core handled (Figure 25). The dose is dominated by inhalation and unintentional ingestion of Pu-239 and Am-241 (see Table 176).

1306. The dose incurred at 60 years after closure is low. Even if 10 cores were handled, all with similar characteristics, the dose would remain more than a factor of 4 to 5 below the lower dose guidance level of 3 mSv for human intrusion scenarios. The potential equivalent dose to skin from close handling of a core, assuming an average distance of 0.05 m (5 cm), is around 4 10^{-4} mSv (0.4 µSv) per core at 60 years. This is well below skin organ dose limit for members of the public of 50 mSv y^{-1}.

1307. The dose estimate at 60 years to a site investigator from disposal of contaminated concrete demolition slabs at the maximum activity concentrations (an average activity of 1120 Bq g^{-1}) is 0.35 mSv y^{-1}.

Figure 25 Time-dependent dose to site investigator from contaminated concrete demolition slabs

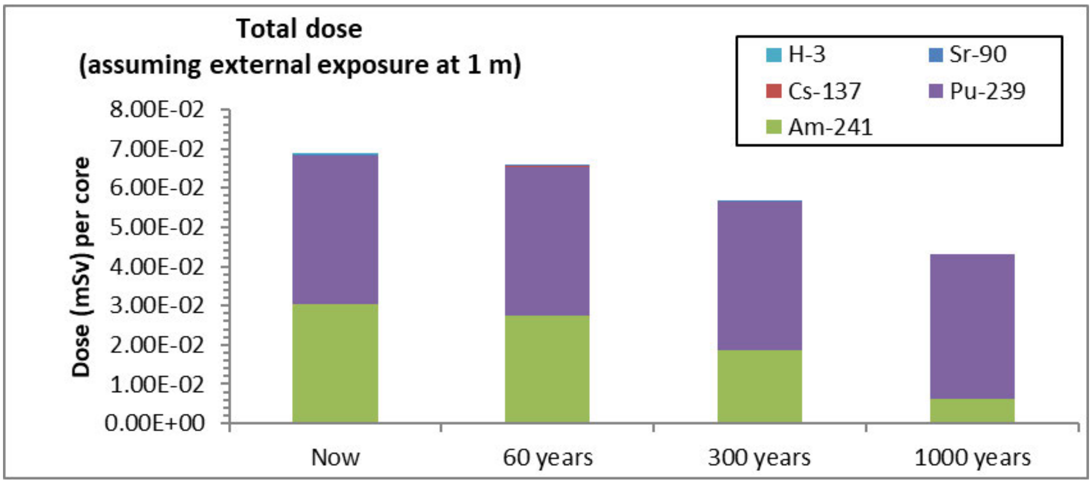


Table 176 Pathway-dependent dose to site investigator from contaminated concrete demolition slabs at 60 years after closure

Radionuclide	Dose (mSv y^{-1}) at 60 years			
	External	Inhalation	Ingestion	Total
Am-241	7.4 10^{-8}	2.7 10^{-2}	6.9 10^{-4}	2.8 10^{-2}
Pu-239	6.2 10^{-10}	3.7 10^{-2}	9.5 10^{-4}	3.8 10^{-2}
Cs-137	6.4 10^{-7}	3.0 10^{-6}	1.2 10^{-5}	1.6 10^{-5}
Sr-90	3.4 10^{-7}	1.2 10^{-5}	2.8 10^{-5}	4.0 10^{-5}
H-3	0	2.7 10^{-9}	2.3 10^{-9}	5.1 10^{-9}
Total	1.1 10^{-6}	6.4 10^{-2}	1.7 10^{-3}	6.5 10^{-2}

Activated concrete shielding blocks - dose to Site Occupant

1308. It is assumed that activated concrete shielding blocks are disposed of with an average activity of 7 Bq g^{-1} comprising H-3, Fe-55, Co-60, Ni-63 and Eu-152. If all of the activity is assumed to be in the surface 1 cm layer the total activity concentration in that layer is 280 Bq g^{-1}.

1309. Although the reference time for a site occupant is 60 years after site closure, results are also given for 300 and 1000 years after site closure. The dose to a site occupant, at 60 years after site closure, assuming 52 hours per year exposure, is 5.4 10^{-3} mSv y^{-1}. The dose is initially dominated by Co-60 and Eu-152 (Figure 26) but the very short half-life of all of the radionuclides within the shielding blocks (Ni-63 has the longest half-life at 100 years, Fe-55 and Co-60 have half-lives of 2.74 and 5.27 years respectively) is such that by 60 years the dose is very low.

1310. The dose at 60 years is dominated by the external component from Eu-152 (Table 177). The dose at later times is negligible.

1311. The dose estimate at 60 years to a site occupant from disposal of activated concrete shielding blocks at the maximum activity concentrations (an average activity of 3440 Bq g^{-1}) is 1.5 mSv y^{-1}.

Figure 26 Time-dependent dose to site occupant from activated concrete shielding blocks

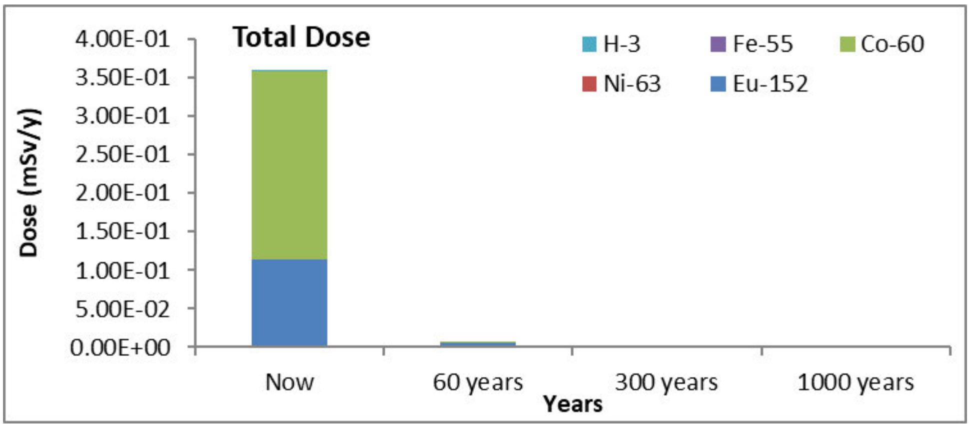


Table 177 Pathway-dependent dose to site occupant from activated concrete shielding blocks

Radionuclide	Dose (mSv y^{-1}) at 60 years			
	External	Inhalation	Ingestion	Total
Eu-152	$5.3\ 10^{-3}$	$5.7\ 10^{-7}$	$9.5\ 10^{-7}$	$5.3\ 10^{-3}$
Ni-63	$8.4\ 10^{-6}$	$2.5\ 10^{-7}$	$1.4\ 10^{-6}$	$1.0\ 10^{-5}$
Co-60	$9.2\ 10^{-5}$	$3.4\ 10^{-9}$	$1.9\ 10^{-8}$	$9.2\ 10^{-5}$
Fe-55	$3.7\ 10^{-18}$	$5.7\ 10^{-14}$	$1.2\ 10^{-12}$	$1.3\ 10^{-12}$
H-3	$3.6\ 10^{-9}$	$2.6\ 10^{-9}$	$9.0\ 10^{-9}$	$1.5\ 10^{-8}$
Total	$5.4\ 10^{-3}$	$8.2\ 10^{-7}$	$2.4\ 10^{-6}$	$5.4\ 10^{-3}$

Activated concrete shielding blocks - dose to Site Investigator

1312. The dose to a site geotechnical worker / investigator taking borehole samples at 60 years after closure is 6.3 10^{-7} mSv (6.3 10^{-4} µSv) per core handled (Figure 27). This very low dose is attributable largely to the short half-lives of all of the radionuclides present. The dose incurred is dominated by exposure from the inventory of Eu-152 and Ni-63 remaining after 60 years (Table 178).

1313. The dose incurred 60 years after site closure is very low and many orders of magnitude below the lower dose guidance level of 3 mSv for human intrusion scenarios for prolonged exposure (even though the exposure is of short duration).

1314. The potential equivalent dose to skin from close handling of a core, assuming an average distance of 0.05 m (5 cm), is around 3.1 10^{-5} mSv (3.1 10^{-2} µSv) per core at

60 years. Comparison may be made with a skin organ dose limit for members of the public of 50 mSv y^{-1}.

1315. The dose estimate to a site investigator from disposal of activated concrete shielding blocks at the maximum activity concentrations (an average activity of 3440 Bq g^{-1}) is 2.8 10^{-4} mSv y^{-1} at 60 years after site closure.

Figure 27 Time-dependent dose to site investigator from activated shielding blocks

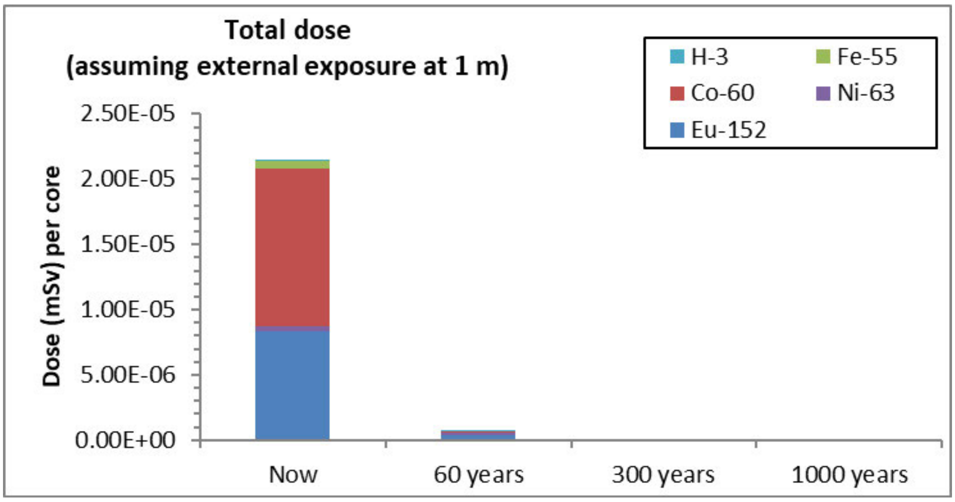


Table 178 Pathway-dependent dose to site investigator from shielding blocks 60 years after site closure

Radionuclide	Dose ($mSv\ y^{-1}$) at 60 years			
	External	Inhalation	Ingestion	Total
Eu-152	7.5 10^{-8}	2.2 10^{-7}	9.1 10^{-8}	3.9 10^{-7}
Ni-63	0	9.7 10^{-8}	1.4 10^{-7}	2.4 10^{-7}
Co-60	1.4 10^{-9}	1.3 10^{-9}	1.8 10^{-9}	4.5 10^{-9}
Fe-55	5.3 10^{-16}	2.2 10^{-14}	1.2 10^{-13}	1.4 10^{-13}
H-3	0	1.0 10^{-9}	8.6 10^{-10}	1.9 10^{-9}
Total	7.6 10^{-8}	3.2 10^{-7}	2.3 10^{-7}	6.3 10^{-7}

Building rubble 1 - dose to Site Occupant

1316. The dose to a site occupant from building rubble with an average activity of 136 Bq g^{-1}, comprising H-3 (99%) and C-14 (1%), 60 years after site closure, is 1.3 10^{-5} mSv y^{-1}, assuming 52 hours per year exposure. In this case, the rubble is assumed to be well mixed as there is no credible mechanism for a contaminated surface layer to be exposed uniformly following disposal.

1317. Although the reference time for a site occupant is 60 after site closure, results were produced 300 and 1000 years after site closure. The dose is dominated by the small C-14 inventory (at 1.4 Bq g^{-1}) as the very short half-life of H-3 (12.3 years) means that it has decayed to very low levels after 60 years.

1318. The dose estimate to a site occupant from disposal of building rubble at the maximum activity concentrations (an average activity of 5000 Bq g^{-1}) is 4.8 10^{-4} mSv y^{-1}.

Building rubble 1 - dose to Site Investigator

1319. The dose to a site geotechnical worker / investigator taking borehole samples 60 years after site closure is about 4 10^{-8} mSv per core handled and arises exclusively from the ingestion / inhalation pathways.

1320. The dose estimate at 60 years to a site investigator from disposal of building rubble at the maximum activity concentrations (an average activity of 5000 Bq g^{-1}) is 1.5 10^{-6} mSv y^{-1}.

Building rubble 2 - dose to Site Occupant

1321. Although the reference time for a site occupant is 60 years after site closure, results are also given for 300 and 1000 years after site closure. The dose to a site occupant from crushed concrete with an average activity of 8 Bq g^{-1}, comprising Co-60, Ni-63, Sr-90, Cs-137, Pu-241 and Am-241, at 60 years after site closure, is 2.7 10^{-3} mSv y^{-1}, assuming 52 hours per year exposure. In this case, the concrete is assumed to be well mixed. As before, even if the concrete initially had all contamination present in the surface layer, once it is crushed there is no credible mechanism to expose only the contaminated material.

1322. The dose is initially dominated by Co-60 (through the external exposure) but by 60 years after site closure the dose contribution from Co-60 is negligible and the dose is dominated by Am-241 (inhalation) and Cs-137 (external), see Figure 28 and Table 179.

1323. The dose estimate to a site occupant from disposal of crushed concrete at the maximum activity concentrations (an average activity of 1783 Bq g^{-1}) is 6.0 10^{-2} mSv y^{-1} at 60 years after site closure.

Figure 28 Time-dependent dose to site occupant from crushed concrete

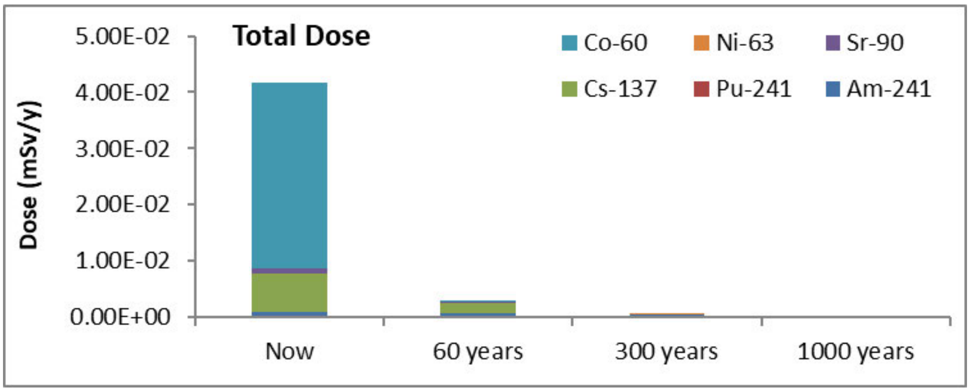


Table 179 Pathway-dependent dose to site occupant from crushed concrete

Radionuclide	Dose (mSv y^{-1}) at 60 years			
	External	Inhalation	Ingestion	Total
Am-241	8.0 10^{-5}	6.0 10^{-4}	6.3 10^{-5}	7.5 10^{-4}
Pu-241	1.7 10^{-9}	8.8 10^{-7}	9.2 10^{-8}	9.7 10^{-7}
Cs-137	1.7 10^{-3}	6.8 10^{-8}	1.1 10^{-6}	1.7 10^{-3}
Sr-90	2.4 10^{-4}	2.6 10^{-7}	2.5 10^{-6}	2.4 10^{-4}
Ni-63	1.1 10^{-6}	5.9 10^{-9}	3.4 10^{-8}	1.1 10^{-6}
Co-60	1.2 10^{-5}	8.1 10^{-11}	4.4 10^{-10}	1.2 10^{-5}
Total	2.1 10^{-3}	6.1 10^{-4}	6.7 10^{-5}	2.7 10^{-3}

Building rubble 2 - dose to Site Investigator

1324. The dose to a site geotechnical worker / investigator taking borehole samples 60 years after site closure is about 2.8 10^{-4} mSv per core handled and is dominated by the presence of Am-241 in the ingestion / inhalation pathways.

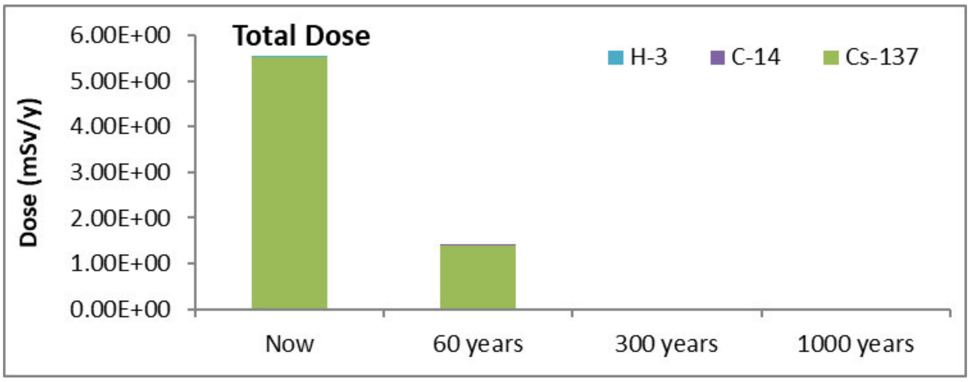
1325. The dose estimate at 60 years to a site investigator from disposal of crushed concrete at the maximum activity concentrations (an average activity of 1783 Bq g^{-1}) is 3.3 10^{-3} mSv y^{-1}.

Reinforced concrete - dose to Site Occupant

1326. It is assumed that contaminated concrete slabs are received with an average activity of 153 Bq g^{-1} comprising H-3 (11%), C-14 (1%) and Cs-137 (88%). If all of the activity is assumed to be in the surface 1 cm layer the total activity concentration in that layer is 6120 Bq g^{-1}.

1327. Although the reference time for a site occupant is 60 years after site closure, results are also given for 300 and 1000 years after site closure. The dose to a site occupant, at 60 years after site closure, assuming 52 hours per year exposure, is 1.4 mSv y^{-1} (Figure 29).

Figure 29 Time-dependent dose to site occupant from contaminated reinforced concrete



1328. The dose is dominated by external exposure from Cs-137 (Table 180).

1329. The dose estimate at 60 years to a site occupant from disposal of contaminated reinforced concrete at the maximum activity concentrations (an average activity of 776 Bq g^{-1}) is 1.8 mSv y^{-1}.

Table 180 Pathway-dependent dose to site occupant from contaminated reinforced concrete

Radionuclide	Dose (mSv y^{-1}) at 60 years			
	External	Inhalation	Ingestion	Total
Cs-137	1.4	2.8 10^{-4}	4.6 10^{-3}	1.4
C-14	1.1 10^{-4}	1.8 10^{-6}	9.2 10^{-6}	1.2 10^{-4}
H-3	4.3 10^{-8}	3.1 10^{-8}	1.1 10^{-7}	1.8 10^{-7}
Total	1.4	2.8 10^{-4}	4.6 10^{-3}	1.4

Reinforced concrete - dose to Site Investigator

1330. The dose to a site geotechnical worker / investigator taking borehole samples at 60 years after site closure is 5.7 10^{-4} mSv (5.7 10^{-1} μSv) per core handled (Table 181). The dose is dominated by unintentional ingestion of Cs-137 (Table 181).

1331. The dose incurred 60 years after site closure is very low and many orders of magnitude below the lower dose guidance level of 3 mSv for human intrusion scenarios.

1332. The potential equivalent dose to skin from close handling of a core, assuming an average distance of 0.05 m (5 cm), is around 9 10^{-3} mSv (9 μSv) per core 60 years after site closure. Comparison may be made with a skin organ dose limit for members of the public of 50 mSv y^{-1}.

1333. The dose estimate at 60 years to a site investigator from disposal of contaminated reinforced concrete at the maximum activity concentrations (an average activity of 776 Bq g^{-1}) is 8.0 10^{-4} mSv y^{-1}.

Figure 30 Time-dependent dose to site investigator from contaminated reinforced concrete

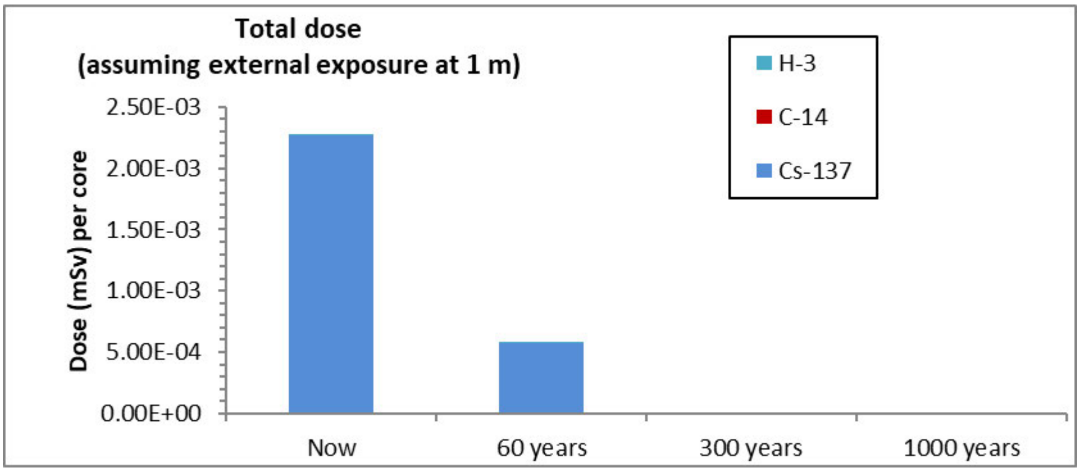


Table 181 Pathway-dependent dose to site investigator from contaminated reinforced concrete at 60 years after site closure

Radionuclide	Dose (mSv y^{-1}) at 60 years			
	External	Inhalation	Ingestion	Total
Cs-137	2.3 10^{-5}	1.1 10^{-4}	4.4 10^{-4}	5.7 10^{-4}
C-14	0	7.1 10^{-7}	8.8 10^{-7}	1.6 10^{-6}
H-3	0	1.2 10^{-8}	1.0 10^{-8}	2.2 10^{-8}
Total	2.3 10^{-5}	1.1 10^{-4}	4.4 10^{-4}	5.7 10^{-4}

Hypothetical concrete block - dose to Site Occupant

1334. In this hypothetical case, contamination is present at an average activity of 200 Bq g^{-1} (the maximum activity concentration for this radionuclide) but is in the surface 1 cm, where the activity concentration rises to 8000 Bq g^{-1}. The activity is assumed to be present as Cs-137.

1335. Although the reference time for a site occupant is 60 years after site closure, results are also given for 300 and 1000 years after site closure. The dose to a site occupant, 60 years after site closure, is 2.1 mSv y^{-1}, assuming 52 hours per year exposure. The dose arises mainly from external exposure, accounting for more than 99% of the total dose.

Hypothetical concrete block - dose to Site Investigator

1336. The dose to a site investigator (driller), assuming an average distance from a point source of 1 m, is 8.5 10^{-4} mSv per core handled.

1337. A skin dose, assuming handling of the core at an average distance of 0.05 m, is 1.4 10^{-2} mSv (14 µSv) per core.

E.6.1.4. Discussion

1338. The doses to the site occupant 60 years after site closure and the site investigator are compared to the human intrusion dose guidance values of 3 to 20 mSv (with the lower value being applicable for doses that may occur over extended periods). The doses from all the items considered here, when calculated using the radionuclide fingerprints for each waste type, are all well below the lower guidance value, even with the proposed maximum activity concentrations.

1339. Exposure of the waste due to coastal erosion may result in exposure of a person who walks along the edge of the site. As discussed in the main report (Section 2.10), the onset of erosion and the impact of sea level rise on the restored landfill is uncertain. The risk guidance level is relevant for casual encounters with exposed waste. The site occupant dose estimates assume exposure for 1 h a week, including inhalation of dust from drilling into the waste. The inhalation of dust from drilling is very conservative for casual exposure. Extrapolating the dose out to 1000 years (a more realistic date for ‘natural’ erosion exposing the waste that is used to illustrate delayed impact) gives an upper dose estimate to the site occupant of 0.14 mSv y^{-1} (from Concrete demolition slabs with the fingerprint and activity concentrations given above). This dose is equivalent to an annual risk of around 7 10^{-6}. Given the grossly conservative nature of the assumptions, it is considered that this risk is broadly consistent with the risk guidance criterion of 10^{-6} for the post-closure period.

1340. Hence, an assessment of the doses arising from exposure to typical decommissioning wastes that may contain large heterogeneously contaminated items has shown that they will comply with the dose and risk criteria in the NS-GRA (UK Environment Agencies, 2009).

E.6.2. Excavation of discrete items

1341. This scenario is included due to the possibility that the site will be eroded by the sea, and walkers along the bank of the estuary near the site may then come into contact with discrete items of waste that have become exposed. As discussed in the main report (Section 2.10) the Port Clarence site is not at risk of erosion from the relatively slow moving River Tees but could be impacted by sea level rise due to climate warming. The onset of erosion and the impact of sea level rise on the restored landfill is uncertain. The start of erosion depends on cell location, the increase in global temperature, the rate of sea level rise and the future management of the estuary, barrage and coastal defences. For these reasons, it is uncertain as to whether and when, sea-level rise will result in erosion exposing LLW at the site. The approach adopted here is to use very cautious assumptions to suggest the earliest time at which it could occur, for this reason a radiological assessment is undertaken at the end of the period of authorisation.

1342. This scenario is not used to constrain landfill capacity. However, it places limits on the radioactivity of specific discrete items within consignments.

1343. LLW Repository Ltd (LLWR Ltd, 2013a) define ‘discrete items’ as “a distinct item of waste that, by its characteristics, is recognisable as unusual or not of natural origin and could be a focus of interest, out of curiosity or potential for recovery and recycling/re-use of materials should the waste item be exposed after repository closure.” This definition is adopted in this assessment.

1344. Examples of discrete items given by LLWR (LLWR Ltd, 2013a) are hand tools, engineered items and equipment of durable materials (such as may be disposed with other wastes in drums for grouting or high-force compaction, or directly to a Disposal Container); grouted drums or pucks from high-force compaction; and large metal items, e.g. steel beams and plates, pipework, shielding, heavy equipment and flasks (but not general scrap metal) such as may be disposed directly to a Disposal Container.

1345. A discrete item has the potential to modify the behaviour of a person that encounters it, i.e. it is visible and therefore an individual may deliberately go towards and inspect, or (if small enough) pick up the item. This is different from the standard assessment calculations in which the estuary bank user carries out activities on the bank of the estuary without regard to the presence of the waste or the radioactive hazard it may pose. Thus, two situations can be envisaged: a casual encounter with a single item and a situation where a person deliberately seeks out, collects, takes away or disrupts discrete items. The future behaviour of people that might lead to them encountering radioactive discrete items uncovered by natural disruptive processes cannot be predicted, and so the probability of exposure cannot be quantified. In this respect, the exposure situation is similar to that of inadvertent human intrusion. Exposure to discrete items exposed by natural processes is specifically addressed in Requirement R12 of the Environment agencies GRR ((Environment Agencies, 2018)), which specifies that the results of illustrative calculations are compared with the dose guidance level for inadvertent human intrusion (3 mSv to 20 mSv); however this guidance relates to the clean-up of nuclear licensed sites, and does not apply to waste disposal sites.

1346. It is very difficult to estimate the exposure time of a person who deliberately seeks out, collects, takes away or disrupts discrete items. However, the lower dose guideline level for inadvertent intrusion is at least two orders of magnitude greater than the effective dose of 20 µSv y^{-1}, which corresponds to the risk guidance level specified in the NS-GRA, assuming a probability of unity. Thus, comparison of the dose from a casual encounter with a single item for 1 hour with a dose criterion of 20 µSv y^{-1} will ensure that the exposure to a person who deliberately seeks out, collects, takes away or disrupts discrete items will meet the lower dose guideline value of 3 mSv.

1347. As such, the case of a casual encounter for 1 hour assessed against a 20 µSv y^{-1} value is expected to be limiting. This conservative approach has been taken in this assessment.

E.6.2.1. Potentially Exposed Group

1348. The assessment of doses resulting from waste that becomes exposed on the estuary bank is based on work undertaken to assess discrete items at the LLWR (LLWR Ltd, 2013a). Members of the exposed group are assumed to be adults and to be exposed as a result of external irradiation from contaminated objects and through the inadvertent ingestion of contaminated dust. Although different encounter characteristics could be postulated for children and infants, leading to different effective doses, the encounter by an adult is deemed the appropriate basis for deriving Discrete Item Limits, and is consistent with the approach taken by LLWR.

1349. The approach used by LLW Repository Ltd is followed. A Discrete Item Limit is suggested based on total activity for items with a mass of 1 kg or less and 100 kg or greater, with a transitional function between these total activity limits.

1350. Doses are calculated assuming that items can be represented as sphere of equivalent mass. For each size of sphere, doses from two cases are calculated:

- Activity is uniformly distributed over the surface of the sphere.
- Activity is distributed uniformly throughout the sphere volume.

1351. These two cases are expected to bound the actual distribution of activity on an item. All spheres are considered to have a reference density of 2000 kg m^{-3}.

1352. Similar to (LLWR Ltd, 2013a), the inhalation pathway is not assessed on the basis that the ingestion pathway will be the dominant intake pathway for most radionuclides assuming the local dust in air carries the same average specific activity as the local substrates and that the discrete items will have a negligible contribution to the local respirable dust.

E.6.2.2. Estimating doses to a local estuary bank user

1353. It is assumed that adults may have an encounter with exposed wastes for a one hour duration, during which time they may closely inspect the item. As such, doses from external irradiation are evaluated at 0.3 m from the surface of the items. This distance is commensurate with being very close to a large item or handling a small item. The same approach was used by LLW Repository Ltd (LLWR Ltd, 2013a).

1354. Effective doses from external irradiation are calculated by applying scaling factors to dose coefficients for a uniformly contaminated infinite plane, in the case of a surface contaminated sphere, and dose coefficients for a uniformly contaminated semi-infinite slab, in the case of a volume contaminated sphere.

1355. The dose rate at 1 m from a uniformly contaminated infinite plane is assumed to be equal to the dose rate at 0.3 m from a surface-contaminated sphere of radius 2 m (LLWR Ltd, 2013a). The dose rate at 0.3 m from a smaller radius sphere is then obtained by appropriate scaling.

1356. The dose rate at 1 m from a uniformly contaminated semi-infinite slab is assumed to be equal to the dose rate at 0.3 m from a volume-contaminated sphere of radius 2 m (Thorne, 2010), (LLWR Ltd, 2013a). The dose rate at 0.3 m from a smaller radius sphere is then obtained by appropriate scaling.

1357. For surface-contaminated items, a secondary ingestion coefficient of 10^{-6} m^2 h^{-1} is assumed. This secondary ingestion coefficient is based on a secondary ingestion coefficient of 10^{-4} m^2 h^{-1} for removable contamination, but assumes that only 1% of the surface activity present at the time of disposal is removable on contact following erosion.

1358. For volume-contaminated items, an inadvertent ingestion coefficient of 0.5 mg h^{-1} is assumed. The value of this coefficient is an order of magnitude less than the standard rate of inadvertent ingestion that would be applied on the basis that not all of the dust or dirt that will be ingested at the time of exposure will come from the discrete item. Such an approach is consistent with the methodology adopted by LLW Repository Ltd. The assessment does not consider pica or the ingestion of stone sized objects for the derivation of waste acceptance criteria [see page 31 of (Environment Agency, 2015)].

1359. The onset of erosion and the impact of sea level rise on the restored landfill is uncertain. The start of erosion depends on cell location, the increase in global temperature, the rate of sea level rise and the future management of the estuary, barrage and coastal defences. For these reasons, it is uncertain as to whether and when, sea-level rise will result in erosion exposing LLW at the site. The approach adopted here is to use very cautious assumptions to suggest the earliest time at which it could occur, for this reason a radiological assessment is undertaken at the end of the period of authorisation.

1360. The effective doses from external radiation and committed effective doses from ingestion are calculated at 60 years after closure. Hence, the calculated Discrete Item Limits will be conservative because some consignments will be disposed of decades before site closure.

1361. An activity of 1 GBq is assumed to be present on the item when undertaking this assessment. Our assessment focuses on a 1 t sphere, but the activity required on an item to give rise to a 20 µSv dose for items of mass 10 g, 100 g, 1 kg, 10 kg, 100 kg and 10 t are also assessed. In reality, discrete items with a mass greater than 10 t would not be expected to be consigned to Port Clarence.

1362. An activity of 1 GBq on a one tonne sphere gives a specific activity concentration of 1 GBq te^{-1} (1000 Bq g^{-1}). The waste acceptance criteria will specify the specific activity concentration limits for a consignment and for a package. We are proposing nuclide dependent specific activity concentration limits for discrete items. Our assessment is based on items that are at the upper end of acceptability at Port Clarence for radionuclides for which the waste acceptance criteria specify that an individual waste package containing that radionuclide should not exceed an activity concentration of 1000 Bq g^{-1}.

E.6.2.3. Assessment calculation for discrete items

1363. For a radionuclide with no decay chain, the dose (Sv y^{-1}) arising from the inadvertent ingestion of contaminated material from a surface-contaminated item is given by:

$$Dose_{Surf,ing} = \frac{I \cdot e^{-\lambda t} \cdot SI_{ing} \cdot D_{ing}^{Rn} \cdot t_{ext}}{A}$$

where:

- $Dose_{Surf,ing}$ is the dose from inadvertent ingestion of surface contamination (Sv y^{-1});
- I is the inventory of radionuclide *Rn* assumed on the object (Bq);
- λ is the decay constant ($year^{-1}$);
- t is the time at which the dose is assessed (years after closure);
- t_{ext} is the exposure time (h);
- SI_{ing} is the secondary ingestion coefficient (m^2 h^{-1});
- D_{ing}^{Rn} is the ingestion dose coefficient for radionuclide *Rn* (Sv Bq^{-1}), see Table 225; and,
- A is the surface area of the sphere assumed to represent the surface-contaminated item (m^2).

1364. For a radionuclide with no decay chain, the dose (Sv y^{-1}) arising from the inadvertent ingestion of contaminated material from a volume-contaminated item is given by:

$$Dose_{Vol,ing} = \frac{I \cdot e^{-\lambda t} \cdot I_{ing} \cdot D_{ing}^{Rn} \cdot t_{ext}}{M}$$

where:

- $Dose_{Vol,ing}$ is the dose from the inadvertent ingestion of surface contamination (Sv y^{-1});
- I is the inventory of radionuclide *Rn* assumed in the object (Bq);
- λ is the decay constant (y^{-1});
- t is the time at which the dose is assessed (years after closure);
- t_{ext} is the exposure time (h);
- I_{ing} is the inadvertent ingestion rate of contaminated material (kg h^{-1});
- D_{ing}^{Rn} is the ingestion dose coefficient for radionuclide *Rn* (Sv Bq^{-1}), see Table 225; and,
- M is the mass of the volume-contaminated item (kg).

1365. For a radionuclide with no decay chain, the dose (Sv y^{-1}) arising from external irradiation from a surface-contaminated item is given by:

$$Dose_{Surf,ext} = \frac{I \cdot e^{-\lambda t} \cdot t_{ext} \cdot SF_{Surf} \cdot D_{ext,Surf}^{Rn} \cdot t_{ext}}{A}$$

where:

- $Dose_{Surf,ext}$ is the dose arising from external irradiation from a surface-contaminated item (Sv y^{-1});
- I is the inventory of radionuclide *Rn* assumed on the object (Bq);
- λ is the decay constant ($years^{-1}$);
- t is the time at which the dose is assessed (years);
- t_{ext} is the exposure time (h);
- SF_{Surf} is the scaling factor from an infinite plane source to a non-sorbing surface-contaminated spherical source at a distance of 0.3 m from the surface of the sphere (dimensionless, see Table 183);
- $D_{ext,Surf}^{Rn}$ is the dose coefficient from an infinite plane source for radionuclide *Rn* (Sv y^{-1} per Bq m^{-2}; see Section E.9.3); and,
- A is the surface area of the sphere assumed to represent the surface-contaminated item (m^2).

1366. For a radionuclide with no decay chain, the dose (Sv y^{-1}) arising from external irradiation to a volume-contaminated item is given by:

$$Dose_{Vol,ext} = \frac{I \cdot e^{-\lambda t} \cdot t_{ext} \cdot SF_{Vol} \cdot D_{ext,Vol}^{Rn} \cdot t_{ext}}{M}$$

where:

- $Dose_{Vol,ext}$ is the dose arising from external irradiation from a volume-contaminated item (Sv y^{-1});
- I is the inventory of radionuclide *Rn* assumed in the object (Bq);
- λ is the decay constant ($year^{-1}$);
- t is the time at which the dose is assessed (years after closure);
- t_{ext} is the exposure time (h);
- SF_{Vol} is the scaling factor from a semi-infinite slab to a volume-contaminated spherical source at a distance of 0.3 m from the surface of the sphere (dimensionless, see Table 184);
- $D^{Rn}_{ext,Vol}$ is the dose coefficient from a semi-infinite slab for radionuclide *Rn* (Sv y^{-1} per Bq kg^{-1}; see Section E.9.3); and,
- M is the mass of the volume-contaminated item (kg).

1367. The doses from contaminated items disposed to Port Clarence with a given level of contamination will lie in between the doses calculated for a surface-contaminated sphere and a volume contaminated sphere. An indication of this dose (Sv y^{-1}) can be given by the geometric mean of the doses from the surface-contaminated sphere and a volume-contaminated sphere:

$$Dose_{GM} = \left(Dose_{Vol} \cdot Dose_{Surf}\right)^{\frac{1}{2}}$$

where:

- $Dose_{GM}$ is the geometric mean of the doses arising from the volume-contaminated item and the surface contaminated item (Sv y^{-1});
- $Dose_{Vol}$ is the dose arising from a volume-contaminated item (Sv y^{-1}); and,
- $Dose_{Surf}$ is the dose arising a surface-contaminated item (Sv y^{-1}).

1368. The parameters used in these calculations are given in Table 182. For radionuclides with decay chains, the approach set out in Section 3.2 is used to determine effective doses and thus Discrete Item Limits.

Table 182 Discrete Item Assessment parameters

Parameter	Units	Value	Description
I	Bq	$1\ 10^{9}$	Radionuclide inventory assumed on item
SI_{ing}	$m^{2}\ h^{-1}$	$1\ 10^{-6}$	Secondary ingestion coefficient for surface contamination
I_{ing}	$kg\ h^{-1}$	$5\ 10^{-7}$	Inadvertent ingestion rate for contaminated material
t_{ext}	$h\ y^{-1}$	1	Exposure time
ρ_{sphere}	$kg\ m^{-3}$	2000	Sphere density
t	y	60	Time at which encounter occurs (years after closure)

Note: Parameters taken from (LLWR Ltd, 2013a) except time of encounter.

Table 183 Scaling factors from an infinite plane source to a non-sorbing surface-contaminated spherical source of given radius at a distance of 0.3 m from the surface of the sphere.

Sphere weight	10g	100g	1 kg	10 kg	100 kg	1 t	10 t
Sphere weight (kg)	0.01	0.1	1	10	100	1000	10000
Sphere radius	0.011	0.023	0.049	0.106	0.229	0.492	1.061
Scaling factor	$1.09\ 10^{-3}$	$4.70\ 10^{-3}$	$1.86\ 10^{-2}$	$6.40\ 10^{-2}$	$1.84\ 10^{-1}$	$4.13\ 10^{-1}$	$7.49\ 10^{-1}$

Note: Taken from Table A4 of (LLWR Ltd, 2013a).

Table 184 Scaling factors from a semi-infinite slab to a volume-contaminated spherical source of given radius at a distance of 0.3 m from the surface of the sphere.

Sphere weight	10g	100g	1 kg	10 kg	100 kg	1 t	10 t
Sphere weight (kg)	0.01	0.1	1	10	100	1000	10000
Sphere radius	0.011	0.023	0.049	0.106	0.229	0.492	1.061
Scaling factor	$3.90\ 10^{-5}$	$3.61\ 10^{-4}$	$3.09\ 10^{-3}$	$2.28\ 10^{-2}$	$1.09\ 10^{-1}$	$3.50\ 10^{-1}$	$7.46\ 10^{-1}$

Note: Taken from Table A4 of (LLWR Ltd, 2013a).

E.6.2.4. Doses from discrete items

1369. The doses arising from 1 hour encounter with a 1 tonne sphere contaminated with 1 GBq of each radionuclide are presented in Table 185. The doses are assessed at 60 years after closure. Doses are reported to a minimum value of $1\ 10^{-27}$ mSv.

Table 185 Doses at 60 years after closure from encounter with a 1 tonne sphere contaminated with 1 GBq of radionuclide at time of consignment

Radionuclide	Total dose from surface contaminated object including daughters (mSv)	Total dose from volume contaminated object including daughters (mSv)	Geometric mean dose (mSv)
H-3	$2.13\ 10^{-7}$	$2.66\ 10^{-9}$	$2.38\ 10^{-8}$
C-14	$4.86\ 10^{-4}$	$6.31\ 10^{-5}$	$1.75\ 10^{-4}$
Cl-36	$9.43\ 10^{-3}$	$8.49\ 10^{-4}$	$2.83\ 10^{-3}$
Ca-41	$6.23\ 10^{-5}$	$9.50\ 10^{-8}$	$2.43\ 10^{-6}$
Mn-54	$1.90\ 10^{-22}$	$3.86\ 10^{-23}$	$8.57\ 10^{-23}$
Fe-55	$2.73\ 10^{-11}$	$4.15\ 10^{-14}$	$1.06\ 10^{-12}$
Co-60	$2.82\ 10^{-4}$	$6.23\ 10^{-5}$	$1.32\ 10^{-4}$
Ni-59	$2.55\ 10^{-5}$	$9.42\ 10^{-7}$	$4.91\ 10^{-6}$
Ni-63	$5.82\ 10^{-5}$	$5.49\ 10^{-6}$	$1.79\ 10^{-5}$
Zn-65	$1.00\ 10^{-27}$	$1.00\ 10^{-27}$	$1.00\ 10^{-27}$
Se-79	$1.28\ 10^{-3}$	$7.18\ 10^{-5}$	$3.04\ 10^{-4}$
Sr-90	$2.00\ 10^{-2}$	$1.20\ 10^{-3}$	$4.91\ 10^{-3}$
Mo-93	$1.04\ 10^{-3}$	$4.93\ 10^{-6}$	$7.15\ 10^{-5}$
Zr-93	$4.07\ 10^{-4}$	$1.03\ 10^{-5}$	$6.48\ 10^{-5}$
Nb-93m	$3.39\ 10^{-6}$	$5.11\ 10^{-8}$	$4.16\ 10^{-7}$
Nb-94	$4.83\ 10^{-1}$	$9.70\ 10^{-2}$	$2.16\ 10^{-1}$
Tc-99	$1.17\ 10^{-3}$	$2.04\ 10^{-4}$	$4.89\ 10^{-4}$
Ru-106	$3.75\ 10^{-19}$	$4.50\ 10^{-20}$	$1.30\ 10^{-19}$
Ag-108m	$4.56\ 10^{-1}$	$8.71\ 10^{-2}$	$1.99\ 10^{-1}$
Ag-110m	$3.34\ 10^{-27}$	$1.00\ 10^{-27}$	$1.83\ 10^{-27}$
Cd-109	$9.61\ 10^{-18}$	$6.50\ 10^{-19}$	$2.50\ 10^{-18}$
Sb-125	$3.81\ 10^{-8}$	$7.05\ 10^{-9}$	$1.64\ 10^{-8}$
Sn-119m	$1.81\ 10^{-26}$	$1.00\ 10^{-27}$	$4.25\ 10^{-27}$
Sn-123	$1.00\ 10^{-27}$	$1.00\ 10^{-27}$	$1.00\ 10^{-27}$
Sn-126	$6.70\ 10^{-1}$	$1.21\ 10^{-1}$	$2.85\ 10^{-1}$
Te-127m	$1.00\ 10^{-27}$	$1.00\ 10^{-27}$	$1.00\ 10^{-27}$
I-129	$3.83\ 10^{-2}$	$2.14\ 10^{-4}$	$2.86\ 10^{-3}$
Ba-133	$2.13\ 10^{-3}$	$3.73\ 10^{-4}$	$8.90\ 10^{-4}$
Cs-134	$8.84\ 10^{-10}$	$1.72\ 10^{-10}$	$3.90\ 10^{-10}$
Cs-135	$1.45\ 10^{-3}$	$1.71\ 10^{-4}$	$4.98\ 10^{-4}$
Cs-137	$4.73\ 10^{-2}$	$8.72\ 10^{-3}$	$2.03\ 10^{-2}$
Ce-144	$4.99\ 10^{-26}$	$5.97\ 10^{-27}$	$1.73\ 10^{-26}$
Pm-147	$7.06\ 10^{-11}$	$1.26\ 10^{-11}$	$2.98\ 10^{-11}$
Sm-147	$1.61\ 10^{-2}$	$2.45\ 10^{-5}$	$6.28\ 10^{-4}$
Sm-151	$5.35\ 10^{-5}$	$7.05\ 10^{-6}$	$1.94\ 10^{-5}$
Eu-152	$1.64\ 10^{-2}$	$3.37\ 10^{-3}$	$7.43\ 10^{-3}$
Eu-154	$3.05\ 10^{-3}$	$6.27\ 10^{-4}$	$1.38\ 10^{-3}$
Eu-155	$2.42\ 10^{-6}$	$3.07\ 10^{-7}$	$8.61\ 10^{-7}$
Gd-153	$1.00\ 10^{-27}$	$1.00\ 10^{-27}$	$1.00\ 10^{-27}$
Pb-210	$9.90\ 10^{-2}$	$3.62\ 10^{-4}$	$5.99\ 10^{-3}$
Po-210	$1.00\ 10^{-27}$	$1.00\ 10^{-27}$	$1.00\ 10^{-27}$
Ra-226	$2.15\ 10^{0}$	$2.97\ 10^{-1}$	$8.00\ 10^{-1}$
Ra-228	$7.42\ 10^{-4}$	$1.14\ 10^{-4}$	$2.91\ 10^{-4}$
Ac-227	$8.68\ 10^{-2}$	$3.49\ 10^{-3}$	$1.74\ 10^{-2}$
Th-228	$1.85\ 10^{-10}$	$3.65\ 10^{-11}$	$8.22\ 10^{-11}$
Th-229	$3.21\ 10^{-1}$	$1.81\ 10^{-2}$	$7.62\ 10^{-2}$
Th-230	$1.26\ 10^{-1}$	$7.94\ 10^{-3}$	$3.16\ 10^{-2}$
Th-232	$1.10\ 10^{0}$	$1.58\ 10^{-1}$	$4.18\ 10^{-1}$

Radionuclide	Total dose from surface contaminated object including daughters (mSv)	Total dose from volume contaminated object including daughters (mSv)	Geometric mean dose (mSv)
Pa-231	$7.41\ 10^{-1}$	$2.22\ 10^{-2}$	$1.28\ 10^{-1}$
U-232	$6.91\ 10^{-1}$	$1.39\ 10^{-1}$	$3.10\ 10^{-1}$
U-233	$1.86\ 10^{-2}$	$1.38\ 10^{-4}$	$1.60\ 10^{-3}$
U-234	$1.62\ 10^{-2}$	$2.84\ 10^{-5}$	$6.77\ 10^{-4}$
U-235	$6.37\ 10^{-2}$	$8.15\ 10^{-3}$	$2.28\ 10^{-2}$
U-236	$1.54\ 10^{-2}$	$2.54\ 10^{-5}$	$6.26\ 10^{-4}$
U-238	$8.64\ 10^{-2}$	$5.31\ 10^{-3}$	$2.14\ 10^{-2}$
Np-237	$1.04\ 10^{-1}$	$1.18\ 10^{-2}$	$3.51\ 10^{-2}$
Pu-238	$4.70\ 10^{-2}$	$7.22\ 10^{-5}$	$1.84\ 10^{-3}$
Pu-239	$8.19\ 10^{-2}$	$1.28\ 10^{-4}$	$3.24\ 10^{-3}$
Pu-240	$8.16\ 10^{-2}$	$1.25\ 10^{-4}$	$3.20\ 10^{-3}$
Pu-241	$2.15\ 10^{-3}$	$1.61\ 10^{-5}$	$1.86\ 10^{-4}$
Pu-242	$7.88\ 10^{-2}$	$1.26\ 10^{-4}$	$3.15\ 10^{-3}$
Pu-244	$2.34\ 10^{-1}$	$2.40\ 10^{-2}$	$7.49\ 10^{-2}$
Am-241	$6.40\ 10^{-2}$	$4.94\ 10^{-4}$	$5.62\ 10^{-3}$
Am-242m	$8.89\ 10^{-2}$	$9.56\ 10^{-4}$	$9.22\ 10^{-3}$
Am-243	$1.28\ 10^{-1}$	$9.66\ 10^{-3}$	$3.51\ 10^{-2}$
Cm-242	$2.40\ 10^{-4}$	$3.69\ 10^{-7}$	$9.41\ 10^{-6}$
Cm-243	$2.02\ 10^{-2}$	$1.41\ 10^{-3}$	$5.33\ 10^{-3}$
Cm-244	$4.16\ 10^{-3}$	$6.54\ 10^{-6}$	$1.65\ 10^{-4}$
Cm-245	$9.61\ 10^{-2}$	$4.00\ 10^{-3}$	$1.96\ 10^{-2}$
Cm-246	$6.95\ 10^{-2}$	$3.54\ 10^{-4}$	$4.96\ 10^{-3}$
Cm-248	$6.88\ 10^{-1}$	$9.23\ 10^{-2}$	$2.52\ 10^{-1}$

1370. These doses are also illustrated graphically in Figure 31, ordered according to geometric mean dose. A value of 3 on the scale corresponds to a dose of 1 µSv, a value of 6 to 1 mSv, and a value of 0 to 1 nano Sievert (nSv). Radionuclides for which calculated geometric mean doses are less than 1 nSv are not shown.

1371. For most radionuclides, calculated geometric mean doses are less than 10 µSv. The highest calculated geometric mean dose is associated with disposal of Ra-226, which gives rise to a geometric mean dose of 3 mSv. Other high impact radionuclides include Pa-231, U-234 and Ba-133, which all give rise to geometric mean doses greater than 0.2 mSv. All calculated doses are below 3 mSv.

1372. The activity that a discrete item must have to give rise to an effective dose of 20 µSv y^{-1} was also calculated for each radionuclide. These activities are presented in Table 186 for doses calculated at 60 years after closure assuming that the discrete item can be modelled as a 1 tonne sphere.

Figure 31 Doses at 60 years after closure from encounter with a 1 tonne sphere contaminated with 1 GBq of radionuclide at consignment

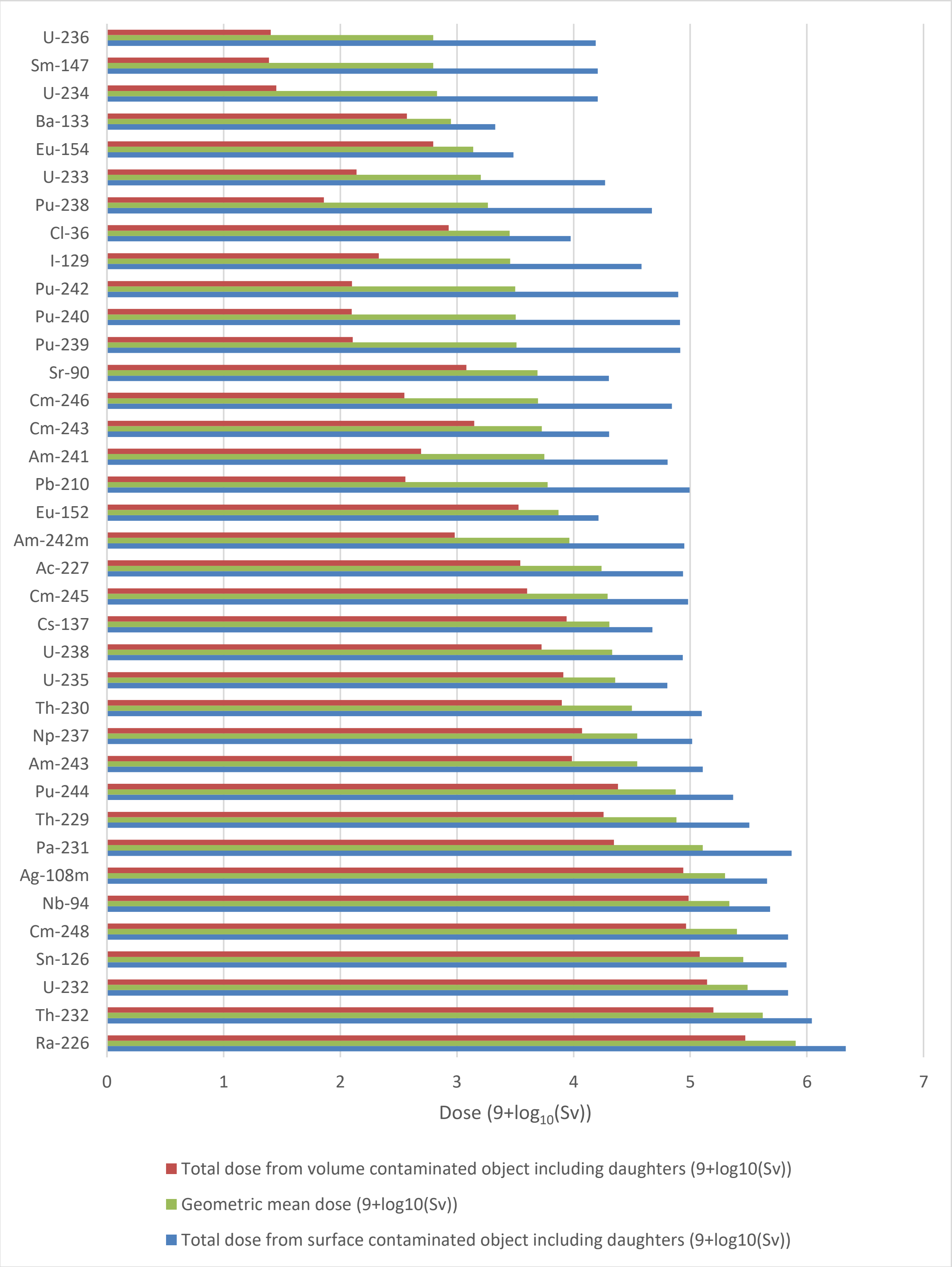


Table 186 Activity at time of consignment to give rise to an effective dose of 20 µSv y^{-1} based on doses calculated at 60 years after closure from a 1 hour encounter with a 1 tonne sphere.

Radionuclide	Activity to give effective dose limit from surface contaminated object including daughters (MBq)	Activity to give effective dose limit from volume contaminated object including daughters (MBq)	Activity to give effective dose limit using geometric mean dose (MBq)
H-3	$9.38\ 10^{7}$	$7.52\ 10^{9}$	$8.40\ 10^{8}$
C-14	$4.12\ 10^{4}$	$3.17\ 10^{5}$	$1.14\ 10^{5}$
Cl-36	$2.12\ 10^{3}$	$2.36\ 10^{4}$	$7.07\ 10^{3}$
Ca-41	$3.21\ 10^{5}$	$2.11\ 10^{8}$	$8.22\ 10^{6}$
Mn-54	$1.05\ 10^{23}$	$5.18\ 10^{23}$	$2.33\ 10^{23}$
Fe-55	$7.34\ 10^{11}$	$4.82\ 10^{14}$	$1.88\ 10^{13}$
Co-60	$7.10\ 10^{4}$	$3.21\ 10^{5}$	$1.51\ 10^{5}$
Ni-59	$7.83\ 10^{5}$	$2.12\ 10^{7}$	$4.08\ 10^{6}$
Ni-63	$3.44\ 10^{5}$	$3.64\ 10^{6}$	$1.12\ 10^{6}$
Zn-65	$2.00\ 10^{28}$	$2.00\ 10^{28}$	$2.00\ 10^{28}$
Se-79	$1.56\ 10^{4}$	$2.79\ 10^{5}$	$6.59\ 10^{4}$
Sr-90	$9.98\ 10^{2}$	$1.66\ 10^{4}$	$4.07\ 10^{3}$
Mo-93	$1.93\ 10^{4}$	$4.06\ 10^{6}$	$2.80\ 10^{5}$
Zr-93	$4.91\ 10^{4}$	$1.94\ 10^{6}$	$3.09\ 10^{5}$
Nb-93m	$5.89\ 10^{6}$	$3.92\ 10^{8}$	$4.80\ 10^{7}$
Nb-94	$4.14\ 10^{1}$	$2.06\ 10^{2}$	$9.24\ 10^{1}$
Tc-99	$1.71\ 10^{4}$	$9.81\ 10^{4}$	$4.09\ 10^{4}$
Ru-106	$5.33\ 10^{19}$	$4.44\ 10^{20}$	$1.54\ 10^{20}$
Ag-108m	$4.39\ 10^{1}$	$2.30\ 10^{2}$	$1.00\ 10^{2}$
Ag-110m	$6.00\ 10^{27}$	$2.00\ 10^{28}$	$1.10\ 10^{28}$
Cd-109	$2.08\ 10^{18}$	$3.08\ 10^{19}$	$8.00\ 10^{18}$
Sb-125	$5.25\ 10^{8}$	$2.84\ 10^{9}$	$1.22\ 10^{9}$
Sn-119m	$1.11\ 10^{27}$	$2.00\ 10^{28}$	$4.70\ 10^{27}$
Sn-123	$2.00\ 10^{28}$	$2.00\ 10^{28}$	$2.00\ 10^{28}$
Sn-126	$2.99\ 10^{1}$	$1.65\ 10^{2}$	$7.03\ 10^{1}$
Te-127m	$2.00\ 10^{28}$	$2.00\ 10^{28}$	$2.00\ 10^{28}$
I-129	$5.23\ 10^{2}$	$9.35\ 10^{4}$	$6.99\ 10^{3}$
Ba-133	$9.41\ 10^{3}$	$5.37\ 10^{4}$	$2.25\ 10^{4}$
Cs-134	$2.26\ 10^{10}$	$1.17\ 10^{11}$	$5.13\ 10^{10}$
Cs-135	$1.38\ 10^{4}$	$1.17\ 10^{5}$	$4.02\ 10^{4}$
Cs-137	$4.23\ 10^{2}$	$2.29\ 10^{3}$	$9.85\ 10^{2}$
Ce-144	$4.01\ 10^{26}$	$3.35\ 10^{27}$	$1.16\ 10^{27}$
Pm-147	$2.83\ 10^{11}$	$1.58\ 10^{12}$	$6.70\ 10^{11}$
Sm-147	$1.24\ 10^{3}$	$8.16\ 10^{5}$	$3.19\ 10^{4}$
Sm-151	$3.74\ 10^{5}$	$2.84\ 10^{6}$	$1.03\ 10^{6}$
Eu-152	$1.22\ 10^{3}$	$5.93\ 10^{3}$	$2.69\ 10^{3}$
Eu-154	$6.56\ 10^{3}$	$3.19\ 10^{4}$	$1.45\ 10^{4}$
Eu-155	$8.27\ 10^{6}$	$6.52\ 10^{7}$	$2.32\ 10^{7}$
Gd-153	$2.00\ 10^{28}$	$2.00\ 10^{28}$	$2.00\ 10^{28}$
Pb-210	$2.02\ 10^{2}$	$5.52\ 10^{4}$	$3.34\ 10^{3}$
Po-210	$2.00\ 10^{28}$	$2.00\ 10^{28}$	$2.00\ 10^{28}$
Ra-226	$9.29\ 10^{0}$	$6.73\ 10^{1}$	$2.50\ 10^{1}$
Ra-228	$2.69\ 10^{4}$	$1.75\ 10^{5}$	$6.87\ 10^{4}$
Ac-227	$2.30\ 10^{2}$	$5.73\ 10^{3}$	$1.15\ 10^{3}$
Th-228	$1.08\ 10^{11}$	$5.48\ 10^{11}$	$2.43\ 10^{11}$

Radionuclide	Activity to give effective dose limit from surface contaminated object including daughters (MBq)	Activity to give effective dose limit from volume contaminated object including daughters (MBq)	Activity to give effective dose limit using geometric mean dose (MBq)
Th-229	$6.23\ 10^{1}$	$1.11\ 10^{3}$	$2.63\ 10^{2}$
Th-230	$1.59\ 10^{2}$	$2.52\ 10^{3}$	$6.33\ 10^{2}$
Th-232	$1.81\ 10^{1}$	$1.26\ 10^{2}$	$4.79\ 10^{1}$
Pa-231	$2.70\ 10^{1}$	$9.03\ 10^{2}$	$1.56\ 10^{2}$
U-232	$2.89\ 10^{1}$	$1.44\ 10^{2}$	$6.45\ 10^{1}$
U-233	$1.07\ 10^{3}$	$1.45\ 10^{5}$	$1.25\ 10^{4}$
U-234	$1.24\ 10^{3}$	$7.05\ 10^{5}$	$2.96\ 10^{4}$
U-235	$3.14\ 10^{2}$	$2.45\ 10^{3}$	$8.78\ 10^{2}$
U-236	$1.29\ 10^{3}$	$7.88\ 10^{5}$	$3.19\ 10^{4}$
U-238	$2.31\ 10^{2}$	$3.77\ 10^{3}$	$9.34\ 10^{2}$
Np-237	$1.92\ 10^{2}$	$1.69\ 10^{3}$	$5.70\ 10^{2}$
Pu-238	$4.26\ 10^{2}$	$2.77\ 10^{5}$	$1.09\ 10^{4}$
Pu-239	$2.44\ 10^{2}$	$1.57\ 10^{5}$	$6.18\ 10^{3}$
Pu-240	$2.45\ 10^{2}$	$1.60\ 10^{5}$	$6.26\ 10^{3}$
Pu-241	$9.29\ 10^{3}$	$1.24\ 10^{6}$	$1.08\ 10^{5}$
Pu-242	$2.54\ 10^{2}$	$1.58\ 10^{5}$	$6.34\ 10^{3}$
Pu-244	$8.56\ 10^{1}$	$8.32\ 10^{2}$	$2.67\ 10^{2}$
Am-241	$3.12\ 10^{2}$	$4.05\ 10^{4}$	$3.56\ 10^{3}$
Am-242m	$2.25\ 10^{2}$	$2.09\ 10^{4}$	$2.17\ 10^{3}$
Am-243	$1.56\ 10^{2}$	$2.07\ 10^{3}$	$5.69\ 10^{2}$
Cm-242	$8.33\ 10^{4}$	$5.42\ 10^{7}$	$2.13\ 10^{6}$
Cm-243	$9.91\ 10^{2}$	$1.42\ 10^{4}$	$3.75\ 10^{3}$
Cm-244	$4.80\ 10^{3}$	$3.06\ 10^{6}$	$1.21\ 10^{5}$
Cm-245	$2.08\ 10^{2}$	$5.00\ 10^{3}$	$1.02\ 10^{3}$
Cm-246	$2.88\ 10^{2}$	$5.65\ 10^{4}$	$4.03\ 10^{3}$
Cm-248	$2.90\ 10^{1}$	$2.17\ 10^{2}$	$7.93\ 10^{1}$

1373. These limits give the maximum level of activity that could be present on an item at consignment in order to give an assessed effective dose of less than 20 µSv y^{-1}, assuming the activity distribution specified.

E.6.2.5. Radionuclide groups and Port Clarence Discrete Item Limits

1374. Following the LLWR approach, rather than set limits on discrete items for every radionuclide, the radionuclides have been placed into groups based on the calculated effective dose from discrete items. Such an approach enables acceptability against a limit to be determined based on the radionuclides with the highest contribution to the total activity within each group, rather than having to make an explicit assessment for each radionuclide.

1375. Initial radionuclide groupings were taken from the assessment undertaken by LLW Repository Ltd. These groupings were subsequently refined based on a comparison of the LLWR Discrete Item Limits and the calculated activities to give an effective dose of 20 µSv y^{-1} for a surface-contaminated 1 tonne sphere at Port Clarence. Consequently, five radionuclide groups are proposed to give Discrete Item limits at Port Clarence. The details and justification of this method are described below.

1376. Where radionuclides were not explicitly assigned groups within LLW repository Ltd's assessment, the guidance provided in (LLWR Ltd, 2013a) was used to allocate a group to that radionuclide. The initial radionuclide groupings used in this assessment are shown in Table 187. These initial radionuclide groupings enabled the calculated activities to give an effective dose of 20 µSv y^{-1} to be compared to the Discrete Item Limits at the LLWR (see Table 188) for each radionuclide. The calculated activity to give an effective dose of 20 µSv y^{-1} from a 1 hour exposure to a surface-contaminated 1 tonne sphere was compared to the LLWR Discrete Item Limit for a 1 tonne item. If this calculated activity was less than the LLWR Discrete Item Limit, then the Port Clarence Discrete Item Limit was set to a factor of 10 lower than the LLWR Discrete Item Limit. If this calculated activity was greater than the LLWR Discrete Item Limit then it was set to a factor of 100 lower than the LLWR Discrete Item Limit. Hence, the Port Clarence Discrete Item Limits are always less than the LLWR Discrete Item Limits.

1377. This approach sets all of the Port Clarence Discrete Item Limits below the calculated activity to give an effective dose of 20 µSv y^{-1} from a 1 hour exposure to a surface-contaminated 1 tonne sphere for all radionuclides except Eu-152, Pb-210 and Ac-227 and therefore, for these, the Port Clarence Discrete Item Limit was decreased by a further factor of ten.

1378. As a result of this method, five radionuclide groups are proposed to give Discrete Item Limits at Port Clarence. These groups and the radionuclides in these groups are given in Table 189.[2] The corresponding Discrete Item Limits proposed for Port Clarence are given in Table 190. The relationship between the Discrete item Limit for different masses is the same as that used by LLWR, namely for items less than 1 kg the Discrete Item Limit is 0.01 of the Discrete Item Limit for 100 kg or over, with a linear relationship for masses in between.

1379. The Discrete Item Limits at Port Clarence are lower (i.e. they are more restrictive) than the LLWR Discrete Item Limits for all radionuclides.

1380. The application of more restrictive limits for discrete items at Port Clarence compared to LLWR is conservative since the calculations indicate that higher Discrete Item Limits could be used for many radionuclides. The changes reflect the fact that the LLWR Discrete Item Limits were based on an assessment of doses some 300 years after closure of that site, whereas at Port Clarence erosion, and hence exposure to items, has been modelled as occurring 60 years after closure.

[2] We denote the five radionuclide groups for Port Clarence using lower-case letters a, b, c, d and e to prevent confusion with the LLWR Discrete Item Limits.

Table 187 Radionuclide groups for Discrete Item Limits as used at LLWR

Parameter	Radionuclides
Group A	Nb-94 Ag-108m Sn-126 Ra-226 Th-229 Th-230 Th-232 Pa-231 U-232 Np-237 Pu-244 Am-243 Cm-248
Group B1	Se-79 I-129 Sm-147 U-235 U-238 Pu-238 Pu-239 Pu-240 Pu-242 Am-241 Am-242m Cm-245 Cm-246
Group B2	C-14 Cl-36 Ca-41 Sr-90 Mo-93 Zr-93 Tc-99 Cs-135 Cs-137 Ac-227 Pb-210 U-233 U-234 U-236 Pu-241 Cm 243 Cm-244
Group C	H-3 Mn-54 Fe-55 Co-60 Ni-59 Ni-63 Zn-65 Nb-93m Ru-106 Ag-110m Cd-109 Sb-125 Sn-119m Sn-123 Te-127m Ba-133 Cs-134 Ce-144 Pm-147 Sm-151 Eu-152 Eu-154 Eu-155 Gd-153 Po-210 Ra-228 Th-228 Cm-242

Note: From Table 6-2 of (LLW Repository Ltd, August 2013). Radionuclides not explicitly grouped at the LLWR are highlighted in red.

Table 188 Discrete Item Limits for LLWR

	Weight 1 kg or less	Weight between 1 and 100 kg	Weight 100 kg or greater
Group A	0.001 GBq	1 GBq te^{-1}	0.1 GBq
Group B1	0.01 GBq	10 GBq te^{-1}	1 GBq
Group B2	0.1 GBq	100 GBq te^{-1}	10 GBq
Group C	1 GBq	1000 GBq te^{-1}	100 GBq

Table 189 Radionuclide groups for Discrete Item Limits at Port Clarence.

Parameter	Radionuclides
Group a	Nb-94, Ag-108m, Sn-126, Ra-226, Th-229, Th-232, Pa-231, U-232, Pu-244, Cm-248
Group b	I-129, Pb-210, Ac-227, Th-230, U-235, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-242, Am-241, Am-242m, Am-243, Cm-245, Cm-246
Group c	Cl-36, Se-79, Sr-90, Cs-137, Sm-147, Eu-152, U-233, U-234, U-236, Pu-241, Cm-243, Cm-244
Group d	C-14, Ca-41, Co-60, Mo-93, Zr-93, Tc-99, Ba-133, Cs-135, Eu-154, Ra-228, Cm-242
Group e	H-3, Mn-54, Fe-55, Ni-59, Ni-63, Zn-65, Nb-93m, Ru-106, Ag-110m, Cd-109, Sb-125, Sn-119m, Sn-123, Te-127m, Cs-134, Ce-144, Pm-147, Sm-151, Eu-155, Gd-153, Po-210, Th-228

Table 190 Discrete Item Limits for Port Clarence

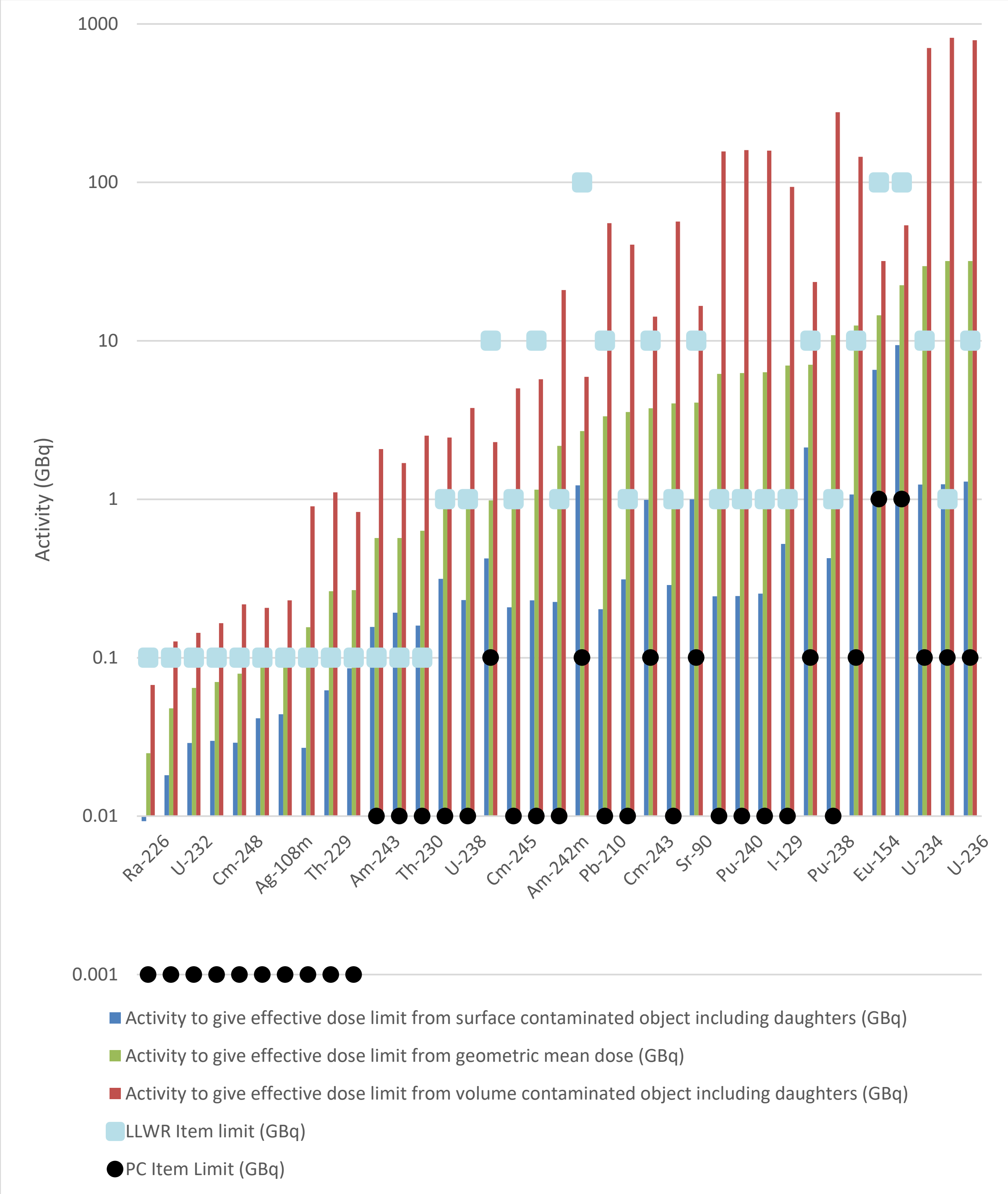
	Weight 1 kg or less	Weight between 1 and 100 kg	Weight 100 kg or greater	LLWR group with the same limit
Group a	0.0001 GBq	0.1 GBq te^{-1}	0.01 GBq	Not used
Group b	0.001 GBq	1 GBq te^{-1}	0.1 GBq	A
Group c	0.01 GBq	10 GBq te^{-1}	1 GBq	B1
Group d	0.1 GBq	100 GBq te^{-1}	10 GBq	B2
Group e	1 GBq	1000 GBq te^{-1}	100 GBq	C

1381. Another conservatism arises from the fact that the Port Clarence Discrete Item Limits have been set on the basis of the dose from a surface-contaminated item of mass 1 tonne. In reality, the activity within wastes will not be solely distributed on the surface of the contaminated items, it will penetrate into the volume of the items. Consequently, the dose calculated from a surface-contaminated item will be an over-estimate of the anticipated dose, and the activity to give an effective dose of 20 µSv y^{-1} from a surface-contaminated sphere will be less than the activity to give an effective dose of 20 µSv y^{-1} for an item with a component of activity distributed within the volume of the item.

1382. Figure 32 demonstrates the item activity that would be required to give an effective dose of 20 µSv y^{-1} for surface- and volume- contaminated spheres of mass 1 tonne. Radionuclides are ordered in terms of geometric dose, and radionuclides for which calculated geometric mean doses are less than 1 nSv are not shown.

1383. The LLWR Discrete Item Limits and proposed Port Clarence Discrete Item Limits for each radionuclide are also plotted on Figure 32. Radionuclides for which calculated geometric mean doses are less than 1 nSv are not shown.

Figure 32 Activity required to give an effective dose of 20 µSv y^{-1} from a 1 hour exposure to a 1 tonne contaminated sphere at 60 years after closure



1384. Not all items to be consigned to Port Clarence will have a mass of around 1 tonne, therefore smaller masses were also considered to check that the proposed Discrete Item Limits were appropriate.

1385. The item activities to give rise to an effective dose of 20 µSv y^{-1} from items with mass 10 g, 100 g, 1 kg and 10 tonnes were calculated for each radionuclide. The radionuclides with the greatest impact from a 10 g sphere, 10 kg sphere and 10 tonne sphere were then identified for each radionuclide group given in Table 189. The results of this analysis are presented in Table 191.

Table 191 Highest impact radionuclides within each Port Clarence group.

Highest impact radionuclide within specified group for specified sphere mass. The bracketed term gives the activity required to give an effective dose of 20 µSv y^{-1} for that radionuclide for the specified sphere mass to one significant figure (Bq)			
	10 g	10 kg	10 tonne
Group a	Ra-226 (5 10^{4})	Ra-226 (3 10^{6})	Ra-226 (1 10^{8})
Group b	Pb-210 (4 10^{5})	Th-230 (6 10^{7})	Np-237 (2 10^{9})
Group c	U-233 (2 10^{6})	Cs-137 (2 10^{8})	Cs-137 (3 10^{9})
Group d	Mo-93 (3 10^{7})	Eu-154 (3 10^{9})	Eu-154 (5 10^{10})
Group e	Ni-63 (1 10^{9})	Ni-63 (1 10^{11})	Sm-151 (4 10^{12})

1386. The proposed Port Clarence Discrete Item Limits for different masses are illustrated in the graphs in Figure 33 to Figure 37 for a number of these high impact radionuclides, namely Ra-226, Pb-210, U-233, Mo-93 and Ni-63.

1387. It is reasonable for the Discrete Item Limit to lie between the activity leading to an effective dose of 20 µSv y^{-1} for the volume- and surface-contaminated items because not all activity will be uniformly distributed within the volume of the item or over its surface. It is also reasonable for the Discrete Item Limit to be less restrictive for small items because, generally speaking, larger items are likely to be of more interest to an estuary bank user and to stay on the riverbank for longer, whereas smaller items are less likely to be seen and more likely to be removed by natural river or tidal action. In addition, comparison with the activity leading to a dose of 20 µSv y^{-1} is a conservative approach to ensuring that the dose to a person deliberately encountering a discrete item will meet the lower dose guidance level of 3 mSv.

1388. The graph for Ra-226 (Figure 33) illustrates that the Discrete Item Limits for Group a radionuclides are below the geometric mean of the activities leading to a dose of 20 µSv y^{-1} from the volume- and surface-contaminated items for all masses. On this basis, and noting that Ra-226 is the radionuclide within Group a that gives rise to the greatest impact, the proposed Discrete Item Limits for Group a are deemed appropriate.

1389. The graph for Pb-210 (Figure 34) illustrates that the Discrete Item Limits for Group b radionuclides are below the geometric mean of the activities leading to a dose of 20 µSv y^{-1} from the volume- and surface-contaminated items for all masses. On this basis, and noting that Pb-210 is the radionuclide within Group b that gives rise to the greatest impact, the proposed Discrete Item Limits for Group b are deemed appropriate.

1390. The graph for U-233 (Figure 35) illustrates that the Discrete Item Limits for Group c radionuclides will ensure that the effective dose is below 20 µSv y^{-1} for all weights above about 30 g if the item is assumed to be surface-contaminated, and for all weights based on the geometric mean and volume-contaminated items for all masses. On this basis, and noting that U-233 is one of the radionuclides within Group c that gives rise to the greatest impact, particularly for smaller item masses, the proposed Discrete Item Limits for Group c are deemed appropriate.

1391. The Group d Discrete Item Limits are illustrated in the graph for Mo-93 (Figure 36) that illustrates the Discrete Item Limits for Group d radionuclides are below the geometric mean of the activities leading to a dose of 20 µSv y^{-1} from the volume- and surface-contaminated items for all masses. On this basis, and noting that Mo-93 is the radionuclide within Group d that gives rise to the greatest impact, the proposed Discrete Item Limits for Group d are deemed appropriate.

1392. The Group e Discrete Item Limits are illustrated in the graph for Ni-63 (Figure 37). The Discrete Item Limits for Group e radionuclides will ensure that the effective dose is below 20 µSv y^{-1} for all weights based on the volume- and surface-contaminated items at all masses. On this basis, and noting that Ni-63 is the radionuclide within Group e that gives rise to the greatest impact, the proposed Discrete Item Limits for Group e are deemed appropriate.

Figure 33 Item activity leading to a dose of 20 µSv y^{-1} for Ra-226

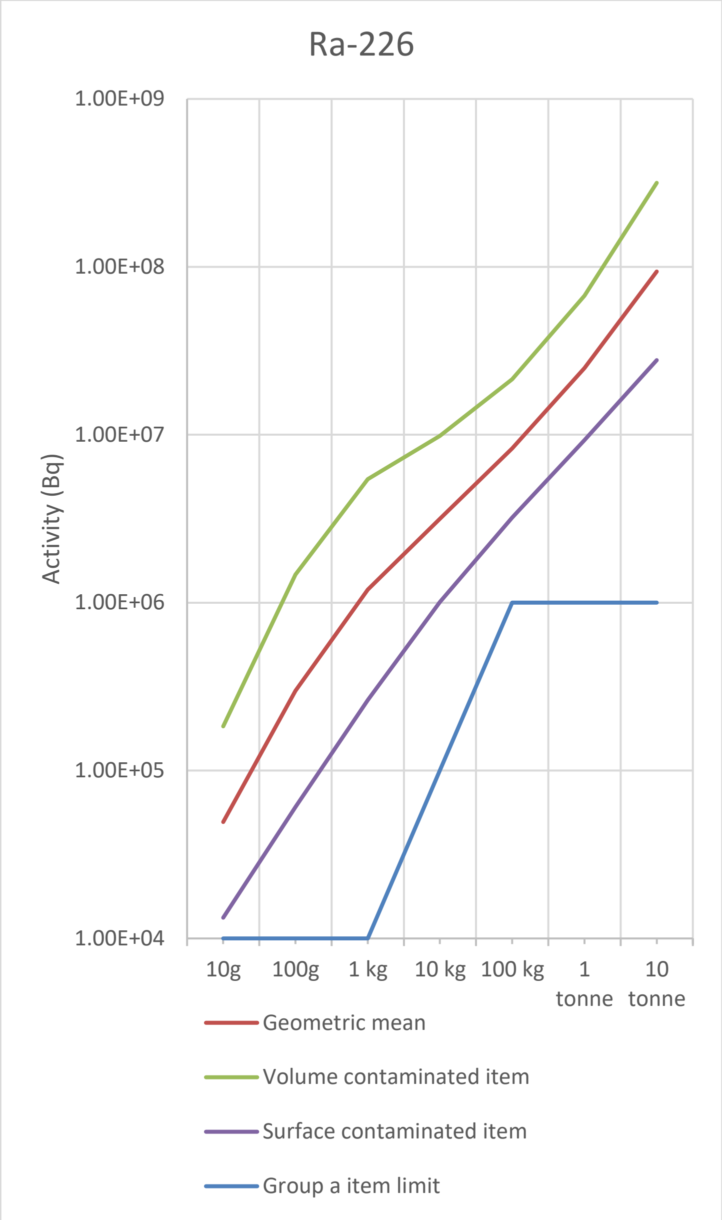


Figure 34 Item activity leading to a dose of 20 µSv y^{-1} for Pb-210

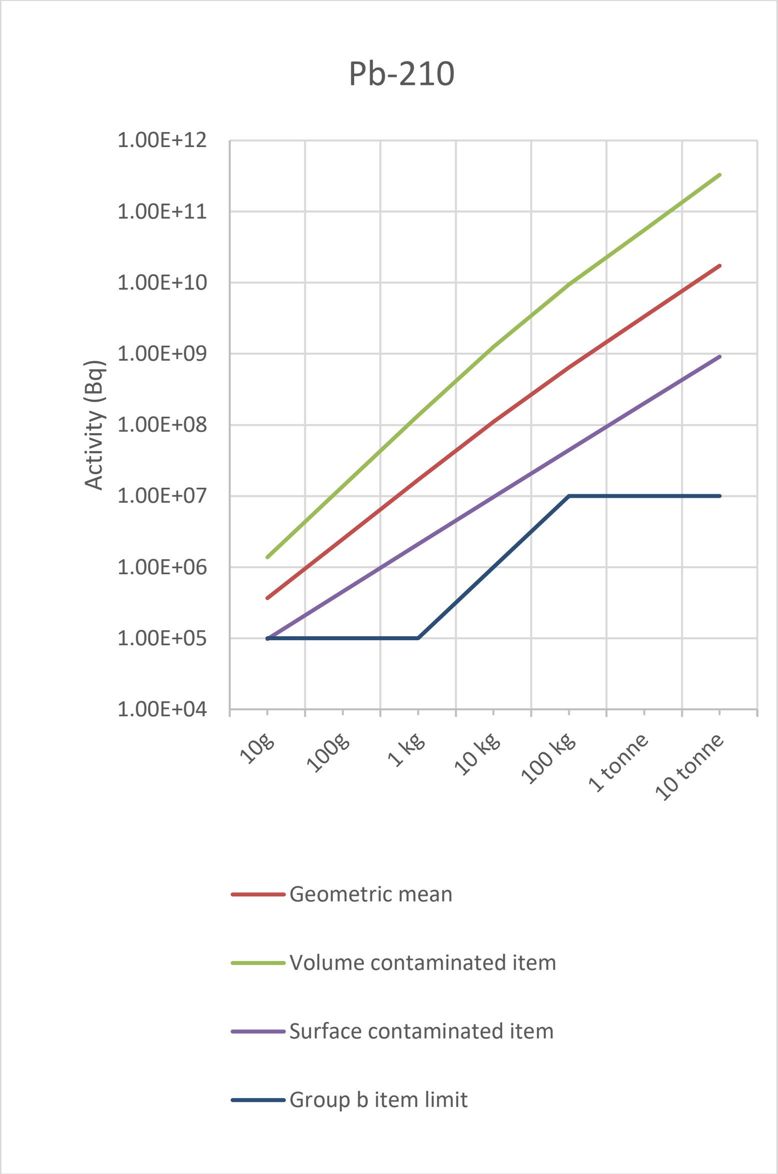


Figure 35 Item activity leading to a dose of 20 µSv y^{-1} for U-233

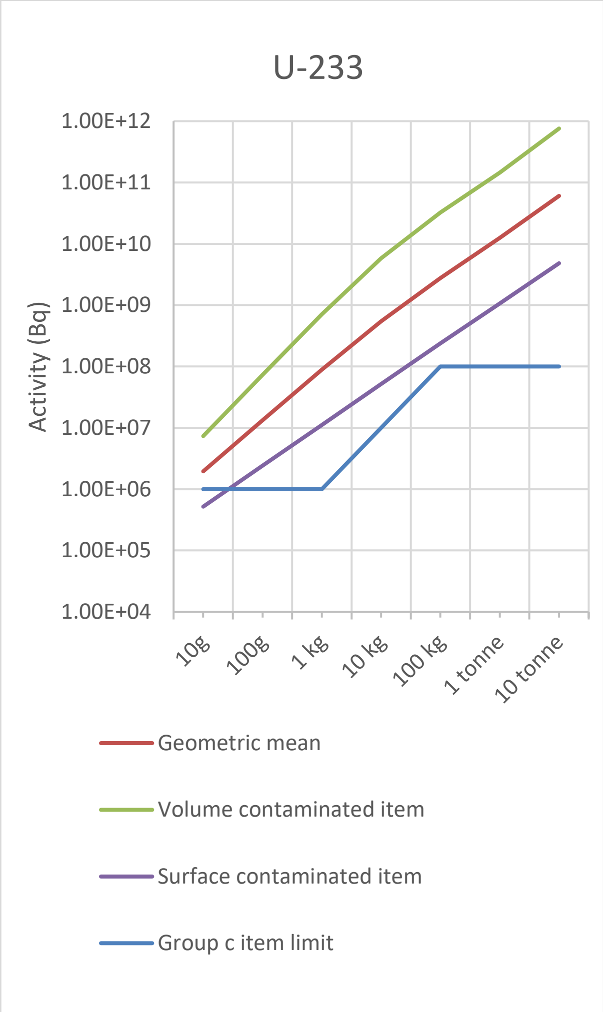


Figure 36 Item activity leading to a dose of 20 µSv y^{-1} for Mo-93

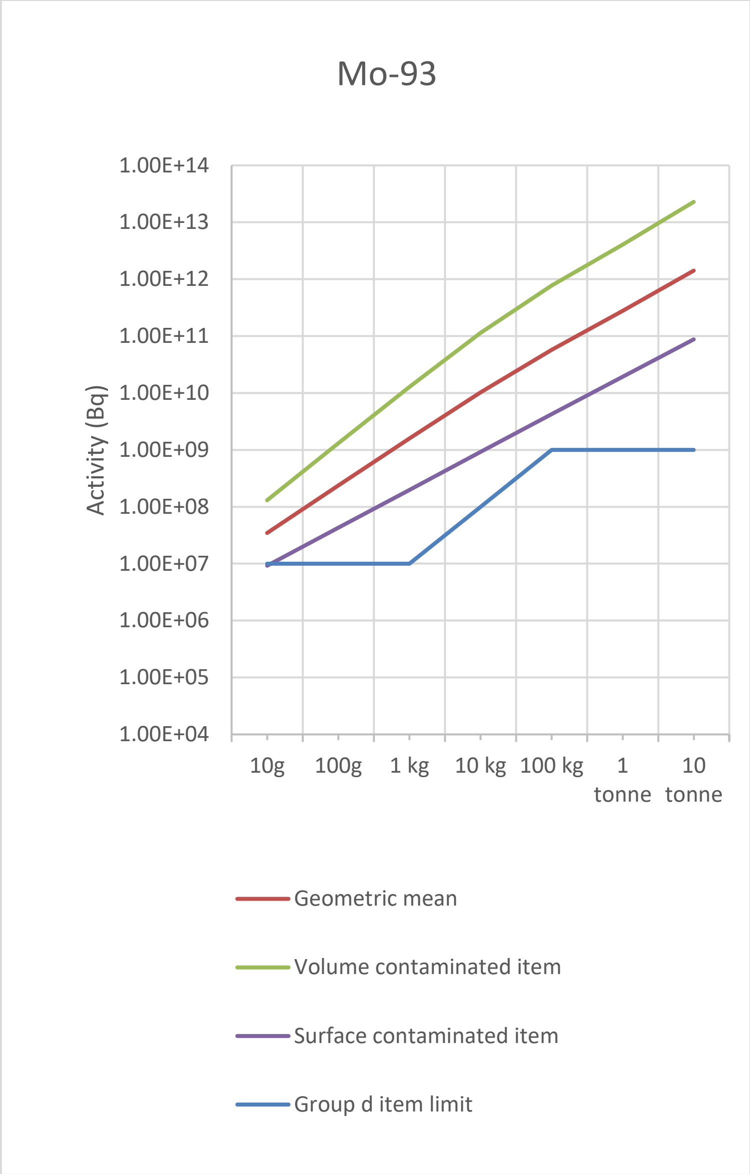
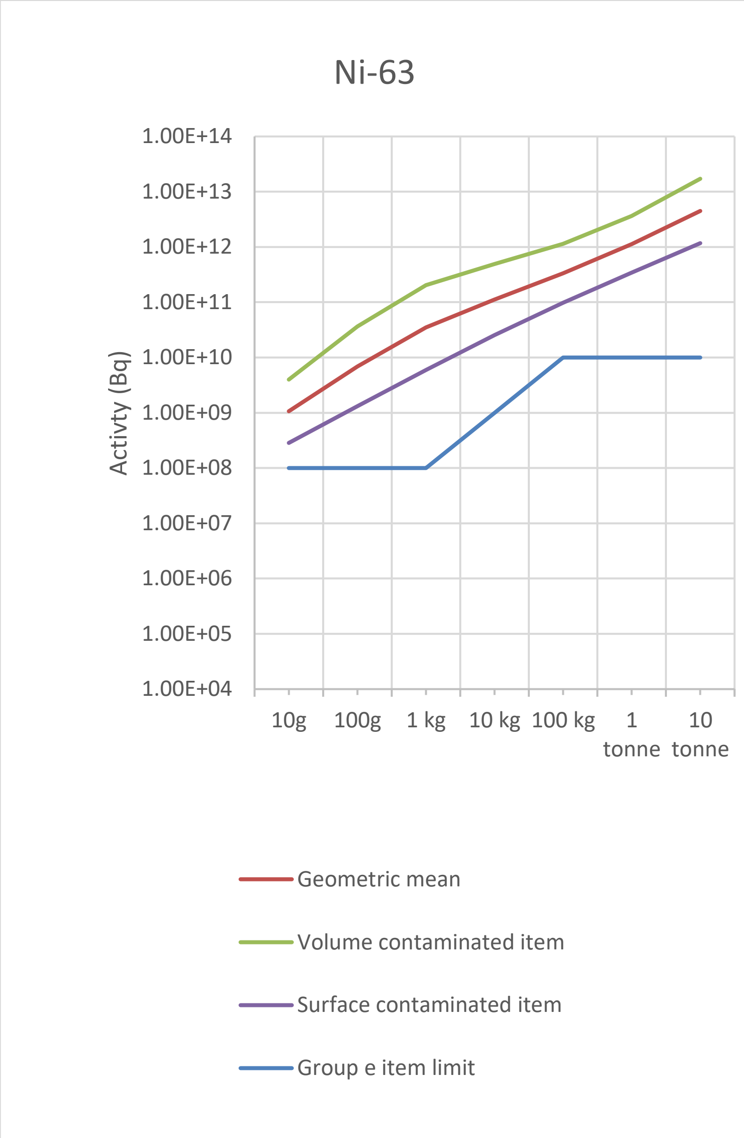


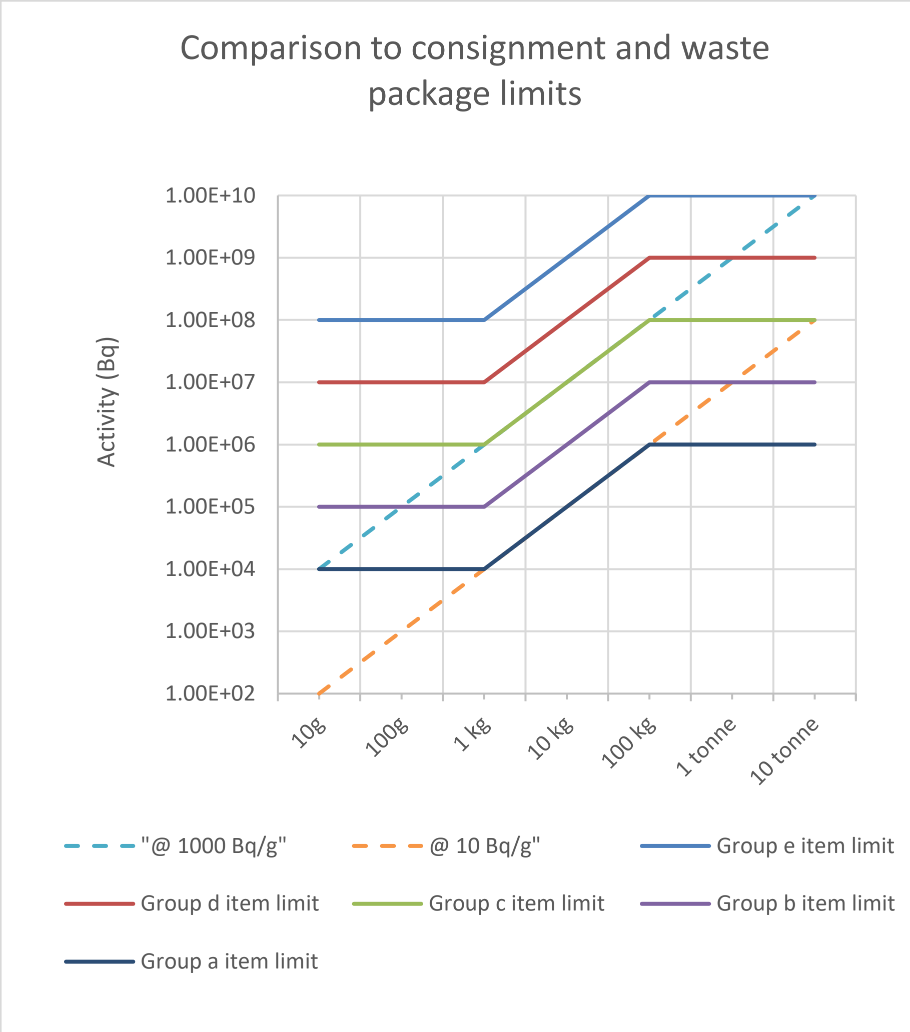
Figure 37 Item activity leading to a dose of 20 µSv y^{-1} for Ni-63



1393. Hence, the proposed Discrete Item Limits will limit the assessed effective doses to an estuary bank user, following erosion of the site, from the disposal of discrete items at Port Clarence to within acceptable levels.

1394. In addition, the specific activity concentration limits for each consignment and each package will tend to prevent items with activities near the Discrete Item Limits being disposed at Port Clarence. This is illustrated in Figure 38 for both a consignment specific activity limit of 10 Bq g^{-1} and a specific activity concentration per package of 1000 Bq g^{-1}.

Figure 38 Comparison of Port Clarence Discrete Item Limits with those for individual consignments and waste packages



E.6.2.6. Waste Acceptance using the Port Clarence Discrete Item Limits

1395. It has been demonstrated that the proposed Discrete Item Limits will provide adequate protection to a potential future user of the bank of the estuary following future erosion of the landfill. Here, a process for applying these Discrete Item Limits to waste is identified.

1396. In the first instance, waste consignors should determine whether any items within a consignment should be classified as a discrete item. Guidance on what can be classified as a discrete item can be obtained by consulting LLW Repository Ltd's Discrete Item Library (LLWR Ltd, 2019). Waste consignors should also contact Augean Ltd for guidance.

1397. If the item concentration is less than the limits set out in Table 38 the consignment would be accepted for disposal. For other items, based on the activity of each radionuclide on the item and the Discrete Item Limits for the item, a Sum of Fractions approach to determine acceptability of that item should then be used.

1398. The Sum of Fractions is given by:

$$SoF = \frac{Q_a}{L_a} + \frac{Q_b}{L_b} + \frac{Q_c}{L_c} + \frac{Q_d}{L_d} + \frac{Q_e}{L_e},$$

where Q_n is the total activity of group n radionuclides on the item and L_n is the Port Clarence Discrete Item Limit for that group (given in Table 190). If a radionuclide is known to be present on an item, is not listed in Table 189 and has a half-life greater than 200 years then the radionuclide should be cautiously assigned to Group a. Otherwise it should be assigned to Group e, unless it decays to an alpha-emitting daughter with a half-life a few tens to hundreds of time the parent half-life, in which it should be assigned to Group a.

1399. If this Sum of Fraction is less than one, the item is acceptable for disposal within a consignment at Port Clarence, subject to meeting other Waste Acceptance Criteria including the activity concentration limits for a consignment and for a package. If a discrete item meets the discrete item sum of fractions limits but exceeds the consignment maximum activity concentrations that are given in Table 38 of the ESC, there are three potential outcomes:

- If the consignment as a whole meets the limits set out in Table 38 and the overall activity concentration of the discrete item meets the limits set out in Table 31 and is less than the upper bounds defining what constitutes LLW, the consignment would be accepted.
- If the consignment as a whole meets the limits set out in Table 38 and the overall activity concentration of the discrete item is more than the upper bounds defining what constitutes LLW or exceeds the limits set out in Table 31, the consignment would **not** be accepted due to the presence of the discrete item.
- If the consignment as a whole exceeds the limits set out in Table 38 the consignment would **not** be accepted.

E.6.3. Excavation of particles

1400. Radioactive particles are small items that could be as small as a grain of sand and could be incorporated in a radioactive waste stream or package. The possibility that future intrusion events could lead to unintentional recovery of, and exposure to, radioactive particles is considered. Migration of particles in groundwater or uptake from soil into the food chain is not considered credible.

1401. The methodology for assessing the dose implications of excavating waste materials that include particles is described here, together with the approach to waste acceptance criteria.

E.6.3.1. Assessment approach

1402. The assessment approach is based on that applied in the ENRMF ESC, see Appendix E, Section E6.1 (Eden NE, 2023). It draws on the work (Mobbs & Sumerling, 2012; Sumerling, 2013) undertaken for the LLWR ESC. The methodology can assess the dose arising from any radionuclide associated with a particle and has been implemented in an Excel workbook (PC Particle assessment tool v2.xlsx) for use by

Augean on decisions regarding acceptability of waste at the ENRMF (Eden NE, 2018). This section describes the methodology implemented in the Excel workbook (referred to here as the spreadsheet) and provides illustrative results of the dose calculations.

1403. The spreadsheet considers the radionuclides which are included in this ESC and allows the user to add "Other Radionuclides" with a half-life greater than 1 year or as specified in writing by the Environment Agency. The dose calculations include the first daughter radionuclide of a decay chain not assumed within dose coefficients to be in secular equilibrium, i.e. those radionuclides listed as radioactive daughters that need to be considered explicitly. A worksheet is also included to allow calculation of doses assuming secular equilibrium.

1404. The pathways considered are as follows:

- Ingestion of 1 mm particle; and,
- External exposure to a 1 mm particle (whole body doses and skin doses).

1405. The doses from these pathways are not considered to be additive.

1406. Inhalation of particles is not considered as it is not relevant for particles of 1 mm in size and inhalation of particles up to 10 µm in size was found not to be an important pathway in other assessments of particles (Sumerling, 2013; HPA, 2005; HPA, 2011).

1407. Two different times of inadvertent intrusion are considered: 60 and 300 years after disposals end, respectively. The earliest time of inadvertent intrusion, 60 years after site closure, corresponds to intrusion occurring at the end of institutional oversight of the restored landfill. However, inadvertent intrusion after a longer period of time is considered more realistic and has been based on the maximum period of active institutional control considered by the Environment Agency (300 years) presented in the NS-GRA (UK Environment Agencies, 2009).

1408. The calculations take no account of the probability that the person who is intruding into the landfill site actually comes into contact with the particle being considered. Given the quantity of soil, waste and other material that would be excavated during an intrusion event, the probability of inadvertently ingesting the particle or of it becoming trapped against the skin or under a nail is extremely small.

1409. Measurements (HPA, 2005; Tyler, et al., 2013; HPA, 2011) have found that particles are not 100% soluble in the gastro-intestinal tract and therefore ingestion doses calculated using the standard ICRP gut uptake factors (ICRP, 2012) are unrealistically high. The spreadsheet allows the user to enter different uptake factors or to enter a particle solubility. The EA is expected to require experimental evidence (for the particles being disposed) that the use of different uptake factors or reduced solubility is justified.

E.6.3.2. Methodology

1410. The methodology considers three exposure pathways: ingestion, external (whole body) and external (skin). The doses due to each of these pathways are not considered to be additive. It is assumed conservatively that exposure occurs 60 or 300 years after site closure, as a result of deliberate excavation of the site.

Ingestion

1411. Inadvertent ingestion is typically size restricted and it is assumed here that particles for inadvertent ingestion are essentially spherical with a nominal diameter of 1 mm. The precise dimensions are not important providing the particle is sufficiently small that it remains inadvertently ingestible (e.g. anywhere in the range of 1 to a few mm diameter). The dose, if ingested, depends on the activity of the particle rather than the size. Dose is estimated on a per particle basis.

1412. Ingestion dose (Sv y^{-1}) is calculated in one of two ways, depending on how the solubility of the particle is taken into account. The first method uses a specified particle solubility, *Sol,* to scale the dose:

$$Dose_{ing} = D_{ing}^{Rn}.Sol.A_{Rn}(t)$$

where:

- $Dose_{ing}$ is the dose from ingestion of the particle (Sv);
- D_{ing}^{Rn} is the ICRP dose coefficient for ingestion of radionuclide *Rn* (Sv Bq^{-1}), see Table 225;
- $A_{Rn}(t)$ is the activity of the particle (Bq) at the time of exposure (t);
- *Sol* is the solubility of the particle in the gastro-intestinal tract.

1413. *Sol* applies to all radionuclides in the particle, including short lived daughter radionuclides in secular equilibrium.

1414. The second method uses specified particle solubility related gut uptake values for each radionuclide on the particle, $f1_{Rn}$, to scale the dose coefficient:

$$Dose_{ing} = D_{ing}^{Rn}.\frac{f1_{Rn}}{ICRP\ f1_{Rn}}.A_{Rn}(t)$$

Where all terms are the same as the previous equation and:

- $f1_{Rn}$ is the realistic gut uptake factor for radionuclide *Rn* allowing for the solubility of the particle; and,
- $ICRP\ f1_{Rn}$ is the ICRP gut uptake factor corresponding to D_{ing}^{Rn} (ICRP, 2012).

1415. The linear scaling of the ICRP dose coefficient shown above is applied in all cases except for Co, Sr, U and Pu isotopes where comparison of the ICRP dose coefficients for different f1 values for these radionuclides showed a non-linear response. The following approach is taken:

$$D_{ing}^{Rn,revised} = (a_{Rn} + b_{Rn}\,.f1_{Rn})$$

where:

a_{Rn} and b_{Rn} are empirically derived constants, representing the dose from the particle to the gut per unit ingestion and the dose from unit uptake in blood, respectively, other terms being the same as immediately above.

1416. Values for a_{Rn} and b_{Rn} are obtained by fitting ICRP dose coefficients for different f1 values for the same radionuclide. The values are given in Table 192.

Table 192 Constants for non-linear scaling of dose per unit ingestion calculations

Radionuclide	Dose to gut per unit ingestion, a_{Rn}	Dose per unit to blood, b_{Rn}
Co-60	$1.60\ 10^{-9}$	$1.80\ 10^{-8}$
Sr-90	$1.83\ 10^{-9}$	$8.72\ 10^{-8}$
U-232	$4.50\ 10^{-9}$	$1.63\ 10^{-5}$
U-233	$3.90\ 10^{-9}$	$2.31\ 10^{-6}$
U-234	$3.80\ 10^{-9}$	$2.26\ 10^{-6}$
U-235	$4.15\ 10^{-9}$	$2.09\ 10^{-6}$
U-236	$3.70\ 10^{-9}$	$2.12\ 10^{-6}$
U-238	$3.60\ 10^{-9}$	$2.02\ 10^{-6}$
Pu-238	$4.30\ 10^{-9}$	$4.51\ 10^{-4}$
Pu-239	$4.10\ 10^{-9}$	$4.92\ 10^{-4}$
Pu-240	$4.10\ 10^{-9}$	$4.92\ 10^{-4}$
Pu-241	$2.50\ 10^{-11}$	$9.35\ 10^{-6}$
Pu-242	$3.90\ 10^{-9}$	$4.72\ 10^{-4}$

1417. The dose coefficients for daughter radionuclides are scaled according to the ratio of the realistic f1 to the ICRP f1 for the parent:

$$D_{ing}^{Rn,revised} = D_{ing}^{Rn}.\frac{f1_{Rn,parent}}{ICRP\ f1_{Rn,parent}}$$

External exposure (whole body)

1418. External exposure is not limited by the size of the particle. A larger particle with the same activity will deliver the same external dose. An exposure time of 8 hours is assumed.

1419. External dose (Sv) is thus calculated as:

$$Dose_{ext,wb} = G_{wb}^{Rn}.T_{ext}.A_{Rn}(t)$$

where:

- $Dose_{ext,wb}$ is the external effective (whole body) dose (Sv);
- G_{wb}^{Rn} is the point source whole body dose rate for radionuclide *Rn* (Sv hour^{-1} Bq^{-1}), from β and / or γ radiation as appropriate for that radionuclide (European Commission, 1993);
- $A_{Rn}(t)$ is the activity of the particle (Bq) at the time of exposure (t); and,

- T_{ext} is the exposure time for external exposure (hours).

External exposure (skin)

1420. Skin dose will depend on the size of a particle. A larger particle will remain in contact with the skin for a shorter time and there will be self-absorption within the particle. It is assumed that the particle becomes lodged in direct contact with the skin (for example under a fingernail) and remains in situ for 1 hour. A nominal particle size of 1 mm is consistent with this assumption.

1421. ICRP (ICRP, 2007) recommends that for radiological protection purposes the skin dose should be evaluated to the cells of the basal layer. The depth of these cells is often referred to in radiation protection as the skin thickness and ICRP recommend a value of 70 μm is used for routine skin dose assessment. For non-uniform exposures the ICRP recommend that this dose should be averaged over the most highly exposed area of 1 cm^2.

1422. External dose (Sv) to skin is thus calculated as:

$$Dose_{ext,skin} = G_{skin}^{Rn}.T_{skin}.A_{Rn}(t)$$

where:

- $Dose_{ext,skin}$ is the skin (organ) dose (Sv);
- G_{skin}^{Rn} is the point-source dose rate for radionuclide *Rn* in contact with the skin (Sv $hour^{-1}$ Bq^{-1}) from β and / or γ radiation as appropriate for that radionuclide, assuming a skin thickness of 70 μm (note that β dose rate factors for 40 μm were used in the calculations as no other data were available, see paragraph 1159, (European Commission, 1993));
- $A_{Rn}(t)$ is the activity of the particle (Bq) at the time of exposure (t); and,
- T_{skin} is the exposure time for skin exposure (hours).

1423. A nominal exposure time of 8 hours walking is assumed (resulting in 8 identical particles each trapped for 1 h under the fingernail).

E.6.3.3. Results for selected radionuclides

1424. Table 193 gives the results of the dose assessments using the particle assessment tool for ten of the radionuclides considered in the ESC. This gives the dose from ingestion (assuming ICRP f1 values), external exposure and skin exposure arising from 1 MBq of each radionuclide, for intrusion at 60 years, and for intrusion at 300 years after closure.

Table 193 Dose (mSv) from 1MBq on a particle, for two intrusion times

Radionuclide	Dose from ingestion at 60 y	Whole body dose at 60 y	Skin Dose at 60 y	Dose from ingestion at 300 y	Whole body dose at 300 y	Skin Dose at 300 y
Pa-231	$1.74\ 10^{3}$	$3.81\ 10^{-5}$	$5.85\ 10^{3}$	$1.91\ 10^{3}$	$3.79\ 10^{-5}$	$6.80\ 10^{3}$
Ra-226	$1.17\ 10^{3}$	$1.77\ 10^{-3}$	$8.47\ 10^{3}$	$1.06\ 10^{3}$	$1.60\ 10^{-3}$	$7.63\ 10^{3}$
Th-232	$1.03\ 10^{3}$	$1.43\ 10^{-3}$	$2.60\ 10^{2}$	$1.03\ 10^{3}$	$1.43\ 10^{-3}$	$2.60\ 10^{2}$
Th-229	$5.96\ 10^{2}$	$3.81\ 10^{-4}$	$8.58\ 10^{3}$	$5.83\ 10^{2}$	$3.72\ 10^{-4}$	$8.39\ 10^{3}$
Sn-126	$7.13\ 10^{0}$	0	$4.67\ 10^{3}$	$7.13\ 10^{0}$	0	$4.67\ 10^{3}$
Pu-239	$2.50\ 10^{2}$	$1.30\ 10^{-7}$	$1.43\ 10^{0}$	$2.48\ 10^{2}$	$1.29\ 10^{-7}$	$1.42\ 10^{0}$
Pu-240	$2.48\ 10^{2}$	$1.38\ 10^{-6}$	$2.58\ 10^{0}$	$2.42\ 10^{2}$	$1.34\ 10^{-6}$	$2.52\ 10^{0}$
Th-230	$2.41\ 10^{2}$	$4.90\ 10^{-5}$	$3.31\ 10^{2}$	$3.56\ 10^{2}$	$2.24\ 10^{-4}$	$1.17\ 10^{3}$
Pu-242	$2.40\ 10^{2}$	$1.15\ 10^{-6}$	$3.07\ 10^{0}$	$2.40\ 10^{2}$	$1.15\ 10^{-6}$	$3.07\ 10^{0}$
U-238	$4.79\ 10^{1}$	$3.51\ 10^{-4}$	$3.83\ 10^{3}$	$4.80\ 10^{1}$	$3.51\ 10^{-4}$	$3.83\ 10^{3}$

E.6.3.4. Waste acceptance

1425. It is not possible to determine generic waste acceptance criteria for waste containing particles as the characteristics of the particle (e.g. nuclides, size, solubility) will be specific to the consignment. Any waste containing particles will be considered on a case-by-case basis and assessed using the spreadsheet tool.

1426. Decisions regarding acceptance for waste containing high activity particles can be made by comparison of the results of dose calculations for the activity on the particle with the NS-GRA intrusion dose guidance level. The ingestion dose and external (whole body) dose are therefore compared to the annual dose guidance level of 3 to 20 mSv. The exposure is regarded as a 'one-off' event and hence the appropriate dose guidance value would lie towards the upper end of the range cited. The dose from contact with the skin is compared with the 50 mSv annual dose limit for the equivalent dose to skin for members of the public, as specified in the NS-GRA. Wastes that do not meet these dose guidance levels are not accepted without specific approval from the Environment Agency. Demonstration that the disposal route adopted represents BAT would also be required. Illustrative activity limits based on the lower dose guidance level (3 mSv) and the skin dose limit (50 mSv) are given in Table 194 below for reference (it is not intended that these are used for screening purposes).

Table 194 Activity limit on a particle, for two intrusion times

Radionuclide	Particle activity limit (MBq) at 60 y	Limiting dose criterion$ at 60 y	Particle activity limit (MBq) at 300 y	Limiting dose criterion$ at 300 y
Pa-231	1.72 10^{-3}	Ingestion	1.57 10^{-3}	Ingestion
Ra-226	2.56 10^{-3}	Ingestion	2.84 10^{-3}	Ingestion
Th-232	2.90 10^{-3}	Ingestion	2.90 10^{-3}	Ingestion
Th-229	5.03 10^{-3}	Ingestion	5.15 10^{-3}	Ingestion
Sn-126	1.07 10^{-2}	Skin	8.44 10^{-3}	Ingestion
Pu-239	1.20 10^{-2}	Ingestion	1.07 10^{-2}	Skin
Pu-240	1.21 10^{-2}	Ingestion	1.21 10^{-2}	Ingestion
Th-230	1.25 10^{-2}	Ingestion	1.24 10^{-2}	Ingestion
Pu-242	1.25 10^{-2}	Ingestion	1.25 10^{-2}	Ingestion
U-238	1.31 10^{-2}	Skin	1.31 10^{-2}	Skin

$ Ingestion and whole body dose criterion of 3 mSv, for the skin it is 50 mSv

1427. The waste acceptance procedure is therefore described by the following steps:

- Use the particle assessment spreadsheet tool to assess the dose from the type of particle in the waste.
- Identify the package and consignment activity concentration limits relevant to the nuclides in the package.
- For ESC radionuclides where the ingestion dose is less than 3 mSv, the external dose to whole body is less than 3 mSv, the skin dose due to external exposure is less than 50 mSv, and the package and consignment meet their respective activity concentration limits, a consignment containing particles may be disposed of without consulting the Environment Agency.
- Where the ingestion dose is between 3 mSv and 20 mSv or the external dose to whole body is between 3 mSv and 20 mSv, then the Environment Agency should be consulted.
- Where the ingestion dose is above 20 mSv or the external dose to whole body is above 20 mSv or the skin dose due to external exposure is above 50 mSv the consignment would not be acceptable for disposal.
- For radionuclides not considered in the ESC or where alternative f1 values or low solubility are proposed then the Environment Agency should be consulted.

E.6.4. Exposure to particles following site erosion

1428. Exposure of members of the public to particles that have become accessible on the bank of the estuary as a result of erosion is compared to the risk guidance level. The relevant pathways are external exposure through a particle becoming trapped in a fingernail or toenail and inadvertent ingestion. The dose if encountered is the same as that calculated in Section E.6.3. The probability of encounter for a walker on the estuary bank is obtained from the number of particles per gram of eroded material on the estuary bank and the time spent on the estuary bank.

1429. There are two important pathways ingestion and skin exposure. The results in Table 194 indicate that some radionuclides are limited by ingestion, and some by skin exposure. This enables simple estimates of the risk arising from particles eroded onto the estuary bank to be made.

1430. The health risk from inadvertent ingestion of a particle that meets the acceptance criterion described in paragraph 1427 is given in Table 195. The total risk from particles on the bank is this risk multiplied by the probability of encounter. This probability depends on the number of particles present per kg of eroded material and the quantity ingested by the walker.

Table 195 Risk calculations for inadvertent ingestion following site erosion

Parameter	Value
Dose criterion for ingestion used to set acceptance criterion (mSv)	3
Health risk from ingestion of particle meeting dose criterion (y^{-1})	$1.8\ 10^{-4}$
Probability of encounter that would meet 1E-6 y^{-1}	$5.6\ 10^{-3}$
Quantity of material inadvertently ingested by walker (g) – 5 mg h^{-1} for 73 h	3.65
Number of particles per 1 kg of eroded material to meet risk guidance level	1.5
Number of particles per kg of disposed radioactive waste to meet risk guidance level (assuming landfill contains 5% radioactive waste)	30

1431. The risk guidance level of 10^{-6} y^{-1} is met if there are 1.5 or fewer particles that meet the acceptance criterion (i.e. give a dose of 3 mSv if ingested) per kg of eroded material. An expected average landfill content of 5% radioactive waste indicates that up to 30 particles per kg of radioactive waste will meet the risk criterion. Since particles are not expected to be in every consignment, this pathway is not likely to be limiting.

1432. The risk from skin exposure to a particle that meets the skin dose criterion is given in Table 196. The risk guidance level is met even if it is assumed that all the activity present on the estuary bank after erosion is radioactive waste that is in the form of particles that meet the skin dose criterion. Hence this pathway is not limiting.

1433. Hence waste acceptance criteria that restrict the activity per particle on the basis of the dose if encountered will ensure that the public is protected if the site erodes and waste becomes exposed on the estuary bank.

Table 196 Risk calculations for skin exposure following site erosion

Parameter	Value
Dose criterion for skin (equivalent dose) used to set acceptance criterion (mSv)	50
Health risk from skin exposure to 1mm particle meeting dose criterion (y^{-1})	$3\ 10^{-8}$
Quantity of material under fingernail (g h^{-1})	0.12
Quantity of material under fingernail for walker (g)	0.9
Frequency of encounter that meets dose criterion	33
No per gram eroded material to meet risk criterion	3.8
No per kg eroded material to meet risk	$3.8\ 10^{3}$
No per kg in package if 5% eroded material is LLW	$7.6\ 10^{4}$
No of particles per kg package meeting 5000 Bq g^{-1}	500
No of particles per kg package if ingestion is limiting	30

E.6.5. Radionuclide activity concentrations

1434. The assessments undertaken to support the ESC for Port Clarence are used to calculate activity concentration limits for disposed waste. Our approach uses an intrusion scenario, the dropped bag scenario, and worker doses after emplacement to derive an activity concentration per consignment for each radionuclide. To simplify operational control these calculated activities are then grouped and the values used are 10, 20, 50, 100, 200, 1000, 2000 and 5000 Bq g^{-1}. The lowest activity concentration adopted is 10 Bq g^{-1} and the only radionuclides assigned to this group are Ra-226, Th-232 and Pa-231. . These activity concentrations are for each radionuclide and the overall activity concentration for the consignment will be obtained using the sum of fractions approach. An overall consignment limit of 2000 Bq g^{-1} is then applied as a separate limit.

1435. The ESC for the ENRMF (Eden NE, 2023) used an activity concentration averaged over a consignment of 200 Bq g^{-1} for all waste and the Trial pit excavator scenario was used to show that averaging over 10 t of waste allowed an upper limit of 1000 Bq g^{-1} in 10% of the waste consignment. For Port Clarence the following scenarios were used to determine appropriate activity concentrations in waste (per consignment and per package) that could be disposed at Port Clarence and not exceed the relevant dose criterion:

- Material recovery user (the Borehole Drill operative did not limit concentrations)
- Waste emplacement - worker
- Dropped load (bag) - worker
- Dose to beach user - dog walker
- Trial pit excavator

1436. The waste handling worker scenario has not been used to limit activity concentrations in LLW. Doses to workers will be controlled through site operating procedures and the CfA requirement that waste packages shall not be exceed a maximum activity measured at 1 m from each package face of 10 μSv h^{-1}.

1437. Radionuclides are assigned to activity concentration groupings as follows:

- Beta/gamma emitting radionuclides assigned a maximum value per consignment of 5,000 Bq g^{-1} – calculated activity concentrations greater than or equal to 5,000 Bq g^{-1} are included in the group (28 radionuclides);
- radionuclides assigned a maximum value per consignment of 2000 Bq g^{-1} – calculated concentrations less than 2000 Bq g^{-1} and greater than or equal to 1000 Bq g^{-1} (5 radionuclides);
- radionuclides assigned a maximum value per consignment of 1000 Bq g^{-1} – calculated concentrations less than 1000 Bq g^{-1} and greater than or equal to 200 Bq g^{-1} (no radionuclides assigned to this group);
- radionuclides assigned a maximum value per consignment of 200 Bq g^{-1} – calculated concentrations less than 200 Bq g^{-1} and greater than or equal to 100 Bq g^{-1} (23 radionuclides);

- radionuclides assigned a maximum value per consignment of 100 Bq g^{-1} – calculated concentrations less than 100 Bq g^{-1} and greater than or equal to 50 Bq g^{-1} (6 radionuclides);
- radionuclides assigned a maximum value per consignment of 50 Bq g^{-1} – calculated concentrations less than 50 Bq g^{-1} and greater than or equal to 20 Bq g^{-1} (1 radionuclide); and,
- radionuclides assigned a maximum value per consignment of 10 Bq g^{-1} – calculated concentrations less than 20 Bq g^{-1} (3 radionuclides).

1438. The calculated concentrations are presented in Table 197 and the groupings are summarised in Table 198. The value for the alpha emitter Cm-242 was lowered 200 Bq g^{-1}.

Table 197 Calculated concentrations for disposal of packaged waste (Bq g^{-1})

Radionuclide	Material recovery user (60y)	Worker emplacement (0.4m cover)	Dropped load (Bag) worker	Erosion (60y)	Trial pit	Paris Convention	Limiting concentrati on
H-3	$2.04\ 10^{9}$	0	$1.64\ 10^{8}$	$6.59\ 10^{7}$	$6.41\ 10^{9}$	10000	5000
C-14	$1.67\ 10^{5}$	0	$7.36\ 10^{6}$	$6.85\ 10^{4}$	$7.70\ 10^{5}$	10000	5000
Cl-36	$1.28\ 10^{4}$	0	$5.84\ 10^{6}$	$1.73\ 10^{4}$	$6.11\ 10^{4}$		5000
Ca-41	$3.54\ 10^{7}$	0	$2.37\ 10^{8}$	$2.11\ 10^{5}$	$5.87\ 10^{7}$		5000
Mn-54	$2.84\ 10^{23}$	$1.19\ 10^{4}$	$2.84\ 10^{7}$	$4.13\ 10^{25}$	$1.36\ 10^{24}$		5000
Fe-55	$6.24\ 10^{13}$	0	$5.54\ 10^{7}$	$1.81\ 10^{11}$	$1.17\ 10^{14}$		5000
Co-60	$1.76\ 10^{5}$	$2.03\ 10^{3}$	$1.38\ 10^{6}$	$1.02\ 10^{7}$	$8.43\ 10^{5}$	200	200
Ni-59	$8.42\ 10^{6}$	0	$9.70\ 10^{7}$	$3.21\ 10^{5}$	$3.23\ 10^{7}$		5000
Ni-63	$1.89\ 10^{6}$	0	$3.28\ 10^{7}$	$1.97\ 10^{5}$	$8.48\ 10^{6}$		5000
Zn-65	$3.23\ 10^{29}$	$1.11\ 10^{4}$	$1.94\ 10^{7}$	$7.43\ 10^{30}$	$1.54\ 10^{30}$		5000
Se-79	$1.43\ 10^{5}$	0	$6.27\ 10^{6}$	$3.91\ 10^{3}$	$6.07\ 10^{5}$		2000
Sr-90	$8.99\ 10^{3}$	0	$2.64\ 10^{5}$	$4.98\ 10^{3}$	$4.21\ 10^{4}$	200	200
Mo-93	$1.32\ 10^{6}$	$1.86\ 10^{9}$	$1.86\ 10^{7}$	$1.60\ 10^{4}$	$2.96\ 10^{6}$		5000
Zr-93	$6.20\ 10^{5}$	$1.24\ 10^{10}$	$1.71\ 10^{6}$	$1.43\ 10^{5}$	$2.20\ 10^{6}$		5000
Nb-93m	$1.17\ 10^{8}$	$1.23\ 10^{10}$	$2.37\ 10^{7}$	$1.58\ 10^{6}$	$3.86\ 10^{8}$		5000
Nb-94	$1.13\ 10^{2}$	$7.04\ 10^{3}$	$8.71\ 10^{5}$	$1.03\ 10^{4}$	$5.41\ 10^{2}$		100
Tc-99	$5.26\ 10^{4}$	$8.72\ 10^{14}$	$3.28\ 10^{6}$	$2.27\ 10^{4}$	$2.47\ 10^{5}$	200	200
Ru-106	$2.44\ 10^{20}$	$1.24\ 10^{5}$	$6.46\ 10^{5}$	$1.00\ 10^{21}$	$1.16\ 10^{21}$		5000
Ag-108m	$1.26\ 10^{2}$	$1.11\ 10^{4}$	$1.15\ 10^{6}$	$1.01\ 10^{4}$	$6.03\ 10^{2}$		100
Ag-110m	$1.60\ 10^{28}$	$3.16\ 10^{3}$	$3.56\ 10^{6}$	$1.78\ 10^{30}$	$7.65\ 10^{28}$		2000
Cd-109	$1.63\ 10^{19}$	$3.94\ 10^{11}$	$5.27\ 10^{6}$	$2.30\ 10^{18}$	$7.37\ 10^{19}$		5000
Sb-125	$1.56\ 10^{9}$	$5.31\ 10^{4}$	$3.29\ 10^{6}$	$4.95\ 10^{10}$	$7.44\ 10^{9}$		5000
Sn-119m	$1.43\ 10^{28}$	$2.39\ 10^{65}$	$1.94\ 10^{7}$	$1.41\ 10^{27}$	$6.44\ 10^{28}$		5000
Sn-123	$5.00\ 10^{54}$	$2.16\ 10^{5}$	$5.27\ 10^{6}$	$7.85\ 10^{54}$	$2.39\ 10^{55}$		5000
Sn-126	$9.07\ 10^{1}$	$7.80\ 10^{3}$	$1.50\ 10^{6}$	$3.28\ 10^{3}$	$4.34\ 10^{2}$		50
Te-127m	$2.57\ 10^{67}$	$2.00\ 10^{9}$	$4.35\ 10^{6}$	$9.15\ 10^{65}$	$1.09\ 10^{68}$		5000
I-129	$3.41\ 10^{4}$	$5.72\ 10^{27}$	$1.19\ 10^{6}$	$4.98\ 10^{2}$	$8.03\ 10^{4}$		200
Ba-133	$2.95\ 10^{4}$	$1.94\ 10^{5}$	$4.27\ 10^{6}$	$8.91\ 10^{5}$	$1.41\ 10^{5}$		5000
Cs-134	$6.39\ 10^{10}$	$8.47\ 10^{3}$	$2.13\ 10^{6}$	$3.61\ 10^{12}$	$3.06\ 10^{11}$		5000

Radionuclide	Material recovery user (60y)	Worker emplacement (0.4m cover)	Dropped load (Bag) worker	Erosion (60y)	Trial pit	Paris Convention	Limiting concentration
Cs-135	6.27 10^{4}	0	4.96 10^{6}	4.73 10^{4}	2.88 10^{5}		5000
Cs-137	1.26 10^{3}	2.47 10^{4}	1.09 10^{6}	3.51 10^{4}	6.01 10^{3}	200	200
Ce-144	1.79 10^{27}	6.86 10^{7}	8.05 10^{5}	3.99 10^{26}	8.32 10^{27}		5000
Pm-147	8.50 10^{11}	6.27 10^{13}	8.53 10^{6}	4.40 10^{11}	4.00 10^{12}		5000
Sm-147	4.55 10^{3}	0	4.44 10^{3}	7.11 10^{2}	1.45 10^{4}		200
Sm-151	1.42 10^{6}	3.94 10^{90}	1.07 10^{7}	2.69 10^{5}	6.40 10^{6}		5000
Eu-152	3.25 10^{3}	7.17 10^{3}	1.02 10^{6}	2.91 10^{5}	1.56 10^{4}		2000
Eu-154	1.75 10^{4}	6.16 10^{3}	8.05 10^{5}	1.08 10^{6}	8.38 10^{4}		5000
Eu-155	3.57 10^{7}	1.26 10^{9}	6.18 10^{6}	3.05 10^{8}	1.71 10^{8}		5000
Gd-153	1.28 10^{31}	2.13 10^{9}	2.03 10^{7}	1.65 10^{32}	6.10 10^{31}		5000
Pb-210	1.10 10^{4}	4.88 10^{5}	4.27 10^{3}	5.74 10^{1}	2.58 10^{4}		50
Po-210	1.88 10^{51}	1.14 10^{9}	9.92 10^{3}	5.80 10^{48}	3.62 10^{51}		2000
Ra-226	3.61 10^{1}	1.01 10^{3}	2.19 10^{3}	8.38 10^{0}	1.68 10^{2}		10
Ra-228	8.76 10^{4}	1.06 10^{3}	7.15 10^{2}	2.19 10^{4}	3.98 10^{5}		200
Ac-227	4.53 10^{2}	4.24 10^{4}	7.50 10^{1}	1.40 10^{2}	1.54 10^{3}		50
Th-228	2.72 10^{11}	1.63 10^{3}	9.78 10^{2}	2.57 10^{11}	1.24 10^{12}		200
Th-229	1.36 10^{2}	2.30 10^{4}	1.67 10^{2}	4.05 10^{1}	4.74 10^{2}		20
Th-230	4.44 10^{2}	2.63 10^{10}	4.27 10^{2}	1.25 10^{2}	1.18 10^{3}		100
Th-232	5.47 10^{1}	1.06 10^{3}	2.52 10^{2}	1.46 10^{1}	2.36 10^{2}		10
Pa-231	2.98 10^{2}	3.29 10^{6}	3.05 10^{2}	1.84 10^{1}	2.10 10^{2}		10
U-232	7.31 10^{1}	1.86 10^{3}	5.29 10^{2}	9.65 10^{1}	3.37 10^{2}		50
U-233	4.52 10^{3}	1.79 10^{8}	4.44 10^{3}	6.30 10^{2}	1.23 10^{4}		200
U-234	4.63 10^{3}	1.18 10^{12}	4.54 10^{3}	7.40 10^{2}	1.47 10^{4}		200
U-235	1.07 10^{3}	3.55 10^{6}	5.02 10^{3}	7.28 10^{2}	4.60 10^{3}		200
U-236	5.00 10^{3}	5.73 10^{11}	4.90 10^{3}	7.47 10^{2}	1.60 10^{4}		200
U-238	1.50 10^{3}	1.19 10^{5}	5.33 10^{3}	6.83 10^{2}	6.29 10^{3}	200	200
Np-237	4.55 10^{2}	5.69 10^{5}	8.53 10^{2}	4.01 10^{2}	1.75 10^{3}		200
Pu-238	6.48 10^{2}	2.55 10^{13}	3.88 10^{2}	3.41 10^{2}	2.11 10^{3}		200
Pu-239	3.70 10^{2}	8.87 10^{9}	3.56 10^{2}	2.02 10^{2}	1.21 10^{3}	100	100
Pu-240	3.72 10^{2}	4.24 10^{14}	3.56 10^{2}	2.03 10^{2}	1.21 10^{3}		200
Pu-241	3.50 10^{5}	4.01 10^{10}	1.86 10^{4}	7.56 10^{3}	4.85 10^{4}		5000
Pu-242	4.03 10^{2}	4.16 10^{16}	3.88 10^{2}	2.12 10^{2}	1.31 10^{3}		200

Radionuclide	Material recovery user (60y)	Worker emplacement (0.4m cover)	Dropped load (Bag) worker	Erosion (60y)	Trial pit	Paris Convention	Limiting concentrati on
Pu-244	$2.15\ 10^{2}$	$5.11\ 10^{4}$	$3.88\ 10^{2}$	$2.03\ 10^{2}$	$8.17\ 10^{2}$		200
Am-241	$5.00\ 10^{2}$	$1.80\ 10^{13}$	$4.44\ 10^{2}$	$2.51\ 10^{2}$	$1.64\ 10^{3}$	100	100
Am-242m	$4.95\ 10^{2}$	$8.40\ 10^{5}$	$3.68\ 10^{2}$	$1.89\ 10^{2}$	$1.17\ 10^{3}$		100
Am-243	$3.31\ 10^{2}$	$3.20\ 10^{6}$	$4.44\ 10^{2}$	$2.29\ 10^{2}$	$1.18\ 10^{3}$		200
Cm-242	$2.52\ 10^{44}$	$2.52\ 10^{12}$	$7.23\ 10^{3}$	$6.67\ 10^{4}$	$4.13\ 10^{5}$		200
Cm-243	$2.00\ 10^{3}$	$4.91\ 10^{6}$	$6.16\ 10^{2}$	$1.07\ 10^{3}$	$7.03\ 10^{3}$		200
Cm-244	$7.75\ 10^{3}$	$1.61\ 10^{68}$	$7.49\ 10^{2}$	$2.84\ 10^{3}$	$2.40\ 10^{4}$		200
Cm-245	$3.88\ 10^{2}$	$7.92\ 10^{7}$	$4.31\ 10^{2}$	$2.26\ 10^{2}$	$1.30\ 10^{3}$		200
Cm-246	$4.52\ 10^{2}$	$7.83\ 10^{29}$	$4.35\ 10^{2}$	$2.30\ 10^{2}$	$1.48\ 10^{3}$		200
Cm-248	$6.07\ 10^{1}$	$6.75\ 10^{63}$	$1.19\ 10^{2}$	$6.09\ 10^{1}$	$2.36\ 10^{2}$		50

Table 198 Activity concentrations used to limit disposal of LLW at Port Clarence

Assigned activity concentration (Bq g^{-1})	Radionuclides
10	Ra-226, Th-232, Pa-231
20	Th-229
50	Sn-126, Pb-210, Ac-227, U-232, Cm-248
100	Nb-94, Ag-108m, Th-230, Pu-239*, Am-241*, Am-242m
200	Co-60*, Sr-90*, Tc-99*, I-129, Cs-137*, Sm-147, Ra-228, Th-228, U-233, U-234, U-235, U-236, U-238*, Np-237, Pu-238, Pu-240, Pu-242, Pu-244, Am-243, Cm-242, Cm-243, Cm-244, Cm-245, Cm-246
1,000	none assigned
2,000	Se-79, Ag-110m, Eu-152, Po-210
5,000	H-3*, C-14*, Cl-36, Ca-41, Mn-54, Fe-55, Ni-59, Ni-63, Zn-65, Mo-93, Zr-93, Nb-93m, Ru-106, Cd-109, Sb-125, Sn-119m, Sn-123, Te-127m, Ba-133, Cs-134, Cs-135, Ce-144, Pm-147, Sm-151, Eu-154, Eu-155, Gd-153, Pu-241

Note: * radionuclides listed in the Paris Convention LLW exclusion. The assigned values are equal to the values listed in the LLW exclusion.

1439. The heterogeneity of waste within a consignment is also considered. The analysis performed for the ENRMF (Eden NE, 2023) demonstrated that a ratio of 5 for the activity concentration in a package compared to the average in the consignment would also meet the dose criterion. Hence, ENRMF applied an average of 200 Bq g^{-1} in a consignment with a maximum of 1000 Bq g^{-1} in a package comprising part of a larger consignment, for all radionuclides.

1440. A ratio of 5 for the activity in a package compared to the average in the consignment will be applied at Port Clarence for radionuclides with an assigned activity concentration between 10 Bq g^{-1} and 200 Bq g^{-1}. Smaller ratios will be used for radionuclides with higher activity concentrations. A ratio of 1.5 will be applied to wastes with an average concentration of 2000 Bq g^{-1} per consignment and a ratio of 1 to wastes with an average concentration of 5,000 Bq g^{-1} per consignment. Using these ratios, the highest exposure is from Pu-244 that produces a dose of 1.1 mSv (Trial pit scenario). Hence, every package will comply with the definition of LLW and meet the dose criteria. This gives the activity concentration levels presented in Table 199.

1441. An overall consignment activity concentration limit of 2000 Bq g^{-1} will be applied to the radionuclide fingerprint. This additional limit will only be important for wastes containing large proportions of (or only) Group 7 radionuclides. All other wastes will meet this limit anyway due to application of the sum of fractions approach.

Table 199 Radionuclide specific maximum average activity in consignment and in a package for radionuclides

Group	Radionuclide specific maximum activity concentration averaged over a consignment (Bq g^{-1})	Radionuclide specific maximum activity concentration in a package that is part of a consignment (Bq g^{-1})
1	10	50
2	20	100
3	50	250
4	100	500
5	200	1,000
6	2,000	3,000
7	5,000	5,000

1442. Activity concentration limits have also been calculated for loose tipping of waste (see Table 74) and these are used to group radionuclides by assigning values of 5, 10, 50 and 100 Bq g^{-1} for loose tipped waste (Table 200). The scenarios included in this analysis were the Dropped load (tipper) for both worker and public exposure, and the Loose tipping assessment for workers (always more cautious than the public assessment)

1443. The radionuclides assigned activity concentrations between 5 and 50 Bq g^{-1} are all limited by workers present during the tipping operation. The calculated concentrations are less than 5 Bq g^{-1} for Ac-227 (1.5 Bq g^{-1}), Th-229 (3.3 Bq g^{-1}), Th-232 (4.96 Bq g^{-1}) and Cm-248 (2.3 Bq g^{-1}). However, the assessment of loose tipping is very cautious and does not consider the benefit of the Port Clarence operating procedures for loose tipping that will ensure that exposure is minimised. We also note that adopting the lower band of 5 Bq g^{-1} for these radionuclides results in a maximum dose to the public of 0.5 µSv. On this basis, placing these radionuclides in the 5 Bq g^{-1} band is considered appropriate.

Table 200 Activity concentrations used to limit tipping of loose LLW at Port Clarence

Assigned activity concentration (Bq g^{-1})	Radionuclides
5	Ac-227, Th-229, Th-230, Th-232, Pa-231, Pu-238, Pu-239, Pu-240, Pu-242, Pu-244, Am-241, Am-242m, Am-243, Cm-245, Cm-246, Cm-248
10	Ra-226, Ra-228, Th-228, U-232, Np-237, Cm-243, Cm-244
50	Sn-126, Sm-147, Pb-210, U-233, U-234, U-235, U-236
100	H-3, C-14, Cl-36, Ca-41, Mn-54, Fe-55, Co-60, Ni-59, Ni-63, Zn-65, Se-79, Sr-90, Mo-93, Zr-93, Nb-93m, Nb-94, Tc-99, Ru-106, Ag-108m, Ag-110m, Cd-109, Sb-125, Sn-119m, Sn-123, Te-127m, I-129, Ba-133, Cs-134, Cs-135, Cs-137,

Assigned activity concentration (Bq g^{-1})	Radionuclides
	Ce-144, Pm-147, Sm-151, Eu-152, Eu-154, Eu-155, Gd-153, Po-210, U-238, Pu-241, Cm-242

E.7. Environmental radioactivity {R9}

E.7.1. Exposure to wildlife from all sources

1444. A radiological assessment of the potential effects on non-human biota (NHB) from the disposal of LLW at Port Clarence has been undertaken using the ERICA (Environmental Risk from Ionising Contaminants: Assessment and Management) Assessment Tool. The ERICA tool is a software system that has a structure based upon the tiered ERICA Integrated Approach to assessing the radiological risk to terrestrial, freshwater and marine biota.

1445. ERICA was developed under an EC funded international programme. Further details are available at: http://www.erica-tool.com/. The ERICA assessment tool is updated periodically. The most recent update, v2.0, was uploaded on 18 November 2021, and that is the version of the tool used in this assessment.

1446. ICRP Reference Animals and Plants (RAPs) have been adopted (ICRP, 2008).

1447. The ERICA assessment tool allows consideration of three ecosystems: terrestrial, freshwater and marine. All three ecosystems are applicable to the environment surrounding Port Clarence. It is assumed that the estuary close to the site can be treated as a marine environment. Within these ecosystems, the ERICA tool considers a range of organisms and wildlife groups as shown in Table 201.

1448. During the operational and active management phases, radioactivity could be released to the biosphere as gas (e.g. very low gas production rates may result in C-14 labelled carbon dioxide or tritiated hydrogen gas), or in discharges from leachate treatment facilities. After the period of authorisation, the majority of releases of radioactivity are likely to be associated with groundwater or as a result of intrusion into the waste.

1449. Input data for the non-human biota dose assessment are radioactivity concentrations in soil and air (terrestrial ecosystem assessment) and water or sediment (freshwater and marine ecosystem assessment). The activity concentrations of radionuclides in soil and water are calculated using the same approaches underlying the dose calculations to the public.

1450. The impact on terrestrial animals that dig into the waste is also considered, based on activity concentrations in the waste.

Table 201 Wildlife groups considered in the ERICA tool

Terrestrial	Freshwater	Marine
Amphibian	Amphibian	Benthic Fish
Annelid	Benthic fish	Bird
Anthropod - detritivorous	Bird	Crustacean
Bird	Crustacean	Macroalgae
Flying insects	Insect larvae	Mammal
Grasses and herbs	Mammal	Mollusc – bivalve
Lichen and bryophytes	Mollusc – bivalve	Pelagic fish
Mammal large	Mollusc – gastropod	Phytoplankton
Mammal small – burrowing	Pelagic fish	Polychaete worm
Mollusc - gastropod	Phytoplankton	Reptile
Reptile	Reptile	Sea anemones and true coral
Shrub	Vascular plant	Vascular plant
Tree	Zooplankton	Zooplankton

E.7.2. The ERICA assessment tool

1451. The Tool guides the user through the assessment process, recording information and decisions and allowing the necessary calculations to be performed to estimate risks to selected animals and plants. The tiered approach offers increasing opportunities to introduce site specific factors. For the NHB assessments we have used ERICA Version 2.0, updated 18.11.2021. The updated ERICA tool includes:

- a new approach for the calculation of the dose contribution from short-lived progeny in a decay chain;
- the ability to assess dose rates from noble gases, radon and thoron;
- new dosimetry (implementing ICRP Publication 136);
- revised concentration ratios (CRs), updated for consistency with the Wildlife Transfer Database (WTD);
- updated distribution coefficients (Kds) for freshwater to be consistent with IAEA MODARIA working group (Boyer, et al., 2018);
- updated Environmental Media Concentration Levels (EMCLs) to take account of changes to parameter values.

1452. Tier 1 assessments are based on media concentration and use pre-calculated environmental media concentration limits (EMCLs) to estimate risk quotients. Tier 2 calculates dose rates but allows the user to examine and edit most of the parameters used in the calculation including concentration ratios, distribution coefficients, percentage dry weight soil or sediment, dose conversion coefficients, radiation weighting factors and occupancy factors. The user can also input biota whole-body activity concentrations in Tier 2 if available rather than rely upon concentration ratios. Tier 3 offers the same flexibility as Tier 2 but allows the option to run the assessment probabilistically if the underling parameter probability distribution functions are defined.

1453. ERICA assessments have been performed for the following scenarios after the period of authorisation: gaseous release of H-3 and C-14; groundwater migration leading to exposure of the marine ecosystem in the estuary; erosion scenario leading to exposure of terrestrial and marine ecosystems; leachate breakout leading to exposure of the freshwater ecosystem; and the dose to burrowing animals on the landfill site.

1454. It should be noted that the philosophy behind a landfill site is to concentrate and contain the waste to protect the environment. The environment inside the landfill is not part of the environment that is to be protected.

1455. Within the terrestrial, marine and freshwater ecosystems, the ERICA Tool considers a range of wildlife groups considered to be representative (see Table 201). The organisms are intended to be interpreted in a generic fashion rather than as individual species, although the categorisation strays across several taxonomic levels or groupings. Life cycle stages are not addressed specifically and the nomenclature adopted indicates that organism types have been identified based on a number of considerations such as food source (detritivorous invertebrates), habitat (flying insects), size (rat and deer, both representing mammals) etc. Specifically, the organism types do not represent individual species. Thus the ‘rat’ and ‘deer’ represent small and large mammals respectively and should not be identified as Roe deer or Red deer (Britain’s two native deer species) or Brown rat (the most common, if not strictly native, rat in the UK).

1456. Similar, but not identical, ICRP Reference Animals and Plants (RAPs) have been adopted (ICRP, 2008) A RAP is defined by ICRP as:

> ‘a hypothetical entity, with the assumed basic biological characteristics of a particular type of animal or plant, as described to the generality of the taxonomic level of family, with defined anatomical, physiological, and life-history properties, that can be used for the purposes of relating exposure to dose, and dose to effects, for that type of living organism’.

1457. It is considered that the range of organism types represented within the ERICA assessment tool is sufficiently broad to characterise the reference ecosystems.

1458. In the Tier 1 assessment, the ERICA tool compares environmental concentrations for individual radionuclides with ‘limiting concentrations’ calculated using generic assumptions about the ecosystem and based on the application of a single dose screening value. These limiting values are based on a screening dose rate of 10 µGy h-1. Hence, if the risk quotient is <1 then this screening level is met.

E.7.3. Screening levels

1459. Different approaches are available to derive numerical benchmark values for protection of NHB. A detailed explanation and proposed framework has been proposed by Jackson and co-workers [(Jackson, et al., 2014), (Smith, et al., 2010) and (Robinson, et al., 2010)]. A number of national and international studies have identified screening criteria, although consistency between countries has not been achieved (Copplestone, et al., 2010). For the present purposes, two screening values for protection of NHB have gained relatively widespread application.

1460. The EC ERICA and PROTECT derived screening value of 10 µGy h^{-1} above background is generally recognised in the UK and Europe. Although concerns may be raised as to whether this value is below natural variability in background exposures, for example (Brown, et al., 2004) indicated that wildlife might receive up to 60 µGy h^{-1} from natural sources in European ecosystems, it does have a demonstrable provenance, being based on the effects database (FREDERICA) developed within the

EC FASSET and ERICA programmes (Copplestone, et al., 2008). It also has a clear definition, representing the dose rate at which 95% of species will not experience more than a 10% change in the observed effect, relative to a control group (this is termed HDR_5).

1461. The FREDERICA database is available online from www.frederica-online.org. The FREDERICA database contains over 1500 references and contains 29,400 data entries. Summary information is available on the effects of ionising radiation on different wildlife groups under seven umbrella endpoints: mutation, morbidity, reproductive capacity, mortality, stimulation, adaptation and ecological fitness. The database can be updated online.

1462. Some organisms, e.g. mammals, are more radiosensitive than others. The EU PROTECT (European Commission, 2008) project, which compares different available screening values, proposes first screening values of 2 µGy h^{-1} for vertebrates, 200 µGy h^{-1} for invertebrates and 70 µGy h^{-1} for plants. In America and Canada, an alternative approach is typically adopted, following the review of available effects data by (UNSCEAR, 2011) [including reference to previous studies by both (IAEA, 1992) and (UNSCEAR, 1996)], who concluded that, "*chronic dose rates of less than 0.1 mGy/h to the most exposed individuals would be unlikely to have significant effects on most terrestrial communities and chronic dose rates of less than 0.4 mGy/h to any individual in aquatic populations would be unlikely to have any detrimental effect at the population level*". This is also consistent with an evaluation of the FREDERICA database for plants, fish and mammals by (Real, et al., 2004), who noted that: "*the reviewed effects data give few indications for readily observable effects at chronic dose rates below 100 µGy/h*". Indeed below 1000 µGy h^{-1} there appears to be little evidence for irreversible impairment, although the general paucity of the database led (Real, et al., 2004) to give a cautionary note when seeking to establish environmentally 'safe levels' of radiation exposure.

1463. The Environment Agency for England and Wales currently recognise a 40 µGy h^{-1} "regulatory action level" such that, if the dose rates predicted to wildlife inhabiting a particular conservation site exceed 40 µGy h^{-1} then the regulators need to consider possible action, although again, this is not a 'limit' and following consideration no action may be required (Environment Agency, 2009). This action level considers all permitted discharges that might affect the conservation sites. It is unlikely that other sites have permitted radioactive discharges that could affect the environment local to Port Clarence.

1464. The current EA 'regulatory action level' was defined on the basis of the FASSET biological effects work that concluded that no adverse effects would be expected on populations at dose rates below 100 µGy h^{-1}, as noted in the preceding text. This was used in combination with a generic background dose rate for European ecosystems of 50 µGy h^{-1} and a safety margin of 10 µGy h^{-1} to account for the background dose rate not being specific to the UK. Below this dose rate, the Environment Agency currently considers that adverse impact is unlikely.

E.7.4. ERICA assessment for a Marine Ecosystem

1465. An assessment of a marine ecosystem was considered to be representative of the estuary close to the Port Clarence site.

1466. The limiting environmental concentrations determined from the ERICA assessment tool are determined for each radionuclide based on a screening dose rate of 10 µGy h^{-1}. This is considered to represent a conservative approach.

1467. Where radionuclides were not available for T2 ERICA assessments (Am-242m), ICRP Biota DC v 1.5.2 was used to obtain dose conversion factors using the time-integral activities ratio methodology and geometries from the ERICA software.

1468. Peak activity concentrations (per MBq disposed) of Tier 2 radionuclides and their Tier 2 daughters in seawater and sediment were taken from the output of the DORIS assessment for the groundwater release to estuary scenario, as discussed in Section E.4.5. The sea water and seabed sediment concentrations for each radionuclide were then scaled to account for the minimum radiological capacity of each radionuclide. Activity concentrations for radionuclides that were ingrown through radioactive decay were calculated separately. The ERICA assessment tool was then used to calculate a risk quotient for each radionuclide, which is defined as the radionuclide specific activity concentration in a medium divided by the limiting activity concentration for that radionuclide and medium. If the risk quotient is higher than one, the dose rate to the most limiting organism exceeds the ERICA screening dose rate of 10 µGy h^{-1}. If the risk quotient is higher than 4, the dose rate to the most limiting organism exceeds the EA guidance dose rate of 40 µGy h^{-1}.

1469. Table 202 below summarises the results of the wildlife assessment for the estuary (marine) ecosystem for the groundwater release to estuary scenario. All risk quotients are well below 1, therefore all non-human biota in the estuary are considered to be sufficiently protected for the groundwater release to estuary scenario.

Table 202 Radionuclide specific risk quotients for the estuarine ecosystem for the groundwater release to estuary scenario, based on a generic screening level of 10 µGy h^{-1}

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Limiting organism	Reduction factor to reduce dose rate to below 40 µGy h^{-1}
H-3	$1.88\ 10^{8}$	$2.79\ 10^{-8}$	Vascular plant	
C-14	$1.19\ 10^{8}$	$7.43\ 10^{-4}$	Mammal	
Cl-36	$5.08\ 10^{5}$	$2.06\ 10^{-8}$	Vascular plant	
Ca-41	$1.05\ 10^{9}$	$1.55\ 10^{-4}$	Crustacean	
Mn-54	$3.10\ 10^{11}$	$8.12\ 10^{-12}$	Crustacean	
Fe-55	$1.96\ 10^{13}$	$2.09\ 10^{-9}$	Polychaete worm	
Co-60	$2.09\ 10^{10}$	$4.98\ 10^{-7}$	Benthic fish	
Ni-59	$3.44\ 10^{10}$	$2.97\ 10^{-3}$	Polychaete worm	
Ni-63	$3.86\ 10^{9}$	$4.15\ 10^{-5}$	Polychaete worm	
Zn-65	$2.48\ 10^{11}$	$4.92\ 10^{-12}$	Mammal	
Se-79	$8.58\ 10^{8}$	$9.64\ 10^{-4}$	Mammal	
Sr-90	$9.61\ 10^{8}$	$1.18\ 10^{-4}$	Vascular plant	
Mo-93	$5.95\ 10^{7}$	$1.44\ 10^{-4}$	Vascular plant	
Zr-93	$3.27\ 10^{9}$	$5.87\ 10^{-4}$	Zooplankton	

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Limiting organism	Reduction factor to reduce dose rate to below 40 µGy h^{-1}
Nb-93m	$2.08\ 10^{10}$	$2.52\ 10^{-5}$	Vascular plant	
Nb-94	$7.83\ 10^{7}$	$9.28\ 10^{-5}$	Vascular plant	
Tc-99	$1.73\ 10^{7}$	$6.48\ 10^{-3}$	Vascular plant	
Ru-106	$1.59\ 10^{11}$	$9.07\ 10^{-12}$	Zooplankton	
Ag-108m	$2.89\ 10^{8}$	$1.22\ 10^{-3}$	Mammal	
Ag-110m	$3.48\ 10^{10}$	$1.01\ 10^{-11}$	Mammal	
Cd-109	$1.39\ 10^{12}$	$3.55\ 10^{-10}$	Mollusc - bivalve	
Sb-125	$2.04\ 10^{10}$	$3.13\ 10^{-11}$	Zooplankton	
Sn-119m	$1.05\ 10^{13}$	$5.74\ 10^{-10}$	Phytoplankton	
Sn-123	$3.71\ 10^{12}$	$2.85\ 10^{-10}$	Phytoplankton	
Sn-126	$1.37\ 10^{8}$	$3.35\ 10^{-3}$	Phytoplankton	
Te-127m	$2.80\ 10^{12}$	$5.64\ 10^{-11}$	Phytoplankton	
I-129	$9.36\ 10^{7}$	$9.58\ 10^{-4}$	Macroalgae	
Ba-133	$2.12\ 10^{8}$	$2.69\ 10^{-5}$	Polychaete worm	
Cs-134	$8.46\ 10^{10}$	$7.89\ 10^{-14}$	Reptile	
Cs-135	$1.43\ 10^{9}$	$2.42\ 10^{-5}$	Reptile	
Cs-137	$1.08\ 10^{9}$	$2.72\ 10^{-6}$	Reptile	
Ce-144	$8.89\ 10^{12}$	$5.41\ 10^{-11}$	Crustacean	
Pm-147	$3.05\ 10^{13}$	$4.60\ 10^{-8}$	Crustacean	
Sm-147	$3.83\ 10^{7}$	$1.18\ 10^{-2}$	Crustacean	
Sm-151	$5.90\ 10^{10}$	$1.58\ 10^{-3}$	Crustacean	
Eu-152	$6.69\ 10^{9}$	$2.26\ 10^{-4}$	Crustacean	
Eu-154	$2.08\ 10^{10}$	$1.36\ 10^{-4}$	Crustacean	
Eu-155	$9.23\ 10^{11}$	$1.41\ 10^{-5}$	Crustacean	
Gd-153	$3.38\ 10^{12}$	$6.90\ 10^{-11}$	Crustacean	
Pb-210	$7.84\ 10^{6}$	$5.21\ 10^{-3}$	Polychaete worm	
Po-210	$8.57\ 10^{9}$	$2.72\ 10^{-9}$	Polychaete worm	
Ra-226	$1.39\ 10^{6}$	$3.92\ 10^{-2}$	Polychaete worm	
Ra-228	$4.80\ 10^{9}$	$2.26\ 10^{-3}$	Phytoplankton	
Ac-227	$3.06\ 10^{7}$	$6.40\ 10^{-3}$	Phytoplankton	
Th-228	$8.11\ 10^{10}$	$2.78\ 10^{-9}$	Phytoplankton	
Th-229	$4.27\ 10^{6}$	$4.96\ 10^{-2}$	Phytoplankton	
Th-230	$2.03\ 10^{6}$	$8.13\ 10^{-2}$	Polychaete worm	
Th-232	$2.16\ 10^{6}$	$3.33\ 10^{-2}$	Phytoplankton	
Pa-231	$7.73\ 10^{5}$	$1.26\ 10^{-2}$	Phytoplankton	
U-232	$2.12\ 10^{7}$	$2.19\ 10^{-2}$	Phytoplankton	
U-233	$2.52\ 10^{5}$	$1.48\ 10^{-3}$	Phytoplankton	
U-234	$1.55\ 10^{6}$	$7.02\ 10^{-3}$	Polychaete worm	
U-235	$2.09\ 10^{5}$	$7.02\ 10^{-4}$	Phytoplankton	
U-236	$4.24\ 10^{6}$	$3.01\ 10^{-4}$	Polychaete worm	

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Limiting organism	Reduction factor to reduce dose rate to below 40 µGy h^{-1}
U-238	4.17 10^{6}	1.09 10^{-3}	Polychaete worm	
Np-237	7.47 10^{4}	2.12 10^{-4}	Vascular plant	
Pu-238	7.47 10^{7}	7.70 10^{-3}	Phytoplankton	
Pu-239	3.89 10^{6}	4.21 10^{-3}	Phytoplankton	
Pu-240	5.98 10^{6}	6.00 10^{-3}	Phytoplankton	
Pu-241	1.66 10^{9}	7.51 10^{-3}	Phytoplankton	
Pu-242	3.41 10^{6}	3.60 10^{-3}	Phytoplankton	
Pu-244	1.80 10^{6}	3.20 10^{-3}	Phytoplankton	
Am-241	5.51 10^{7}	7.25 10^{-3}	Phytoplankton	
Am-242m	4.14 10^{7}	3.77 10^{-2}	Phytoplankton	
Am-243	7.73 10^{6}	5.48 10^{-3}	Phytoplankton	
Cm-242	1.46 10^{10}	7.70 10^{-3}	Phytoplankton	
Cm-243	2.36 10^{8}	1.70 10^{-3}	Phytoplankton	
Cm-244	6.24 10^{8}	3.00 10^{-3}	Phytoplankton	
Cm-245	1.45 10^{7}	1.04 10^{-2}	Phytoplankton	
Cm-246	4.78 10^{7}	9.17 10^{-3}	Phytoplankton	
Cm-248	1.25 10^{6}	9.58 10^{-4}	Phytoplankton	

1470. For the erosion to estuary scenario, peak activity concentrations (per MBq disposed) of Tier 2 radionuclides and their Tier 2 daughters in seawater and sediment were taken from the output of the DORIS assessment for the release via erosion to estuary scenario, as discussed in Section E.4.8. The sea water and seabed sediment concentrations for each radionuclide were then scaled to account for the minimum radiological capacity of each radionuclide. Activity concentrations for radionuclides that were ingrown through radioactive decay were calculated separately. The ERICA assessment tool was then used to calculate a risk quotient for each radionuclide, which is defined as the radionuclide specific activity concentration in a medium divided by the limiting activity concentration for that radionuclide and medium. If the risk quotient is higher than one, the dose rate to the most limiting organism exceeds the ERICA screening dose rate of 10 µGy h^{-1}. If the risk quotient is higher than 4, the dose rate to the most limiting organism exceeds the EA guidance dose rate of 40 µGy h^{-1}.

1471. Table 203 below summarises the results of the wildlife assessment for the estuary (marine) ecosystem for the erosion to estuary scenario. All risk quotients are well below 1, with the exception of Am-242m which was calculated using ICRP BIOTA DC rather than using the ERICA T2 assessment since it was not included in the ERICA list of radionuclides. The maximum inventory of Am-242m is about half the minimum radiological capacity so does not offer protection to Phytoplankton. Am-242m comprises a very low proportion of LLW (<0.002%) and is unlikely to be disposed at the maximum inventory. On the basis that both the risk quotient and the assumption concerning availability of radionuclides released during erosion are very cautious, we do not propose using the erosion to estuary assessment to limit radiological capacity.

Table 203 Radionuclide specific risk quotients for the estuarine ecosystem for the erosion to estuary scenario, based on a generic screening level of 10 µGy h^{-1}.

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Limiting organism	Reduction factor to reduce dose rate to below 40 µGy h^{-1}
H-3	1.88 10^{8}	7.44 10^{-10}	Vascular plant	
C-14	1.19 10^{8}	5.41 10^{-4}	Mammal	
Cl-36	5.08 10^{5}	4.29 10^{-10}	Vascular plant	
Ca-41	1.05 10^{9}	1.47 10^{-5}	Polychaete worm	
Mn-54	3.10 10^{11}			
Fe-55	1.96 10^{13}	9.82 10^{-7}	Polychaete worm	
Co-60	2.09 10^{10}	5.48 10^{-4}	Polychaete worm	
Ni-59	3.44 10^{10}	5.81 10^{-3}	Polychaete worm	
Ni-63	3.86 10^{9}	4.57 10^{-4}	Sea anemones & True coral	
Zn-65	2.48 10^{11}			
Se-79	8.58 10^{8}	1.22 10^{-3}	Mammal	
Sr-90	9.61 10^{8}	4.10 10^{-4}	Vascular plant	
Mo-93	5.95 10^{7}	1.37 10^{-4}	Vascular plant	
Zr-93	3.27 10^{9}	7.41 10^{-3}	Vascular plant	
Nb-93m	2.08 10^{10}	1.66 10^{-3}	Vascular plant	
Nb-94	7.83 10^{7}	2.49 10^{-2}	Polychaete worm	
Tc-99	1.73 10^{7}	3.19 10^{-4}	Vascular plant	
Ru-106	1.59 10^{11}			
Ag-108m	2.89 10^{8}	1.33 10^{-2}	Mammal	
Ag-110m	3.48 10^{10}			
Cd-109	1.39 10^{12}	1.51 10^{-13}	Mollusc - bivalve	
Sb-125	2.04 10^{10}	2.29 10^{-8}	Phytoplankton	
Sn-119m	1.05 10^{13}			
Sn-123	3.71 10^{12}			
Sn-126	1.37 10^{8}	3.48 10^{-2}	Phytoplankton	
Te-127m	2.80 10^{12}			
I-129	9.36 10^{7}	8.47 10^{-5}	Macroalgae	
Ba-133	2.12 10^{8}	9.55 10^{-6}	Polychaete worm	
Cs-134	8.46 10^{10}	3.35 10^{-10}	Polychaete worm	
Cs-135	1.43 10^{9}	1.88 10^{-4}	Reptile	
Cs-137	1.08 10^{9}	9.39 10^{-4}	Polychaete worm	
Ce-144	8.89 10^{12}			
Pm-147	3.05 10^{13}	6.47 10^{-3}	Crustacean	
Sm-147	3.83 10^{7}	6.24 10^{-2}	Crustacean	
Sm-151	5.90 10^{10}	5.15 10^{-2}	Polychaete worm	
Eu-152	6.69 10^{9}	5.08 10^{-1}	Polychaete worm	
Eu-154	2.08 10^{10}	1.15 10^{-2}	Polychaete worm	

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Limiting organism	Reduction factor to reduce dose rate to below 40 µGy h^{-1}
Eu-155	$9.23\ 10^{11}$	$6.71\ 10^{-4}$	Polychaete worm	
Gd-153	$3.38\ 10^{12}$			
Pb-210	$7.84\ 10^{6}$	$7.58\ 10^{-2}$	Polychaete worm	
Po-210	$8.57\ 10^{9}$			
Ra-226	$1.39\ 10^{6}$	$6.91\ 10^{-2}$	Polychaete worm	
Ra-228	$4.80\ 10^{9}$	$2.37\ 10^{-1}$	Phytoplankton	
Ac-227	$3.06\ 10^{7}$	$4.09\ 10^{-1}$	Phytoplankton	
Th-228	$8.11\ 10^{10}$	$1.89\ 10^{-6}$	Phytoplankton	
Th-229	$4.27\ 10^{6}$	$8.60\ 10^{-1}$	Phytoplankton	
Th-230	$2.03\ 10^{6}$	$4.67\ 10^{-2}$	Phytoplankton	
Th-232	$2.16\ 10^{6}$	$3.13\ 10^{-1}$	Phytoplankton	
Pa-231	$7.73\ 10^{5}$	$1.15\ 10^{-1}$	Phytoplankton	
U-232	$2.12\ 10^{7}$	$7.74\ 10^{-1}$	Phytoplankton	
U-233	$2.52\ 10^{5}$	$2.48\ 10^{-4}$	Phytoplankton	
U-234	$1.55\ 10^{6}$	$1.66\ 10^{-4}$	Sea anemones & True coral	
U-235	$2.09\ 10^{5}$	$4.06\ 10^{-5}$	Phytoplankton	
U-236	$4.24\ 10^{6}$	$3.80\ 10^{-4}$	Polychaete worm	
U-238	$4.17\ 10^{6}$	$3.55\ 10^{-4}$	Polychaete worm	
Np-237	$7.47\ 10^{4}$	$5.16\ 10^{-5}$	Vascular plant	
Pu-238	$7.47\ 10^{7}$	$2.20\ 10^{-1}$	Phytoplankton	
Pu-239	$3.89\ 10^{6}$	$1.90\ 10^{-2}$	Phytoplankton	
Pu-240	$5.98\ 10^{6}$	$2.91\ 10^{-2}$	Phytoplankton	
Pu-241	$1.66\ 10^{9}$	$4.26\ 10^{-1}$	Phytoplankton	
Pu-242	$3.41\ 10^{6}$	$1.59\ 10^{-2}$	Phytoplankton	
Pu-244	$1.80\ 10^{6}$	$8.41\ 10^{-3}$	Phytoplankton	
Am-241	$5.51\ 10^{7}$	$4.31\ 10^{-1}$	Phytoplankton	
Am-242m	$4.14\ 10^{7}$	$1.06\ 10^{3}$	Phytoplankton	264
Am-243	$7.73\ 10^{6}$	$6.70\ 10^{-2}$	Phytoplankton	
Cm-242	$1.46\ 10^{10}$	$2.20\ 10^{-1}$	Phytoplankton	
Cm-243	$2.36\ 10^{8}$	$4.64\ 10^{-1}$	Phytoplankton	
Cm-244	$6.24\ 10^{8}$	$4.73\ 10^{-1}$	Phytoplankton	
Cm-245	$1.45\ 10^{7}$	$1.69\ 10^{-1}$	Phytoplankton	
Cm-246	$4.78\ 10^{7}$	$5.22\ 10^{-1}$	Phytoplankton	
Cm-248	$1.25\ 10^{6}$	$5.06\ 10^{-2}$	Phytoplankton	

E.7.5. ERICA assessment for a Freshwater Ecosystem

1472. There is an existing freshwater pond at the north-west corner of the site and further ponds are planned in the restoration plan, as shown in Figure 6. The distance of the pond from the landfill liner is 80 m. Although the GoldSim model showed that radionuclides will not be transferred to these bodies by water that has become contaminated assuming that leachate from the landfill overtops the liner (the bathtubbing scenario), a 'what-if' scenario was considered assuming contamination of a hypothetical pond.

1473. The activity concentration in the pond was cautiously assumed to be equal to the peak activity in water in the GoldSim 'fast pathway' (flow overland) for the bathtubbing scenario for each radionuclide, reduced by the same factor ($1\ 10^{-3}$) applied in the leachate spillage scenario (see Appendix E.3.10). This value was then scaled to the minimum radiological capacity for that radionuclide. The activity concentration in pond sediment was calculated using kd values from ERICA.

1474. The ERICA assessment tool was then used to calculate a risk quotient for each radionuclide using a Tier 2 assessment. The Tier 2 assessment determined the risk quotients for each radionuclide for all organisms based on a screening level of 10 µGy h^{-1}. The most restrictive organism was selected.

1475. Table 204 below shows the calculated risk quotients. below summarises the results of the wildlife assessment for freshwater ecosystem for seepage from the landfill. All risk quotients are well below 1, therefore all non-human biota in the freshwater ecosystem are considered to be sufficiently protected for leachate breakout in the 'what-if' hypothetical pond contamination in the "bathtubbing" scenario.

Table 204 Radionuclide specific risk quotients for freshwater ecosystems, based on a generic screening level of 10 µGy h^{-1} and the reduction required to reduce the dose rate to 40 µGy h^{-1}

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Limiting organism	Reduction factor to reduce dose rate to below 40 µGy h^{-1}
H-3	$1.88\ 10^{8}$	$2.01\ 10^{-7}$	Phytoplankton	
C-14	$1.19\ 10^{8}$	$9.35\ 10^{-2}$	Mammal	
Cl-36	$5.08\ 10^{5}$	$4.34\ 10^{-4}$	Mammal	
Ca-41	$1.05\ 10^{9}$	$1.29\ 10^{0}$	Mollusc - bivalve	
Mn-54	$3.10\ 10^{11}$	$3.00\ 10^{-8}$	Insect larvae	
Fe-55	$1.96\ 10^{13}$	$3.30\ 10^{-8}$	Insect larvae	
Co-60	$2.09\ 10^{10}$	$2.68\ 10^{-4}$	Insect larvae	
Ni-59	$3.44\ 10^{10}$	$1.21\ 10^{-1}$	Mollusc - bivalve	
Ni-63	$3.86\ 10^{9}$	$1.66\ 10^{-3}$	Insect larvae	
Zn-65	$2.48\ 10^{11}$	$2.39\ 10^{-9}$	Insect larvae	
Se-79	$8.58\ 10^{8}$	$9.35\ 10^{-3}$	Zooplankton	
Sr-90	$9.61\ 10^{8}$	$4.80\ 10^{-1}$	Mollusc - bivalve	
Mo-93	$5.95\ 10^{7}$	$4.96\ 10^{-2}$	Insect larvae	
Zr-93	$3.27\ 10^{9}$	$3.65\ 10^{-3}$	Insect larvae	

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Limiting organism	Reduction factor to reduce dose rate to below 40 µGy h^{-1}
Nb-93m	2.08 10^{10}	8.02 10^{-4}	Insect larvae	
Nb-94	7.83 10^{7}	3.73 10^{-1}	Insect larvae	
Tc-99	1.73 10^{7}	2.25 10^{-4}	Mammal	
Ru-106	1.59 10^{11}	3.14 10^{-9}	Insect larvae	
Ag-108m	2.89 10^{8}	3.14 10^{-1}	Insect larvae	
Ag-110m	3.48 10^{10}	2.78 10^{-9}	Insect larvae	
Cd-109	1.39 10^{12}	1.95 10^{-9}	Mollusc - gastropod	
Sb-125	2.04 10^{10}	4.35 10^{-8}	Insect larvae	
Sn-119m	1.05 10^{13}	7.05 10^{-9}	Insect larvae	
Sn-123	3.71 10^{12}	1.89 10^{-8}	Insect larvae	
Sn-126	1.37 10^{8}	8.11 10^{-1}	Insect larvae	
Te-127m	2.80 10^{12}	3.21 10^{-10}	Insect larvae	
I-129	9.36 10^{7}	2.46 10^{-3}	Reptile	
Ba-133	2.12 10^{8}	3.44 10^{-2}	Insect larvae	
Cs-134	8.46 10^{10}	1.25 10^{-10}	Insect larvae	
Cs-135	1.43 10^{9}	4.44 10^{-3}	Reptile	
Cs-137	1.08 10^{9}	2.89 10^{-3}	Insect larvae	
Ce-144	8.89 10^{12}	9.75 10^{-8}	Insect larvae	
Pm-147	3.05 10^{13}	5.90 10^{-7}	Insect larvae	
Sm-147	3.83 10^{7}	8.13 10^{-2}	Phytoplankton	
Sm-151	5.90 10^{10}	1.07 10^{-2}	Phytoplankton	
Eu-152	6.69 10^{9}	3.48 10^{-1}	Insect larvae	
Eu-154	2.08 10^{10}	1.39 10^{-1}	Insect larvae	
Eu-155	9.23 10^{11}	2.68 10^{-3}	Insect larvae	
Gd-153	3.38 10^{12}	2.32 10^{-8}	Insect larvae	
Pb-210	7.84 10^{6}	2.57 10^{-2}	Insect larvae	
Po-210	8.57 10^{9}	1.34 10^{-8}	Insect larvae	
Ra-226	1.39 10^{6}	2.40 10^{-1}	Insect larvae	
Ra-228	4.80 10^{9}	1.24 10^{-2}	Vascular plant	
Ac-227	3.06 10^{7}	7.36 10^{-2}	Insect larvae	
Th-228	8.11 10^{10}	1.53 10^{-8}	Vascular plant	
Th-229	4.27 10^{6}	2.84 10^{-1}	Vascular plant	
Th-230	2.03 10^{6}	4.84 10^{-1}	Insect larvae	
Th-232	2.16 10^{6}	1.84 10^{-1}	Vascular plant	
Pa-231	7.73 10^{5}	1.32 10^{-1}	Insect larvae	
U-232	2.12 10^{7}	1.21 10^{-1}	Vascular plant	
U-233	2.52 10^{5}	8.63 10^{-3}	Vascular plant	
U-234	1.55 10^{6}	4.77 10^{-2}	Insect larvae	
U-235	2.09 10^{5}	8.15 10^{-3}	Insect larvae	

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Limiting organism	Reduction factor to reduce dose rate to below 40 µGy h^{-1}
U-236	4.24 10^{6}	1.70 10^{-2}	Insect larvae	
U-238	4.17 10^{6}	2.72 10^{-2}	Insect larvae	
Np-237	7.47 10^{4}	3.09 10^{-2}	Mollusc - bivalve	
Pu-238	7.47 10^{7}	1.66 10^{-1}	Insect larvae	
Pu-239	3.89 10^{6}	9.20 10^{-2}	Insect larvae	
Pu-240	5.98 10^{6}	1.31 10^{-1}	Insect larvae	
Pu-241	1.66 10^{9}	9.56 10^{-2}	Insect larvae	
Pu-242	3.41 10^{6}	7.86 10^{-2}	Insect larvae	
Pu-244	1.80 10^{6}	7.21 10^{-2}	Insect larvae	
Am-241	5.51 10^{7}	9.23 10^{-2}	Insect larvae	
Am-242m	4.14 10^{7}	8.73 10^{-2}	Insect larvae	
Am-243	7.73 10^{6}	8.34 10^{-2}	Insect larvae	
Cm-242	1.46 10^{10}	1.66 10^{-1}	Insect larvae	
Cm-243	2.36 10^{8}	2.13 10^{-2}	Insect larvae	
Cm-244	6.24 10^{8}	5.01 10^{-2}	Insect larvae	
Cm-245	1.45 10^{7}	1.26 10^{-1}	Insect larvae	
Cm-246	4.78 10^{7}	9.55 10^{-2}	Insect larvae	
Cm-248	1.25 10^{6}	1.22 10^{-2}	Insect larvae	

E.7.6. ERICA assessment for a Terrestrial Ecosystem

1476. The assessment for the terrestrial ecosystem for the erosion scenario (post POA) used the radionuclide concentrations in waste cells at the end of the PoA (per MBq disposed) from the Goldsim model, applying the same dilution factors used for the smallholder scenario (E.5.10) and assigning these values as soil concentrations in ERICA. The soil concentrations for each radionuclide were then scaled to account for the lowest radiological capacity of each radionuclide. Activity concentrations for radionuclides that were ingrown through radioactive decay were calculated separately.

1477. The assessment for the gas release scenario (operational period) considered C-14 and H-3 activity concentrations in air (Bq m^{-3}) per MBq disposed taken from the gas release scenario assessment (see Section E.3.5.3). The activity concentrations in soil and air per MBq were then scaled to account for the minimum radiological capacity of each radionuclide.

1478. The ERICA assessment tool was then used to calculate a risk quotient for each radionuclide using the Tier 2 assessment, for the two scenarios. The higher of the risk quotients for the two scenarios are given in Table 205. The risk quotients for the gas release and exposure to waste cells at the end of the PoA due to erosion were all low except for Cm-243 and Cm-244 when the radiological capacity was used and these show doses slightly in excess of 40 µGy h^{-1}. When the maximum inventory was considered no radionuclides exceed a dose rate of 40 µGy h^{-1} and most were substantially below 1 µGy h^{-1}. Hence, based on a realistic waste composition, terrestrial non-human biota are sufficiently protected

Table 205 Radionuclide specific risk quotients for terrestrial ecosystems (maximum of erosion and gas release scenarios), based on a generic screening level of 10 µGy h^{-1} and the reduction required to reduce the dose rate to 40 µGy h^{-1}

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Most limiting organism	Reduction factor to reduce dose rate to below 40 µGy h^{-1}
H-3	$1.88\ 10^{8}$	$4.31\ 10^{-6}$	Tree	
C-14	$1.19\ 10^{8}$	$1.47\ 10^{-3}$	Mammal - large	
Cl-36	$5.08\ 10^{5}$	$4.81\ 10^{-3}$	Grasses & Herbs	
Ca-41	$1.05\ 10^{9}$	$6.19\ 10^{-1}$	Mammal - large	
Mn-54	$3.10\ 10^{11}$	$3.32\ 10^{-8}$	Arthropod - detritivorous	
Fe-55	$1.96\ 10^{13}$	$3.35\ 10^{-5}$	Mollusc - gastropod	
Co-60	$2.09\ 10^{10}$	$8.98\ 10^{-2}$	Arthropod - detritivorous	
Ni-59	$3.44\ 10^{10}$	$4.10\ 10^{-1}$	Reptile	
Ni-63	$3.86\ 10^{9}$	$3.85\ 10^{-2}$	Reptile	
Zn-65	$2.48\ 10^{11}$	$1.25\ 10^{-8}$	Mammal - large	
Se-79	$8.58\ 10^{8}$	$3.03\ 10^{-1}$	Annelid	
Sr-90	$9.61\ 10^{8}$	$1.51\ 10^{0}$	Lichen & Bryophytes	
Mo-93	$5.95\ 10^{7}$	$2.58\ 10^{-3}$	Bird	
Zr-93	$3.27\ 10^{9}$	$2.48\ 10^{-2}$	Reptile	
Nb-93m	$2.08\ 10^{10}$	$2.77\ 10^{-2}$	Annelid	
Nb-94	$7.83\ 10^{7}$	$5.21\ 10^{-1}$	Arthropod - detritivorous	
Tc-99	$1.73\ 10^{7}$	$5.29\ 10^{-2}$	Grasses & Herbs	
Ru-106	$1.59\ 10^{11}$	$8.67\ 10^{-9}$	Annelid	
Ag-108m	$2.89\ 10^{8}$	$1.93\ 10^{0}$	Arthropod - detritivorous	
Ag-110m	$3.48\ 10^{10}$	$4.47\ 10^{-9}$	Arthropod - detritivorous	
Cd-109	$1.39\ 10^{12}$	$9.92\ 10^{-9}$	Annelid	
Sb-125	$2.04\ 10^{10}$	$2.15\ 10^{-5}$	Annelid	
Sn-119m	$1.05\ 10^{13}$	$1.00\ 10^{-8}$	Lichen & Bryophytes	
Sn-123	$3.71\ 10^{12}$	$7.18\ 10^{-9}$	Lichen & Bryophytes	
Sn-126	$1.37\ 10^{8}$	$1.19\ 10^{0}$	Arthropod - detritivorous	
Te-127m	$2.80\ 10^{12}$	$3.70\ 10^{-8}$	Annelid	
I-129	$9.36\ 10^{7}$	$6.90\ 10^{-3}$	Arthropod - detritivorous	
Ba-133	$2.12\ 10^{8}$	$8.09\ 10^{-3}$	Bird	
Cs-134	$8.46\ 10^{10}$	$3.34\ 10^{-6}$	Mammal - large	
Cs-135	$1.43\ 10^{9}$	$1.10\ 10^{0}$	Lichen & Bryophytes	

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Most limiting organism	Reduction factor to reduce dose rate to below 40 µGy h^{-1}
Cs-137	1.08 10^{9}	1.43 10^{0}	Mammal - large	
Ce-144	8.89 10^{12}	1.54 10^{-8}	Reptile	
Pm-147	3.05 10^{13}	6.06 10^{-5}	Reptile	
Sm-147	3.83 10^{7}	1.30 10^{-1}	Amphibian	
Sm-151	5.90 10^{10}	1.26 10^{-1}	Amphibian	
Eu-152	6.69 10^{9}	1.46 10^{0}	Arthropod - detritivorous	
Eu-154	2.08 10^{10}	8.82 10^{-1}	Arthropod - detritivorous	
Eu-155	9.23 10^{11}	2.70 10^{-2}	Amphibian	
Gd-153	3.38 10^{12}	9.40 10^{-9}	Amphibian	
Pb-210	7.84 10^{6}	2.25 10^{-1}	Lichen & Bryophytes	
Po-210	8.57 10^{9}	6.90 10^{-9}	Lichen & Bryophytes	
Ra-226	1.39 10^{6}	6.72 10^{-1}	Lichen & Bryophytes	
Ra-228	4.80 10^{9}	1.33 10^{0}	Lichen & Bryophytes	
Ac-227	3.06 10^{7}	1.74 10^{0}	Lichen & Bryophytes	
Th-228	8.11 10^{10}	1.33 10^{-5}	Lichen & Bryophytes	
Th-229	4.27 10^{6}	4.80 10^{-1}	Lichen & Bryophytes	
Th-230	2.03 10^{6}	5.86 10^{-2}	Lichen & Bryophytes	
Th-232	2.16 10^{6}	5.89 10^{-1}	Lichen & Bryophytes	
Pa-231	7.73 10^{5}	3.05 10^{-1}	Lichen & Bryophytes	
U-232	2.12 10^{7}	3.05 10^{0}	Lichen & Bryophytes	
U-233	2.52 10^{5}	9.43 10^{-3}	Lichen & Bryophytes	
U-234	1.55 10^{6}	5.63 10^{-2}	Lichen & Bryophytes	
U-235	2.09 10^{5}	7.24 10^{-3}	Lichen & Bryophytes	
U-236	4.24 10^{6}	1.45 10^{-1}	Lichen & Bryophytes	
U-238	4.17 10^{6}	1.35 10^{-1}	Lichen & Bryophytes	
Np-237	7.47 10^{4}	4.78 10^{-3}	Lichen & Bryophytes	
Pu-238	7.47 10^{7}	7.11 10^{-1}	Lichen & Bryophytes	
Pu-239	3.89 10^{6}	5.58 10^{-2}	Lichen & Bryophytes	
Pu-240	5.98 10^{6}	8.54 10^{-2}	Lichen & Bryophytes	
Pu-241	1.66 10^{9}	3.28 10^{0}	Lichen & Bryophytes	
Pu-242	3.41 10^{6}	4.64 10^{-2}	Lichen & Bryophytes	
Pu-244	1.80 10^{6}	2.70 10^{-2}	Lichen & Bryophytes	
Am-241	5.51 10^{7}	3.38 10^{0}	Lichen & Bryophytes	
Am-242m	4.14 10^{7}	2.01 10^{0}	Lichen & Bryophytes	
Am-243	7.73 10^{6}	5.07 10^{-1}	Lichen & Bryophytes	
Cm-242	1.46 10^{10}	7.11 10^{-1}	Lichen & Bryophytes	
Cm-243	2.36 10^{8}	4.36 10^{0}	Lichen & Bryophytes	1.09
Cm-244	6.24 10^{8}	4.84 10^{0}	Lichen & Bryophytes	1.21

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Most limiting organism	Reduction factor to reduce dose rate to below 40 µGy h^{-1}
Cm-245	1.45 10^{7}	1.08 10^{0}	Lichen & Bryophytes	
Cm-246	4.78 10^{7}	3.39 10^{0}	Lichen & Bryophytes	
Cm-248	1.25 10^{6}	3.31 10^{-1}	Lichen & Bryophytes	

E.7.7. Tier 2 assessment for Burrowing Animals

1479. A minimum of 1 m soil will be put on top of the facility as a restoration layer. Below this soil, there are membranes and 30 cm of granular material. In addition, the top 1 m of waste is not radioactive, which means that the depth at which the first radioactive material is found is at least 2.3 m below the restored surface. The granular layer deters burrowing animals at least for a few hundred years, until it is naturally broken down and mixed with soil.

1480. A review of soil movement by burrowing animals was published as part of the Nirex Safety Studies (Bishop, 1989) and reported a maximum depth of 2.7 m for a warren, with a typical depth of 1.8 m. More recent information suggests a maximum depth of a rabbit burrow or warren is 3 m (Rabbitmatters, 2024). Hence, although a typical warren will not intercept waste, one at the maximum depth could. Rabbits are not a protected species.

1481. Badgers are a common, protected species. They like to dig their setts where the ground is easy to dig, e.g. in sandy soil, and in sites where the sett stays dry. Badgers do not like digging into clay, as this is wet and sticky. Badger tunnels can be 4 m deep, though most are less than 1 m underground and follow surface contours (http://www.badgerland.co.uk/animals/sett.html). Other burrowing animals (mice, voles, moles) have a maximum burrow depth that is less than 1 m and therefore will not burrow into the waste.

1482. A Tier 2 ERICA assessment was therefore undertaken to estimate the potential dose to animals burrowing into the waste cells after closure. While this assessment was focused on burrowing animals (rabbits), all the parameters (concentration factors, dose factors, etc.) were set to default ERICA values.

1483. Radionuclide concentrations in the waste cells 60 years after closure were calculated in the GoldSim groundwater model. The concentrations for each radionuclide were then scaled to account for the minimum radiological capacity, see Section 7.4.2.2. Activity concentrations of radionuclides that were ingrown through radioactive decay were calculated separately.

1484. A Tier 2 assessment was carried out within ERICA to calculate a risk quotient for each radionuclide for burrowing mammals. If the risk quotient is higher than one, the dose rate to the most limiting organism exceeds the screening dose rate of 10 µGy h^{-1}. Table 206 shows the calculated risk quotients.

Table 206 Radionuclide specific risk quotients for terrestrial ecosystems for burrowing animals in the waste cells, based on a generic screening level of 10 µGy h^{-1}

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Reduction factor to reduce dose rate to below 40 µGy h^{-1}	Adjusted radiological capacity (MBq)
H-3	$1.88\ 10^{8}$	$6.14\ 10^{-6}$		
C-14	$1.19\ 10^{8}$	$2.95\ 10^{-3}$		
Cl-36	$5.08\ 10^{5}$	$1.05\ 10^{-2}$		
Ca-41	$1.05\ 10^{9}$	$3.28\ 10^{0}$		
Mn-54	$3.10\ 10^{11}$	$6.57\ 10^{-8}$		
Fe-55	$1.96\ 10^{13}$	$7.39\ 10^{-5}$		
Co-60	$2.09\ 10^{10}$	$2.07\ 10^{-1}$		
Ni-59	$3.44\ 10^{10}$	$2.95\ 10^{-1}$		
Ni-63	$3.86\ 10^{9}$	$2.34\ 10^{-2}$		
Zn-65	$2.48\ 10^{11}$	$2.74\ 10^{-8}$		
Se-79	$8.58\ 10^{8}$	$3.21\ 10^{-1}$		
Sr-90	$9.61\ 10^{8}$	$4.00\ 10^{0}$	1.14	$9.61\ 10^{8}$
Mo-93	$5.95\ 10^{7}$	$1.38\ 10^{-3}$		
Zr-93	$3.27\ 10^{9}$	$2.14\ 10^{-3}$		
Nb-93m	$2.08\ 10^{10}$	$2.75\ 10^{-2}$		
Nb-94	$7.83\ 10^{7}$	$1.17\ 10^{0}$		
Tc-99	$1.73\ 10^{7}$	$6.86\ 10^{-3}$		
Ru-106	$1.59\ 10^{11}$	$4.04\ 10^{-9}$		
Ag-108m	$2.89\ 10^{8}$	$4.00\ 10^{0}$	6.87	$2.89\ 10^{8}$
Ag-110m	$3.48\ 10^{10}$	$9.48\ 10^{-9}$		
Cd-109	$1.39\ 10^{12}$	$1.69\ 10^{-8}$		
Sb-125	$2.04\ 10^{10}$	$3.71\ 10^{-5}$		
Sn-119m	$1.05\ 10^{13}$	$9.22\ 10^{-9}$		
Sn-123	$3.71\ 10^{12}$	$7.28\ 10^{-9}$		
Sn-126	$1.37\ 10^{8}$	$2.57\ 10^{0}$		
Te-127m	$2.80\ 10^{12}$	$3.63\ 10^{-8}$		
I-129	$9.36\ 10^{7}$	$5.96\ 10^{-3}$		
Ba-133	$2.12\ 10^{8}$	$1.62\ 10^{-2}$		
Cs-134	$8.46\ 10^{10}$	$8.02\ 10^{-6}$		
Cs-135	$1.43\ 10^{9}$	$4.00\ 10^{0}$	7.23	$1.43\ 10^{9}$
Cs-137	$1.08\ 10^{9}$	$4.00\ 10^{0}$	7.12	$1.08\ 10^{9}$
Ce-144	$8.89\ 10^{12}$	$2.36\ 10^{-8}$		
Pm-147	$3.05\ 10^{13}$	$1.12\ 10^{-4}$		
Sm-147	$3.83\ 10^{7}$	$2.48\ 10^{-1}$		
Sm-151	$5.90\ 10^{10}$	$2.42\ 10^{-1}$		
Eu-152	$6.69\ 10^{9}$	$3.36\ 10^{0}$		
Eu-154	$2.08\ 10^{10}$	$1.99\ 10^{0}$		
Eu-155	$9.23\ 10^{11}$	$5.32\ 10^{-2}$		
Gd-153	$3.38\ 10^{12}$	$1.94\ 10^{-8}$		
Pb-210	$7.84\ 10^{6}$	$6.68\ 10^{-2}$		
Po-210	$8.57\ 10^{9}$	$2.73\ 10^{-9}$		
Ra-226	$1.39\ 10^{6}$	$4.04\ 10^{-1}$		
Ra-228	$4.80\ 10^{9}$	$3.33\ 10^{-1}$		
Ac-227	$3.06\ 10^{7}$	$4.13\ 10^{-1}$		
Th-228	$8.11\ 10^{10}$	$1.24\ 10^{-6}$		
Th-229	$4.27\ 10^{6}$	$2.50\ 10^{-2}$		
Th-230	$2.03\ 10^{6}$	$1.58\ 10^{-2}$		
Th-232	$2.16\ 10^{6}$	$1.71\ 10^{-1}$		
Pa-231	$7.73\ 10^{5}$	$7.24\ 10^{-2}$		

Radionuclide	Radiological capacity (MBq)	Risk quotient (10 µGy h^{-1} screening)	Reduction factor to reduce dose rate to below 40 µGy h^{-1}	Adjusted radiological capacity (MBq)
U-232	2.12 10^{7}	2.61 10^{-1}		
U-233	2.52 10^{5}	3.92 10^{-4}		
U-234	1.55 10^{6}	2.33 10^{-3}		
U-235	2.09 10^{5}	5.70 10^{-4}		
U-236	4.24 10^{6}	5.99 10^{-3}		
U-238	4.17 10^{6}	6.41 10^{-3}		
Np-237	7.47 10^{4}	1.21 10^{-3}		
Pu-238	7.47 10^{7}	3.89 10^{-1}		
Pu-239	3.89 10^{6}	3.05 10^{-2}		
Pu-240	5.98 10^{6}	4.67 10^{-2}		
Pu-241	1.66 10^{9}	8.13 10^{-1}		
Pu-242	3.41 10^{6}	2.54 10^{-2}		
Pu-244	1.80 10^{6}	1.92 10^{-2}		
Am-241	5.51 10^{7}	8.37 10^{-1}		
Am-242m	4.14 10^{7}	5.30 10^{-1}		
Am-243	7.73 10^{6}	1.35 10^{-1}		
Cm-242	1.46 10^{10}	3.89 10^{-1}		
Cm-243	2.36 10^{8}	1.05 10^{0}		
Cm-244	6.24 10^{8}	1.12 10^{0}		
Cm-245	1.45 10^{7}	2.58 10^{-1}		
Cm-246	4.78 10^{7}	7.81 10^{-1}		
Cm-248	1.25 10^{6}	8.99 10^{-2}		

1485. There are four radionuclides for which the dose rate to the burrowing mammal is greater than 40 µGy h^{-1}, three by almost an order of magnitude. Given the design of the landfill facility and the design of the cap, it seems very unlikely that burrowing animals will build their nesting chambers in the disposed waste. In addition, the purpose of the landfill site is to concentrate and contain the waste to protect the environment, so the environment in the actual landfill (the waste cell) is not the part of the environment that is being protected (it is not a conservation area).

1486. Rabbits are not a protected species. Their high fecundity also means that the population will recover quickly if 10% are affected and a more reasonable value to use for protecting the population may be the HDR50 (or even the EDR50). However, badgers are a protected species.

1487. We note that in their review of the ENRMF ESC, the EA commented that it would be precautionary to apply radiological capacity reduction factors based on the ERICA Tier 2 assessment for burrowing animals.

1488. There are four radionuclides for which the dose rate to the burrowing mammal is greater than 40 µGy h^{-1}. As such, the radiological capacities could be reduced to ensure that dose rates to burrowing mammals would be below 40 µGy h^{-1}. This would ensure that burrowing mammals will be sufficiently protected.

1489. The alternative is to ensure that wastes containing these radionuclides are buried at a depth below the surface that is greater than 4 m. This will ensure that rabbit warrens or badger tunnels will not enter the waste. The radiological capacity without this reduction is considered as a sensitivity analysis.

E.8. Management of uncertainty

1490. Uncertainties in dose assessments arise from natural variability, limitations in the knowledge of processes or data, alternative interpretations, and the potential for change in the future, and are generally assigned to one of three categories:

- conceptual model uncertainty - uncertainty in the appropriateness of models used to represent the system;
- scenario uncertainty - uncertainty in the completeness of the set of exposure scenarios; and,
- parameter uncertainty - uncertainty in the parameter values selected for use in the assessment.

1491. Conceptual model uncertainties are not examined in detail within this ESC and are addressed by adopting a generally conservative approach to defining pathways and uptake routes. Confidence building in the GoldSim model used for migration in groundwater has been performed by running another model and comparing the results for a few radionuclides. This is described in Appendix F.

1492. Scenario uncertainties relate to the choice of scenarios. A wide range of scenarios has been considered in this ESC based on an analysis of FEPs and other ESCs. Hence it is considered that the scenarios encompass the range of future exposure scenarios.

1493. Parameter value uncertainties have been considered in terms of the sensitivity of the dose assessments to parameter selection. The analysis is described in the next section.

E.8.1. Parameter sensitivity

1494. The equations used in the assessment models are, with the exception of radon migration through a cap and the groundwater pathway, linear. For the linear cases the effect of parameter changes is simply multiplicative.

1495. The radon calculations include an exponential decay of radon through the cap, controlled by the ratio of the cap thickness to the radon relaxation length in the cap. Changing either of these two parameters will result in large changes in radon flux (note, though, that the dose is linear with respect to the flux, so once the change in flux has been determined, the change in dose is again linear).

1496. Non-linearities also arise in the determination of the source term where there is an exponential term to model radioactive decay or leaching of radionuclides out of the waste cells. The key uncertainty here is likely to be the hydraulic conductivity of the barrier, as this will dictate the long-term radionuclide concentration in the waste cells.

E.8.1.1. Intrusion: Smallholder

1497. Although the Smallholder scenario (see Section E.5.10) is not one of the scenarios with specified scenario radiological capacities to be considered when calculating the sum of fractions, it is considered here to show how the scenario radiological capacity and hence the capacity limiting scenarios can change when parameter sensitivity is considered. The impact of changes to parameter values has considered the dilution factor and the timing of the event. The impact is to produce a linear change in the radiological capacity for this scenario.

1498. The reference dilution factor used in the assessment is 0.0027, based on a dilution factor of waste with cap material during excavation of 0.54, a dilution of 0.05 to account for the average LLW content of the landfill, and a dilution of spoil with clean soil of 0.1. The sensitivity of dose to dilution factors of 0.00027, 0.0027, and 0.054 is shown in Table 207. The radionuclides listed are those where the Smallholder scenario would then become a radiological capacity limiting scenario with an alternative dilution factor. The impact of a numerically smaller dilution factor is to reduce the dose since it is applied as a multiplying factor.

Table 207 Sensitivity of dose to dilution factor: Smallholder at 60 y

Radionuclide	Dose per unit disposal; *DIL*=0.00027 (μSv MBq^{-1})	Dose per unit disposal; *DIL*=0.0027 (μSv MBq^{-1})	Dose per unit disposal; *DIL*=0.054 (μSv MBq^{-1})
Se-79	$2.11\ 10^{-7}$	$2.11\ 10^{-6}$	$4.23\ 10^{-5}$
Sr-90	$1.97\ 10^{-8}$	$1.97\ 10^{-7}$	$3.95\ 10^{-6}$

1499. The change in dilution factor results in a linear change in dose, equivalent to the factors applied. The impact on scenario radiological capacity is illustrated in Table 208. The Smallholder scenario would become a radiological capacity limiting scenario for the radionuclides listed in Table 208 if a higher value of the dilution factor is applied.

Table 208 Sensitivity of radiological capacity to dilution factor: Smallholder at 60 y

Radionuclide	Scenario radiological capacity; *DIL*=0.00027 (MBq)	Scenario radiological capacity; *DIL*=0.0027 (MBq)	Scenario radiological capacity; *DIL*=0.054 (MBq)
Se-79	$1.42\ 10^{10}$	$1.42\ 10^{9}$	$7.10\ 10^{7}$
Sr-90	$1.52\ 10^{11}$	$1.52\ 10^{10}$	$7.60\ 10^{8}$

1500. The impact of changing the timing of the intrusion event is shown for two times of intrusion: 60 y after closure and 200 years after closure. The results are shown in Table 209 for the radionuclides with the 10 lowest scenario radiological capacities. It can be seen that a later intrusion time results in a lower dose for some radionuclides, since the radiological capacity increases, and for other long-lived radionuclides the dose remains the same. In one case in-growth of Ac-227 from Pa-231 reduces the capacity slightly.

Table 209 Sensitivity of scenario radiological capacity to timing of intrusion: Smallholder

Radionuclide	Radiological capacity when intrusion occurs at 60y	Radiological capacity when intrusion occurs at 200y
C-14	$2.84\ 10^{8}$	$2.55\ 10^{9}$
Cl-36	$4.38\ 10^{8}$	$4.38\ 10^{8}$
Pa-231	$7.34\ 10^{8}$	$7.24\ 10^{8}$

Radionuclide	Radiological capacity when intrusion occurs at 60y	Radiological capacity when intrusion occurs at 200y
Se-79	$1.42\ 10^{9}$	$1.42\ 10^{9}$
Tc-99	$1.69\ 10^{9}$	$1.69\ 10^{9}$
Th-232	$3.08\ 10^{9}$	$3.08\ 10^{9}$
U-232	$3.47\ 10^{9}$	$1.42\ 10^{10}$
Sn-126	$3.97\ 10^{9}$	$3.97\ 10^{9}$
Pb-210	$4.39\ 10^{9}$	$3.48\ 10^{11}$
Cm-248	$4.74\ 10^{9}$	$4.74\ 10^{9}$

E.8.1.2. Groundwater

1501. Several conservative assumptions underlie the Goldsim groundwater model. It is assumed that there is no sorption of radionuclides to waste materials, whereas in reality the waste received at Port Clarence is likely to provide sorption sites within waste cells. Radionuclides are assumed to interact with other soil like materials and with the clay barrier but not with the alluvium within the aquifer. The rate of infiltration to the landfill through the cap is also conservative (see paragraph 930). The depth of clay beneath the landfill used in the assessment (1 m) is less than that beneath the hazardous landfill site (1.5 m).

1502. The application of peak dose output from the model to calculate radiological capacity for use in the sum of fractions is also conservative since the time to peak dose varies from radionuclide to radionuclide and the sum of fractions approach assumes that each radionuclide affects the same individual at the same time.

E.8.1.3. Erosion scenarios

Erosion: dog walker

1503. The erosion: dog walker scenario is one of the scenarios with a specified scenario radionuclide capacity for the sum of fractions approach. It has a lower scenario radiological capacity than other scenarios for 13 radionuclides (see Section E.4.7).

1504. The external dose to the dog walker following coastal erosion uses the external dose coefficient for a slab, which is conservative.

1505. The sensitivity to different exposure times to eroded material was investigated for the walker. If the walker were to spend more time close to the waste (300 h), there are nine more radionuclides for which the erosion - dog walker scenario gives the lowest scenario radiological capacity. The impact on the scenario radiological capacity for these 9 radionuclides is summarised in Table 210. Although the scenario radiological capacity would be reduced for these radionuclides, in most cases it is not much smaller than the lowest scenario radiological capacity from a different scenario.

Table 210 Impact on radiological capacity of different exposure times for the erosion - dog walker scenario

Radionuclide	Scenario capacity using original exposure time (73 h/y) (MBq)	Scenario capacity using 1 h per month exposure time (MBq)	Scenario capacity using 300 h per year exposure time (MBq)	Lowest radiological capacity from other scenarios (MBq)
Ni-59	$7.05\ 10^{10}$	$4.29\ 10^{11}$	$1.72\ 10^{10}$	$3.44\ 10^{10}$
Sr-90	$1.09\ 10^{9}$	$6.65\ 10^{9}$	$2.66\ 10^{8}$	$9.61\ 10^{8}$
I-129	$1.09\ 10^{8}$	$6.65\ 10^{8}$	$2.66\ 10^{7}$	$9.36\ 10^{7}$
Sm-147	$1.56\ 10^{8}$	$9.49\ 10^{8}$	$3.80\ 10^{7}$	$3.83\ 10^{7}$
Pb-210	$1.26\ 10^{7}$	$7.66\ 10^{7}$	$3.06\ 10^{6}$	$7.84\ 10^{6}$
Ra-226	$1.84\ 10^{6}$	$1.12\ 10^{7}$	$4.48\ 10^{5}$	$1.39\ 10^{6}$
Th-229	$8.88\ 10^{6}$	$5.40\ 10^{7}$	$2.16\ 10^{6}$	$4.27\ 10^{6}$
Th-232	$3.20\ 10^{6}$	$1.95\ 10^{7}$	$7.79\ 10^{5}$	$2.16\ 10^{6}$
Cm-245	$4.95\ 10^{7}$	$3.02\ 10^{8}$	$1.21\ 10^{7}$	$1.45\ 10^{7}$
Cm-246	$5.05\ 10^{7}$	$1.23\ 10^{7}$	$7.57\ 10^{7}$	$4.78\ 10^{7}$

1506. Dose per MBq was calculated for the cases where the walker spends less time (1 h per month) or more time close to the eroded material (300 h per year). The doses for the original 13 radionuclides where the erosion-dog walker scenario has the lowest scenario radiological capacity and the additional nine discussed above are shown in Table 211.

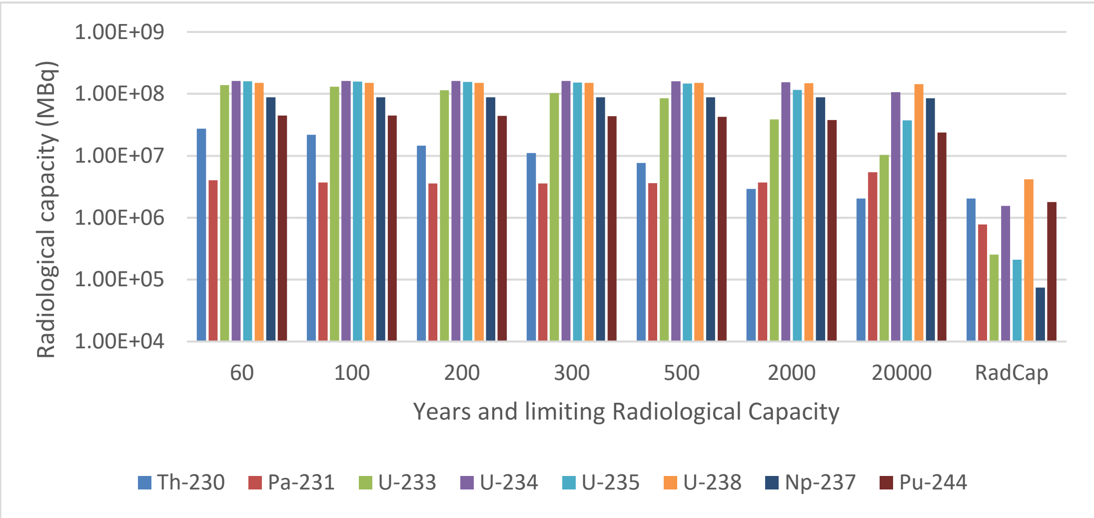
Table 211 Sensitivity of projected dose to exposure time: Erosion – dog walker

Radionuclide	Dose per MBq (73 h per year - default) $\mu Sv\ MBq^{-1}$	Dose per MBq (1 h per month exposure time) $\mu Sv\ MBq^{-1}$	Dose per MBq (300 h per year exposure time) $\mu Sv\ MBq^{-1}$
Ni-59	$2.84\ 10^{-10}$	$4.66\ 10^{-11}$	$1.16\ 10^{-9}$
Se-79	$2.33\ 10^{-8}$	$3.83\ 10^{-9}$	$9.57\ 10^{-8}$
Sr-90	$1.83\ 10^{-8}$	$3.01\ 10^{-9}$	$7.52\ 10^{-8}$
I-129	$1.83\ 10^{-7}$	$3.01\ 10^{-8}$	$7.52\ 10^{-7}$
Sm-147	$1.28\ 10^{-7}$	$2.11\ 10^{-8}$	$5.27\ 10^{-7}$
Sm-151	$3.39\ 10^{-10}$	$5.57\ 10^{-11}$	$1.39\ 10^{-9}$
Pb-210	$1.59\ 10^{-6}$	$2.61\ 10^{-7}$	$6.53\ 10^{-6}$
Ra-226	$1.09\ 10^{-5}$	$1.79\ 10^{-6}$	$4.47\ 10^{-5}$
Ra-228	$4.17\ 10^{-9}$	$6.84\ 10^{-10}$	$1.71\ 10^{-8}$
Ac-227	$6.53\ 10^{-7}$	$1.07\ 10^{-7}$	$2.68\ 10^{-6}$
Th-229	$2.25\ 10^{-6}$	$3.70\ 10^{-7}$	$9.25\ 10^{-6}$
Th-230	$9.86\ 10^{-6}$	$1.62\ 10^{-6}$	$4.05\ 10^{-5}$
Th-232	$6.25\ 10^{-6}$	$1.03\ 10^{-6}$	$2.57\ 10^{-5}$
U-232	$9.44\ 10^{-7}$	$1.55\ 10^{-7}$	$3.88\ 10^{-6}$
Pu-238	$2.68\ 10^{-7}$	$4.40\ 10^{-8}$	$1.10\ 10^{-6}$
Pu-241	$1.21\ 10^{-8}$	$1.98\ 10^{-9}$	$4.95\ 10^{-8}$
Am-241	$3.63\ 10^{-7}$	$5.97\ 10^{-8}$	$1.49\ 10^{-6}$
Am-242m	$4.83\ 10^{-7}$	$7.93\ 10^{-8}$	$1.98\ 10^{-6}$
Cm-242	$1.37\ 10^{-9}$	$2.25\ 10^{-10}$	$5.61\ 10^{-9}$
Cm-243	$8.48\ 10^{-8}$	$1.39\ 10^{-8}$	$3.48\ 10^{-7}$

Radionuclide	Dose per MBq (73 h per year - default) µSv MBq^{-1}	Dose per MBq (1 h per month exposure time) µSv MBq^{-1}	Dose per MBq (300 h per year exposure time) µSv MBq^{-1}
Cm-244	3.20 10^{-8}	5.26 10^{-9}	1.32 10^{-7}
Cm-245	4.04 10^{-7}	6.63 10^{-8}	1.66 10^{-6}
Cm-246	3.96 10^{-7}	6.51 10^{-8}	1.63 10^{-6}

1507. The in-growth of radionuclides following a delay to the onset of erosion is illustrated below (Figure 39) for those radionuclides impacted. The last cluster (RadCap) indicates the lowest scenario radiological capacity from all the capacity limiting scenarios. The figure shows that with the exception of Th-230, radionuclide in-growth would not reduce the radiological capacity of the listed radionuclides to the extent that it would lower the capacity of the site. In the case of Th-230 the radiological capacity (last cluster) is the same as that at 20,000 years indicating this is the lowest value for the scenarios assessed in the ESC.

Figure 39 Impact of delayed onset of erosion on scenario radiological capacity due to in-growth



Impact of including erosion scenarios on radiological capacity

1508. The timing of erosion is uncertain and may not occur at all. The sensitivity to including or not including erosion was investigated for site erosion and subsequent leaching of radionuclides to the sea (Section E.4.8) and for the site erosion: dog walker scenarios (Section E.4.7). The scenario with the lowest scenario radiological capacity if the coastal erosion scenarios are excluded from the scenario radiological capacity assessments is presented in Table 212 for the radionuclides that are impacted.

Table 212 Sensitivity of scenario radiological capacity to erosion occurrence

Radionuclide	Scenario radiological capacity from coastal erosion (MBq)	Lowest scenario radiological capacity if coastal erosion is excluded (MBq)	Scenario with the lowest scenario radiological capacity if coastal erosion is excluded
Se-79	$8.58\ 10^{8}$	$1.24\ 10^{9}$	Seepage Default (bypass, standard cap) All ages - Residential
Nb-94	$7.83\ 10^{7}$	$2.56\ 10^{8}$	ERICA results for Mammals - small-burrowing
Sn-126	$1.37\ 10^{8}$	$2.04\ 10^{8}$	ERICA results for Mammals - small-burrowing
Sm-151	$5.90\ 10^{10}$	$9.31\ 10^{11}$	ERICA results for Mammals - small-burrowing
Eu-152	$6.69\ 10^{9}$	$7.61\ 10^{9}$	ERICA results for Mammals - small-burrowing
Pb-210	$7.84\ 10^{6}$	$4.48\ 10^{8}$	ERICA results for Mammals - small-burrowing
Ra-226	$1.39\ 10^{6}$	$1.32\ 10^{7}$	ERICA results for Mammals - small-burrowing
Ra-228	$4.80\ 10^{9}$	$5.00\ 10^{9}$	Leachate spillage (0y) All ages
Ac-227	$3.06\ 10^{7}$	$2.83\ 10^{8}$	ERICA results for Mammals - small-burrowing
Th-230	$2.03\ 10^{6}$	$2.81\ 10^{6}$	Seepage Default (bypass, standard cap) All ages - Residential
U-232	$2.12\ 10^{7}$	$7.30\ 10^{7}$	Seepage Default (bypass, standard cap) All ages - Residential
Pu-238	$7.47\ 10^{7}$	$7.35\ 10^{8}$	ERICA results for Mammals - small-burrowing
Pu-241	$1.66\ 10^{9}$	$7.80\ 10^{9}$	ERICA results for Mammals - small-burrowing
Am-241	$5.51\ 10^{7}$	$2.51\ 10^{8}$	ERICA results for Mammals - small-burrowing
Am-242m	$4.14\ 10^{7}$	$2.99\ 10^{8}$	ERICA results for Mammals - small-burrowing
Cm-242	$1.46\ 10^{10}$	$1.44\ 10^{11}$	ERICA results for Mammals - small-burrowing
Cm-243	$2.36\ 10^{8}$	$8.59\ 10^{8}$	ERICA results for Mammals - small-burrowing
Cm-244	$6.24\ 10^{8}$	$1.84\ 10^{9}$	Seepage Default (bypass, standard cap) All ages - Residential

1509. For all 18 radionuclides where the erosion scenarios have the lowest scenario radiological capacity, the lowest scenario radiological capacity increases if erosion does not occur. The increase can be quite small, as for Eu-152, and is generally below one order of magnitude. However, large increases are noted for Sm-151 and Pb-210 if coastal erosion does not occur. For most of the radionuclides the scenario with the lowest scenario radiological capacity becomes the Burrowing Mammals scenario. Note that if waste is disposed of below the burrowing depth then this scenario is not relevant.

Impact of increasing erosion rate

1510. The review that Bangor University undertook presented an upper bounding erosion rate of 0.8 m y^{-1} (Bangor University, 2023). The sensitivity of the radiological capacity using this higher rate was considered (see Table 213).

Table 213 Sensitivity of scenario radiological capacity to erosion rate

Radionuclide	Lowest radiological capacity at reference coastal erosion 0.21 m y^{-1} (MBq)	Erosion scenario radiological capacity using higher erosion rate 0.8 m y^{-1} (MBq)	Scenario with lowest scenario radiological capacity at reference erosion rate
Ni-59	$3.44\ 10^{10}$	$1.96\ 10^{10}$	Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth
Se-79	$8.58\ 10^{8}$	$4.82\ 10^{8}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages
Nb-94	$7.83\ 10^{7}$	$2.06\ 10^{7}$	Erosion to coast (60y) All ages (PC-Cream: 0.21)
Sn-126	$1.37\ 10^{8}$	$3.61\ 10^{7}$	Erosion to coast (60y) All ages (PC-Cream: 0.21)
Eu-152	$6.69\ 10^{9}$	$1.75\ 10^{9}$	Erosion to coast (60y) All ages (PC-Cream: 0.21)
Eu-154	$2.08\ 10^{10}$	$1.41\ 10^{10}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)
Pb-210	$7.84\ 10^{6}$	$2.06\ 10^{6}$	Erosion to coast (60y) All ages (PC-Cream: 0.21)
Ra-226	$1.39\ 10^{6}$	$3.65\ 10^{5}$	Erosion to coast (60y) All ages (PC-Cream: 0.21)

1511. For the radionuclides where the erosion to the coast scenario gave the lowest scenario radiological capacity with the reference erosion rate of 0.21 m y^{-1}, the scenario radiological capacity for the higher erosion rate is about 26% of the value calculated using the reference erosion rate (a factor of about 4). The higher erosion rate results in the erosion scenario giving the lowest scenario radiological capacity for three additional radionuclides (Ni-59, Se-79 and Eu-154) but the reduction to the capacity is less in these cases.

E.8.1.4. Leachate spillage

1512. The leachate spillage scenario gives the lowest scenario radiological capacity for 11 radionuclides (see Section E.3.10). If the leachate spillage scenario is not included in the calculation of radiological capacity, the lowest radiological capacities would change as shown in Table 214.

Table 214 Radiological capacity limits if leachate spillage does not occur

Radionuclide	Scenario radiological capacity for leachate spillage (MBq)	Lowest scenario radiological capacity if no leachate spillage (MBq)	Scenario giving lowest scenario radiological capacity if no spillage
Fe-55	$1.96\ 10^{13}$	$4.49\ 10^{15}$	Gas + Ext. (Recreational 0y) All ages Ra-226 at 5m depth
Zn-65	$2.48\ 10^{11}$	$3.46\ 10^{11}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)
Cd-109	$1.39\ 10^{12}$	$1.02\ 10^{13}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)
Sn-119m	$1.05\ 10^{13}$	$7.96\ 10^{14}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)
Sn-123	$3.71\ 10^{12}$	$1.74\ 10^{13}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)

Radionuclide	Scenario radiological capacity for leachate spillage (MBq)	Lowest scenario radiological capacity if no leachate spillage (MBq)	Scenario giving lowest scenario radiological capacity if no spillage
Te-127m	$2.80\ 10^{12}$	$2.71\ 10^{14}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)
Cs-134	$8.46\ 10^{10}$	$9.30\ 10^{10}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)
Ce-144	$8.89\ 10^{12}$	$1.69\ 10^{13}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)
Pm-147	$3.05\ 10^{13}$	$3.19\ 10^{13}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)
Po-210	$8.57\ 10^{9}$	$2.50\ 10^{11}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)
Th-228	$8.11\ 10^{10}$	$3.08\ 10^{10}$	Sewage treatment - worker (0y) 20,158 m3 (WRP)

1513. For seven of these radionuclides, the lowest scenario radiological capacity would increase by an order of magnitude or more if the spillage scenario is excluded. The exceptions are Zn-65, Cs-134, Pm-147 and Th-228 for which the increase is smaller.

1514. It was assumed that the volume of the water body into which leachate spills was 2,000,000 m^3. The sensitivity of dose to this volume was investigated by varying it by a factor of 1.5, and the results shown in Table 215 are for the 11 radionuclides where leachate spillage gives the lowest scenario radiological capacity. The tables show that the change in dose is linear with respect to leachate dilution. No other radionuclides have a lowest scenario radiological capacity from the leachate spillage scenario if the volume of the diluting water is decreased by a factor of 1.5.

Table 215 Sensitivity of projected dose to dilution: Leachate Spillage

Radionuclide	Dose per MBq (default dilution) µSv MBq^{-1}	Dose per MBq (increased dilution) µSv MBq^{-1}	Dose per MBq (decreased dilution) µSv MBq^{-1}
Fe-55	$1.53\ 10^{-11}$	$1.02\ 10^{-11}$	$2.30\ 10^{-11}$
Zn-65	$1.21\ 10^{-9}$	$8.05\ 10^{-10}$	$1.81\ 10^{-9}$
Cd-109	$2.16\ 10^{-10}$	$1.44\ 10^{-10}$	$3.24\ 10^{-10}$
Sn-119m	$2.85\ 10^{-11}$	$1.90\ 10^{-11}$	$4.27\ 10^{-11}$
Sn-123	$8.09\ 10^{-11}$	$5.39\ 10^{-11}$	$1.21\ 10^{-10}$
Te-127m	$1.07\ 10^{-10}$	$7.14\ 10^{-11}$	$1.61\ 10^{-10}$
Cs-134	$3.55\ 10^{-9}$	$2.36\ 10^{-9}$	$5.32\ 10^{-9}$
Ce-144	$3.37\ 10^{-11}$	$2.25\ 10^{-11}$	$5.06\ 10^{-11}$
Pm-147	$9.83\ 10^{-12}$	$6.55\ 10^{-12}$	$1.47\ 10^{-11}$
Po-210	$3.50\ 10^{-8}$	$2.33\ 10^{-8}$	$5.25\ 10^{-8}$
Th-228	$3.70\ 10^{-9}$	$2.47\ 10^{-9}$	$5.55\ 10^{-9}$

1515. If irrigation using water containing spilled leachate did not occur, the scenario radiological capacities would change as shown in Table 216

Table 216 Scenario radiological capacity if irrigation using water incorporating spilled leachate does not occur

Radionuclide	Irrigation			No irrigation		
	Dose per MBq (µSv MBq^{-1})	Age group	Scenario radiological capacity (MBq)	Dose per MBq (µSv MBq^{-1})	Age group	Scenario radiological capacity (MBq)
Fe-55	1.53 10^{-11}	Infant	1.96 10^{13}	1.27 10^{-11}	Infant	2.35 10^{13}
Zn-65	1.21 10^{-9}	Infant	2.48 10^{11}	1.20 10^{-9}	Infant	2.50 10^{11}
Cd-109	2.16 10^{-10}	Infant	1.39 10^{12}	1.69 10^{-10}	Infant	1.78 10^{12}
Sn-119m	2.85 10^{-11}	Infant	1.05 10^{13}	2.76 10^{-11}	Infant	1.09 10^{13}
Sn-123	8.09 10^{-11}	Infant	3.71 10^{12}	7.84 10^{-11}	Infant	3.83 10^{12}
Te-127m	1.07 10^{-10}	Infant	2.80 10^{12}	9.97 10^{-11}	Infant	3.01 10^{12}
Cs-134	3.55 10^{-9}	Adult	8.46 10^{10}	3.50 10^{-9}	Adult	8.57 10^{10}
Ce-144	3.37 10^{-11}	Infant	8.89 10^{12}	1.62 10^{-11}	Infant	1.85 10^{13}
Pm-147	9.83 10^{-12}	Infant	3.05 10^{13}	5.87 10^{-12}	Infant	5.11 10^{13}
Po-210	3.50 10^{-8}	Infant	8.57 10^{9}	2.37 10^{-8}	Infant	1.26 10^{10}
Th-228	3.70 10^{-9}	Infant	8.11 10^{10}	3.21 10^{-9}	Infant	9.35 10^{10}

1516. The greatest increase in radiological capacity is for Ce-144, which increases by a factor of about 2. Smaller increases are observed for other radionuclides showing the irrigation pathway has little impact on the dose incurred.

E.8.1.5. Leachate processing at the WRP

1517. The doses to leachate processing workers at the WRP gives the lowest scenario radiological capacity for nine radionuclides. The amount of liquid that can be processed at the WRP will vary with the weather and other factors relating to the capping of the waste cells. The sensitivity of scenario radiological capacity to the amount of leachate processed on-site is considered in Table 217. The minimum processed between 2019 and 2024 CE is used as a lower value (13,020 m^3) and the upper value is the maximum annual leachate production (25,450 m^3) at Port Clarence over the same period. The value used in the ESC is the average for the period (20,158 m^3).

Table 217 Sensitivity of scenario radiological capacity to volume of leachate: WRP processing

Radionuclide	Scenario radiological capacity (MBq)	Scenario radiological capacity (MBq) with higher volume	Scenario radiological capacity (MBq) with lower volume
Mn-54	3.10 10^{11}	2.07 10^{11}	4.04 10^{11}
Co-60	2.09 10^{10}	1.39 10^{10}	2.72 10^{10}
Ru-106	1.59 10^{11}	1.06 10^{11}	2.08 10^{11}
Ag-110m	3.48 10^{10}	2.32 10^{10}	4.53 10^{10}
Sb-125	2.04 10^{10}	1.36 10^{10}	2.66 10^{10}
Ba-133	2.12 10^{8}	1.55 10^{8}	3.02 10^{8}
Eu-154	2.08 10^{10}	1.39 10^{10}	2.72 10^{10}
Eu-155	9.23 10^{11}	6.16 10^{11}	1.20 10^{12}
Gd-153	3.38 10^{12}	2.26 10^{12}	4.41 10^{12}

1518. Processing the higher volume at the WRP reduces the scenario radiological capacity by a small amount, the change is inversely linear to the amount processed.

E.8.1.6. Recreational use (Gas and external)

1519. The gas and external doses to a recreational user at 0 y (see Section E.4.3) gives the lowest scenario radiological capacity for five radionuclides: C-14, Ni-59, Ni-63, Zr-93 and Nb-93m. The sensitivity of the projected dose as a result of gas generation rate (for H-3 and C-14) and for the exposure time have been examined. The impacts on the projected dose per unit inventory are given in Table 218 using the adult dose to illustrate.

1520. The gas generation rate is increased or decreased by a factor of 1.5. The exposure time for the assessment is 750 h and this has been increased to 1000 h or decreased to 500 h. The impact on doses scales linearly to changes in exposure time and the rate of gas release.

Table 218 Sensitivity of projected dose: Recreational use (0y)

Radionuclide	Dose per MBq (slower gas production)	Dose per MBq (faster gas production)	Dose per MBq (default)	Dose per MBq (longer exposure: 1000 h)	Dose per MBq (shorter exposure: 500 h)
H-3	$3.31\ 10^{-9}$	$7.40\ 10^{-9}$	$4.95\ 10^{-9}$	$6.59\ 10^{-9}$	$3.30\ 10^{-9}$
C-14	$1.12\ 10^{-7}$	$2.53\ 10^{-7}$	$1.69\ 10^{-7}$	$2.25\ 10^{-7}$	$1.12\ 10^{-7}$
Ni-59			$4.65\ 10^{-10}$	$6.20\ 10^{-10}$	$3.10\ 10^{-10}$
Ni-63			$4.21\ 10^{-9}$	$5.61\ 10^{-9}$	$2.81\ 10^{-9}$
Zr-93			$4.98\ 10^{-9}$	$6.64\ 10^{-9}$	$3.32\ 10^{-9}$
Nb-93m			$3.13\ 10^{-10}$	$4.17\ 10^{-10}$	$2.09\ 10^{-10}$

1521. The impact on scenario radiological capacity is shown below and scales inversely to dose in the same manner.

Table 219 Sensitivity of scenario radiological capacity: Recreational use (0y)

Radionuclide	Radiological capacity: MBq (slower gas production)	Radiological capacity: MBq (faster gas production)	Scenario radiological capacity: MBq	Radiological capacity: MBq (longer exposure: 1000 h)	Radiological capacity: MBq (shorter exposure: 500 h)
H-3	$6.05\ 10^{9}$	$2.70\ 10^{9}$	$4.04\ 10^{9}$	$3.03\ 10^{9}$	$6.07\ 10^{9}$
C-14	$1.78\ 10^{8}$	$7.91\ 10^{7}$	$1.19\ 10^{8}$	$8.90\ 10^{7}$	$1.78\ 10^{8}$
Ni-59			$4.30\ 10^{10}$	$3.22\ 10^{10}$	$6.45\ 10^{10}$
Ni-63			$4.75\ 10^{9}$	$3.56\ 10^{9}$	$7.13\ 10^{9}$
Zr-93			$4.01\ 10^{9}$	$3.01\ 10^{9}$	$6.02\ 10^{9}$
Nb-93m			$6.39\ 10^{10}$	$4.79\ 10^{10}$	$9.59\ 10^{10}$

E.8.1.7. Small burrowing mammals

1522. A Tier 2 assessment was performed for burrowing animals that enter the waste. Given the design of the landfill facility and the design of the cap, it seems very unlikely that burrowing animals will build their nesting chambers in the disposed waste.

1523. This scenario gave the lowest scenario radiological capacity for 4 radionuclides. If this scenario is excluded then the lowest scenario radiological capacity for these 4 radionuclides is from erosion scenarios.

1524. One approach is to ensure that LLW containing these radionuclides at the activity concentration limits is buried sufficiently deep that burrowing mammals would not enter the waste. If this is the case, the radiological capacity for these radionuclides will increase to the values presented in Table 220.

Table 220 Radiological capacity for radionuclides if burrowing mammals are not impacted.

Radionuclide	Radiological capacity from burrowing mammals (MBq)	Radiological capacity if burrowing mammals are excluded (MBq)	New limiting scenario
Sr-90	$9.61\ 10^{8}$	$1.09\ 10^{9}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages
Ag-108m	$2.89\ 10^{8}$	$1.99\ 10^{9}$	Erosion to coast (60y) All ages (PC-Cream: 0.21)
Cs-135	$1.43\ 10^{9}$	$1.04\ 10^{10}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages
Cs-137	$1.08\ 10^{9}$	$7.70\ 10^{9}$	Erosion - Dog walker (Combine 60y and 20,000 y) All ages

E.8.1.8. Fire in non-hazardous waste cell

1525. The landfill fire scenario is used in the sum of fractions for disposals to the non-hazardous landfill and this scenario gives the lowest scenario radiological capacity for 18 radionuclides. In practice only Pb-210 disposal will be impacted by the fire scenario radiological capacity because the maximum inventory is smaller than the fire scenario radiological capacity for all radionuclides. If the risk of fires is increased by a factor of two (having the same impact as doubling the fire volume or exposure time) then a further 5 radionuclides (listed in Table 221) would have lower scenario radiological capacities for the fire scenario than for other scenarios. However, in each case the maximum inventory would limit disposals and the maximum impact from the fire would remain lower than the dose constraint.

Table 221 The impact of greater exposure on scenario radiological capacity: landfill fire scenario

Radionuclide	Lowest radiological capacity for other scenarios (MBq)	Maximum inventory (MBq)	Scenario Radiological capacity: fire doubled (MBq)
Se-79	$8.58\ 10^{8}$	$4.39\ 10^{8}$	$7.75\ 10^{8}$
Eu-155	$9.23\ 10^{11}$	$1.10\ 10^{9}$	$7.63\ 10^{11}$
Gd-153	$3.38\ 10^{12}$	$1.10\ 10^{9}$	$1.72\ 10^{12}$
Pu-238	$7.47\ 10^{7}$	$4.39\ 10^{7}$	$4.79\ 10^{7}$
Am-241	$5.51\ 10^{7}$	$2.19\ 10^{7}$	$5.49\ 10^{7}$

E.8.1.9. Trial pit excavator

1526. The dose to a trial pit excavator who uncovers only LLW i.e. a single consignment of 10 t, corresponding to 10 packages, each at the limiting specific activity (see Table 151) was investigated. The highest doses are for Pu-244, Cm-248, Nb-94, Am-243 and Ag-108m which were between 0.5 and 0.73 mSv y^{-1} (see Section E.5.3.2).

1527. Further analysis was undertaken to consider the dose that could occur if a disproportionate amount of activity in a 10 t consignment was in a single package and this was examined for disproportionately longer by the excavator. It is cautiously assumed that there are 10 packages of 1 t each and that 1 package contains the maximum activity concentration for the band with an exposure to this package lasting 4 hours (the remaining exposure time, 16 hours, and activity is split between the other 9 packages). In these circumstances, the dose to the trial pit excavator increases and the highest doses are between 0.59 and 1.06 mSv y^{-1} (see Table 222).

Table 222 Sensitivity to package content in 10 t consignment

Radionuclide	Activity concentration limit (Bq g^{-1})	Dose with all packages at banding (mSv)	Dose with 1 package at banding multiplier (mSv)
Pu-244	200	0.73	1.06
Cm-248	50	0.64	0.92
Nb-94	100	0.55	0.80
Am-243	200	0.51	0.73
Ag-108m	100	0.50	0.72
Pu-240	200	0.50	0.72
Cm-245	200	0.46	0.67
Pu-242	200	0.46	0.66
U-232	50	0.45	0.64
Cm-246	200	0.41	0.59

E.9. Tables of universal model parameters

1528. The following Tables list model parameters that are common to all models used in the assessments.

E.9.1. Radionuclide half-lives and decay constants

Table 223 Radionuclide half-lives and decay constants

Radionuclide	Half-life (y)	Decay constant (y^{-1})
H-3	12.3	$5.63\ 10^{-2}$
C-14	$5.70\ 10^{3}$	$1.22\ 10^{-4}$
Cl-36	$3.01\ 10^{5}$	$2.30\ 10^{-6}$
Ca-41	$1.02\ 10^{5}$	$6.80\ 10^{-6}$
Mn-54	**0.855**	**$8.11\ 10^{-1}$**
Fe-55	2.74	$2.53\ 10^{-1}$
Co-60	5.27	$1.32\ 10^{-1}$
Ni-59	$1.01\ 10^{5}$	$6.86\ 10^{-6}$
Ni-63	100	$6.92\ 10^{-3}$
Zn-65	**0.668**	**$1.04\ 10^{0}$**
Se-79	$2.95\ 10^{5}$	$2.35\ 10^{-6}$
Sr-90	28.8	$2.41\ 10^{-2}$
Mo-93	$4.0\ 10^{3}$	$1.73\ 10^{-4}$
Zr-93	$1.53\ 10^{6}$	$4.53\ 10^{-7}$
Nb-93m	16.1	$4.30\ 10^{-2}$
Nb-94	$2.03\ 10^{4}$	$3.41\ 10^{-5}$
Tc-99	$2.11\ 10^{5}$	$3.28\ 10^{-6}$
Ru-106	**1.02**	**$6.78\ 10^{-1}$**
Ag-108m	418	$1.66\ 10^{-3}$
Ag-110m	**0.684**	**$1.01\ 10^{0}$**
Cd-109	1.26	$5.49\ 10^{-1}$
Sb-125	2.76	$2.51\ 10^{-1}$
Sn-119m	**0.802**	**$8.64\ 10^{-1}$**
Sn-123	**0.354**	**$1.96\ 10^{0}$**
Sn-126	$2.30\ 10^{5}$	$3.01\ 10^{-6}$
Te-127m	**0.290**	**$2.39\ 10^{0}$**
I-129	$1.57\ 10^{7}$	$4.41\ 10^{-8}$
Ba-133	10.5	$6.59\ 10^{-2}$
Cs-134	2.07	$3.36\ 10^{-1}$
Cs-135	$2.30\ 10^{6}$	$3.01\ 10^{-7}$
Cs-137	30.2	$2.30\ 10^{-2}$
Ce-144	**0.780**	**$8.89\ 10^{-1}$**
Pm-147	2.62	$2.64\ 10^{-1}$
Sm-147	$1.06\ 10^{11}$	$6.54\ 10^{-12}$

Radionuclide	Half-life (y)	Decay constant (y^{-1})
Sm-151	90.0	$7.70\ 10^{-3}$
Eu-152	13.5	$5.12\ 10^{-2}$
Eu-154	8.59	$8.07\ 10^{-2}$
Eu-155	4.76	$1.46\ 10^{-1}$
Gd-153	**0.658**	**$1.05\ 10^{0}$**
Pb-210	22.2	$3.12\ 10^{-2}$
Po-210	0.379	$1.83\ 10^{0}$
Ra-226	$1.60\ 10^{3}$	$4.33\ 10^{-4}$
Ra-228	5.75	$1.21\ 10^{-1}$
Ac-227	21.8	$3.18\ 10^{-2}$
Th-228	1.91	$3.63\ 10^{-1}$
Th-229	$7.34\ 10^{3}$	$9.44\ 10^{-5}$
Th-230	$7.54\ 10^{4}$	$9.20\ 10^{-6}$
Th-232	$1.41\ 10^{10}$	$4.93\ 10^{-11}$
Pa-231	$3.28\ 10^{4}$	$2.12\ 10^{-5}$
U-232	68.9	$1.01\ 10^{-2}$
U-233	$1.59\ 10^{5}$	$4.35\ 10^{-6}$
U-234	$2.46\ 10^{5}$	$2.82\ 10^{-6}$
U-235	$7.04\ 10^{8}$	$9.85\ 10^{-10}$
U-236	$2.34\ 10^{7}$	$2.96\ 10^{-8}$
U-238	$4.47\ 10^{9}$	$1.55\ 10^{-10}$
Np-237	$2.14\ 10^{6}$	$3.23\ 10^{-7}$
Pu-238	87.7	$7.90\ 10^{-3}$
Pu-239	$2.41\ 10^{4}$	$2.87\ 10^{-5}$
Pu-240	$6.56\ 10^{3}$	$1.06\ 10^{-4}$
Pu-241	14.4	$4.83\ 10^{-2}$
Pu-242	$3.75\ 10^{5}$	$1.85\ 10^{-6}$
Pu-244	$8.0\ 10^{7}$	$8.66\ 10^{-9}$
Am-241	432	$1.60\ 10^{-3}$
Am-242m	141	$4.92\ 10^{-3}$
Am-243	$7.37\ 10^{3}$	$9.40\ 10^{-5}$
Cm-242	0.446	$1.56\ 10^{0}$
Cm-243	29.1	$2.38\ 10^{-2}$
Cm-244	18.1	$3.83\ 10^{-2}$
Cm-245	$8.50\ 10^{3}$	$8.15\ 10^{-5}$
Cm-246	$4.76\ 10^{3}$	$1.46\ 10^{-4}$
Cm-248	$3.48\ 10^{5}$	$1.99\ 10^{-6}$

From (LLWR Ltd, 2011b) unless marked bold that are from IAEA Isotope Browser

E.9.2. Sorption Distribution coefficients

Table 224 Sorption distribution coefficients for the filling materials in the waste cells, sub-soil to top soil factor and release fraction in a fire

Radionuclide	K_d soil ($m^3\ kg^{-1}$)	K_d clay ($m^3\ kg^{-1}$)	Sub-soil to top soil factor	Release fraction in a fire
H-3	$1.00\ 10^{-4}$	$1.00\ 10^{-4}$	1	1
C-14$	$1.00\ 10^{-1}$	$1.00\ 10^{-3}$	0.0001	1
Cl-36	$3.00\ 10^{-4}$	$2.00\ 10^{-4}$	0.1	1
Ca-41	$8.00\ 10^{-3}$	$7.00\ 10^{-3}$	0.01	0.001
Mn-54	$1.20\ 10^{0}$	$1.30\ 10^{0}$	0.001	0.001
Fe-55	$8.80\ 10^{-1}$	$1.60\ 10^{0}$	0.0001	0.001
Co-60	$4.80\ 10^{-1}$	$3.80\ 10^{0}$	0.001	0.001
Ni-59	$2.80\ 10^{-1}$	$9.80\ 10^{-1}$	0.0001	0.001
Ni-63	$2.80\ 10^{-1}$	$9.80\ 10^{-1}$	0.0001	0.001
Zn-65	$9.50\ 10^{-1}$	$2.40\ 10^{0}$	0.0001	0.1
Se-79	$2.00\ 10^{-1}$	$2.20\ 10^{-1}$	0.0001	1
Sr-90	$5.20\ 10^{-2}$	$6.90\ 10^{-2}$	0.001	0.001
Mo-93	$4.00\ 10^{-2}$	$4.00\ 10^{-2}$	0.01	0.001
Zr-93	$4.10\ 10^{-1}$	$5.00\ 10^{0}$	0.0001	0.001
Nb-93m	$1.50\ 10^{0}$	$2.50\ 10^{0}$	0.0001	0.001
Nb-94	$1.50\ 10^{0}$	$2.50\ 10^{0}$	0.0001	0.001
Tc-99	$1.40\ 10^{-4}$	$4.00\ 10^{-2}$	0.1	0.001
Ru-106	$2.70\ 10^{-1}$	$4.00\ 10^{-1}$	0.001	0.1
Ag-108m	$3.80\ 10^{-1}$	$1.40\ 10^{-1}$	0.001	0.01
Ag-110m	$3.80\ 10^{-1}$	$1.40\ 10^{-1}$	0.001	0.01
Cd-109	$1.50\ 10^{-1}$	$1.10\ 10^{-1}$	0.0001	0.001
Sb-125	$6.20\ 10^{-2}$	$1.40\ 10^{-1}$	0.001	0.1
Sn-119m	$1.60\ 10^{0}$	$2.80\ 10^{-1}$	0.0001	0.001
Sn-123	$1.60\ 10^{0}$	$2.80\ 10^{-1}$	0.0001	0.001
Sn-126	$1.60\ 10^{0}$	$2.80\ 10^{-1}$	0.0001	0.001
Te-127m	$4.80\ 10^{-1}$	$4.80\ 10^{-1}$	0.0001	0.1
I-129	$6.90\ 10^{-3}$	$7.00\ 10^{-3}$	0.01	1
Ba-133	$4.00\ 10^{-4}$	$4.00\ 10^{-4}$	0.0001	0.001
Cs-134	$1.20\ 10^{0}$	$3.70\ 10^{-1}$	0.0001	0.1
Cs-135	$1.20\ 10^{0}$	$3.70\ 10^{-1}$	0.0001	0.1
Cs-137	$1.20\ 10^{0}$	$3.70\ 10^{-1}$	0.0001	0.1
Ce-144	$1.20\ 10^{0}$	$1.80\ 10^{0}$	0.0001	0.001
Pm-147	$4.50\ 10^{-1}$	$4.50\ 10^{-1}$	0.0001	0.001
Sm-147	$9.30\ 10^{-1}$	$6.30\ 10^{-1}$	0.0001	0.001
Sm-151	$9.30\ 10^{-1}$	$6.30\ 10^{-1}$	0.0001	0.001
Eu-152$	$2.40\ 10^{-1}$	$1.00\ 10^{0}$	0.0001	0.001
Eu-154$	$2.40\ 10^{-1}$	$1.00\ 10^{0}$	0.0001	0.001

Radionuclide	K_d soil ($m^3 kg^{-1}$)	K_d clay ($m^3 kg^{-1}$)	Sub-soil to top soil factor	Release fraction in a fire
Eu-155$	$2.40\ 10^{-1}$	$1.00\ 10^{0}$	0.0001	0.001
Gd-153$	$4.90\ 10^{-1}$	$4.30\ 10^{1}$	0.0001	0.001
Pb-210	$2.00\ 10^{0}$	$1.30\ 10^{1}$	0.0001	0.5
Po-210	$2.10\ 10^{-1}$	$1.90\ 10^{-1}$	0.0001	0.001
Ra-226	$2.50\ 10^{0}$	$3.80\ 10^{1}$	0.0001	0.001
Ra-228	$2.50\ 10^{0}$	$3.80\ 10^{1}$	0.0001	0.001
Ac-227	$1.70\ 10^{0}$	$1.20\ 10^{0}$	0.0001	0.001
Th-228	$1.90\ 10^{0}$	$4.50\ 10^{0}$	0.0001	0.001
Th-229	$1.90\ 10^{0}$	$4.50\ 10^{0}$	0.0001	0.001
Th-230	$1.90\ 10^{0}$	$4.50\ 10^{0}$	0.0001	0.001
Th-232	$1.90\ 10^{0}$	$4.50\ 10^{0}$	0.0001	0.001
Pa-231	$2.00\ 10^{0}$	$1.40\ 10^{0}$	0.0001	0.001
U-232	$2.00\ 10^{-1}$	$1.80\ 10^{-1}$	0.001	0.001
U-233	$2.00\ 10^{-1}$	$1.80\ 10^{-1}$	0.001	0.001
U-234	$2.00\ 10^{-1}$	$1.80\ 10^{-1}$	0.001	0.001
U-235	$2.00\ 10^{-1}$	$1.80\ 10^{-1}$	0.001	0.001
U-236	$2.00\ 10^{-1}$	$1.80\ 10^{-1}$	0.001	0.001
U-238	$2.00\ 10^{-1}$	$1.80\ 10^{-1}$	0.001	0.001
Np-237	$3.50\ 10^{-2}$	$2.00\ 10^{-2}$	0.01	0.001
Pu-238	$7.40\ 10^{-1}$	$1.10\ 10^{0}$	0.0001	0.001
Pu-239	$7.40\ 10^{-1}$	$1.10\ 10^{0}$	0.0001	0.001
Pu-240	$7.40\ 10^{-1}$	$1.10\ 10^{0}$	0.0001	0.001
Pu-241	$7.40\ 10^{-1}$	$1.10\ 10^{0}$	0.0001	0.001
Pu-242	$7.40\ 10^{-1}$	$1.10\ 10^{0}$	0.0001	0.001
Pu-244	$7.40\ 10^{-1}$	$1.10\ 10^{0}$	0.0001	0.001
Am-241	$2.60\ 10^{0}$	$4.30\ 10^{0}$	0.0001	0.001
Am-242m	$2.60\ 10^{0}$	$4.30\ 10^{0}$	0.0001	0.001
Am-243	$2.60\ 10^{0}$	$4.30\ 10^{0}$	0.0001	0.001
Cm-242	$9.30\ 10^{0}$	$9.30\ 10^{0}$	0.0001	0.001
Cm-243	$9.30\ 10^{0}$	$9.30\ 10^{0}$	0.0001	0.001
Cm-244	$9.30\ 10^{0}$	$9.30\ 10^{0}$	0.0001	0.001
Cm-245	$9.30\ 10^{0}$	$9.30\ 10^{0}$	0.0001	0.001
Cm-246	$9.30\ 10^{0}$	$9.30\ 10^{0}$	0.0001	0.001
Cm-248	$9.30\ 10^{0}$	$9.30\ 10^{0}$	0.0001	0.001

$Values from (Augean, 2009a). Gd-153 based on Ce-144 values in (SNIFFER, 2006). All other data from the IAEA handbook of parameter values (IAEA, 2010).
Sub-soil to Topsoil transfer derived from (Wheater, et al., 2007).
Fire release fraction from (European Commission, 1995).

E.9.3. Dose Coefficients

Table 225 Radionuclide dose coefficients for ingestion and inhalation for adult, child and infant

Radionuclide	Ingestion - adult ($Sv\ Bq^{-1}$)	Ingestion - child ($Sv\ Bq^{-1}$)	Ingestion - infant ($Sv\ Bq^{-1}$)	Inhalation - adult ($Sv\ Bq^{-1}$)	Inhalation - child ($Sv\ Bq^{-1}$)	Inhalation - infant ($Sv\ Bq^{-1}$)
H-3	$1.80\ 10^{-11}$	$2.60\ 10^{-10}$	$2.30\ 10^{-11}$	$3.80\ 10^{-10}$	$4.80\ 10^{-11}$	$1.00\ 10^{-9}$
C-14	$5.80\ 10^{-10}$	$5.80\ 10^{-9}$	$8.00\ 10^{-10}$	$7.40\ 10^{-9}$	$1.60\ 10^{-9}$	$1.70\ 10^{-8}$
Cl-36	$9.30\ 10^{-10}$	$7.30\ 10^{-9}$	$1.90\ 10^{-9}$	$1.00\ 10^{-8}$	$6.30\ 10^{-9}$	$2.60\ 10^{-8}$
Ca-41	$1.90\ 10^{-10}$	$1.80\ 10^{-10}$	$4.80\ 10^{-10}$	$3.30\ 10^{-10}$	$5.20\ 10^{-10}$	$6.00\ 10^{-10}$
Mn-54	$7.10\ 10^{-10}$	$1.50\ 10^{-9}$	$1.30\ 10^{-9}$	$2.40\ 10^{-9}$	$3.10\ 10^{-9}$	$6.20\ 10^{-9}$
Fe-55	$3.30\ 10^{-10}$	$7.70\ 10^{-10}$	$1.10\ 10^{-9}$	$1.40\ 10^{-9}$	$2.40\ 10^{-9}$	$3.20\ 10^{-9}$
Co-60	$3.40\ 10^{-9}$	$3.10\ 10^{-8}$	$1.10\ 10^{-8}$	$4.00\ 10^{-8}$	$2.70\ 10^{-8}$	$8.60\ 10^{-8}$
Ni-59	$6.30\ 10^{-11}$	$4.40\ 10^{-10}$	$1.10\ 10^{-10}$	$5.90\ 10^{-10}$	$3.40\ 10^{-10}$	$1.50\ 10^{-9}$
Ni-63	$1.50\ 10^{-10}$	$1.30\ 10^{-9}$	$2.80\ 10^{-10}$	$1.70\ 10^{-9}$	$8.40\ 10^{-10}$	$4.30\ 10^{-9}$
Zn-65	$3.90\ 10^{-9}$	$2.20\ 10^{-9}$	$6.40\ 10^{-9}$	$3.80\ 10^{-9}$	$1.60\ 10^{-8}$	$1.00\ 10^{-8}$
Se-79	$2.90\ 10^{-9}$	$6.80\ 10^{-9}$	$1.40\ 10^{-8}$	$8.70\ 10^{-9}$	$2.80\ 10^{-8}$	$2.00\ 10^{-8}$
Sr-90	$3.07\ 10^{-8}$	$1.62\ 10^{-7}$	$6.59\ 10^{-8}$	$1.83\ 10^{-7}$	$9.30\ 10^{-8}$	$4.09\ 10^{-7}$
Mo-93	$3.10\ 10^{-9}$	$2.30\ 10^{-9}$	$4.00\ 10^{-9}$	$2.80\ 10^{-9}$	$6.90\ 10^{-9}$	$5.80\ 10^{-9}$
Zr-93	$1.10\ 10^{-9}$	$2.50\ 10^{-8}$	$5.80\ 10^{-10}$	$9.70\ 10^{-9}$	$7.60\ 10^{-10}$	$6.40\ 10^{-9}$
Nb-93m	$1.20\ 10^{-10}$	$1.80\ 10^{-9}$	$2.70\ 10^{-10}$	$2.50\ 10^{-9}$	$9.10\ 10^{-10}$	$6.50\ 10^{-9}$
Nb-94	$1.70\ 10^{-9}$	$4.90\ 10^{-8}$	$3.40\ 10^{-9}$	$5.80\ 10^{-8}$	$9.70\ 10^{-9}$	$1.20\ 10^{-7}$
Tc-99	$6.40\ 10^{-10}$	$1.30\ 10^{-8}$	$1.30\ 10^{-9}$	$1.70\ 10^{-8}$	$4.80\ 10^{-9}$	$3.70\ 10^{-8}$
Ru-106	$7.00\ 10^{-9}$	$6.60\ 10^{-8}$	$1.50\ 10^{-8}$	$9.10\ 10^{-8}$	$4.90\ 10^{-8}$	$2.30\ 10^{-7}$
Ag-108m	$2.30\ 10^{-9}$	$3.70\ 10^{-8}$	$4.30\ 10^{-9}$	$4.40\ 10^{-8}$	$1.10\ 10^{-8}$	$8.70\ 10^{-8}$
Ag-110m	$2.80\ 10^{-9}$	$1.20\ 10^{-8}$	$5.20\ 10^{-9}$	$1.80\ 10^{-8}$	$1.40\ 10^{-8}$	$4.10\ 10^{-8}$
Cd-109	$2.00\ 10^{-9}$	$8.10\ 10^{-9}$	$3.50\ 10^{-9}$	$1.40\ 10^{-8}$	$9.50\ 10^{-9}$	$3.70\ 10^{-8}$
Sb-125	$1.30\ 10^{-9}$	$1.30\ 10^{-8}$	$2.53\ 10^{-9}$	$1.73\ 10^{-8}$	$7.54\ 10^{-9}$	$4.10\ 10^{-8}$
Sn-119m	$3.40\ 10^{-10}$	$2.20\ 10^{-9}$	$7.50\ 10^{-10}$	$3.10\ 10^{-9}$	$2.50\ 10^{-9}$	$7.90\ 10^{-9}$
Sn-123	$2.10\ 10^{-9}$	$8.10\ 10^{-9}$	$4.60\ 10^{-9}$	$1.20\ 10^{-8}$	$1.60\ 10^{-8}$	$3.10\ 10^{-8}$
Sn-126	$5.07\ 10^{-9}$	$2.85\ 10^{-8}$	$1.06\ 10^{-8}$	$4.18\ 10^{-8}$	$3.22\ 10^{-8}$	$1.02\ 10^{-7}$
Te-127m	$2.30\ 10^{-9}$	$9.80\ 10^{-9}$	$5.20\ 10^{-9}$	$1.40\ 10^{-8}$	$1.80\ 10^{-8}$	$3.30\ 10^{-8}$

Radionuclide	Ingestion - adult (Sv Bq^{-1})	Ingestion - child (Sv Bq^{-1})	Ingestion - infant (Sv Bq^{-1})	Inhalation - adult (Sv Bq^{-1})	Inhalation - child (Sv Bq^{-1})	Inhalation - infant (Sv Bq^{-1})
I-129	1.10 10^{-7}	3.60 10^{-8}	1.90 10^{-7}	6.70 10^{-8}	2.20 10^{-7}	8.60 10^{-8}
Ba-133	1.50 10^{-9}	1.00 10^{-8}	4.60 10^{-9}	1.30 10^{-8}	6.20 10^{-9}	2.90 10^{-8}
Cs-134	1.90 10^{-8}	2.00 10^{-8}	1.40 10^{-8}	2.80 10^{-8}	1.60 10^{-8}	6.30 10^{-8}
Cs-135	2.00 10^{-9}	8.60 10^{-9}	1.70 10^{-9}	1.10 10^{-8}	2.30 10^{-9}	2.40 10^{-8}
Cs-137	1.30 10^{-8}	3.90 10^{-8}	1.00 10^{-8}	4.80 10^{-8}	1.20 10^{-8}	1.00 10^{-7}
Ce-144	5.20 10^{-9}	5.30 10^{-8}	1.10 10^{-8}	7.80 10^{-8}	3.90 10^{-8}	2.70 10^{-7}
Pm-147	2.60 10^{-10}	5.00 10^{-9}	5.70 10^{-10}	7.00 10^{-9}	1.90 10^{-9}	1.80 10^{-8}
Sm-147	4.90 10^{-8}	9.60 10^{-6}	6.40 10^{-8}	1.10 10^{-5}	1.40 10^{-7}	2.30 10^{-5}
Sm-151	9.80 10^{-11}	4.00 10^{-9}	2.00 10^{-10}	4.50 10^{-9}	6.40 10^{-10}	1.00 10^{-8}
Eu-152	1.40 10^{-9}	4.20 10^{-8}	2.60 10^{-9}	4.90 10^{-8}	7.40 10^{-9}	1.00 10^{-7}
Eu-154	2.00 10^{-9}	5.30 10^{-8}	4.10 10^{-9}	6.50 10^{-8}	1.20 10^{-8}	1.50 10^{-7}
Eu-155	3.20 10^{-10}	6.90 10^{-9}	6.80 10^{-10}	9.20 10^{-9}	2.20 10^{-9}	2.30 10^{-8}
Gd-153	2.70 10^{-10}	2.10 10^{-9}	5.80 10^{-10}	3.90 10^{-9}	1.80 10^{-9}	1.20 10^{-8}
Pb-210	1.89 10^{-6}	9.99 10^{-6}	4.50 10^{-6}	1.32 10^{-5}	1.24 10^{-5}	3.23 10^{-5}
Po-210	1.20 10^{-6}	4.30 10^{-6}	2.60 10^{-6}	5.90 10^{-6}	8.80 10^{-6}	1.40 10^{-5}
Ra-226	2.17 10^{-6}	1.95 10^{-5}	5.30 10^{-6}	2.53 10^{-5}	1.34 10^{-5}	6.14 10^{-5}
Ra-228	8.34 10^{-7}	5.96 10^{-5}	4.32 10^{-6}	7.98 10^{-5}	6.80 10^{-6}	2.08 10^{-4}
Ac-227	1.21 10^{-6}	5.69 10^{-4}	1.98 10^{-6}	7.45 10^{-4}	4.29 10^{-6}	1.65 10^{-3}
Th-228	1.43 10^{-7}	4.36 10^{-5}	4.21 10^{-7}	5.97 10^{-5}	1.09 10^{-6}	1.60 10^{-4}
Th-229	6.13 10^{-7}	2.56 10^{-4}	1.17 10^{-6}	3.11 10^{-4}	2.38 10^{-6}	5.55 10^{-4}
Th-230	2.10 10^{-7}	1.00 10^{-4}	2.40 10^{-7}	1.10 10^{-4}	4.10 10^{-7}	2.00 10^{-4}
Th-232	1.06 10^{-6}	1.70 10^{-4}	4.61 10^{-6}	2.10 10^{-4}	7.25 10^{-6}	4.28 10^{-4}
Pa-231	7.10 10^{-7}	1.40 10^{-4}	9.20 10^{-7}	1.50 10^{-4}	1.30 10^{-6}	2.30 10^{-4}
U-232	4.73 10^{-7}	8.06 10^{-5}	9.91 10^{-7}	1.03 10^{-4}	1.91 10^{-6}	2.57 10^{-4}
U-233	5.10 10^{-8}	9.60 10^{-6}	7.80 10^{-8}	1.20 10^{-5}	1.40 10^{-7}	3.00 10^{-5}
U-234	4.90 10^{-8}	9.40 10^{-6}	7.40 10^{-8}	1.20 10^{-5}	1.30 10^{-7}	2.90 10^{-5}
U-235	4.73 10^{-8}	8.50 10^{-6}	7.17 10^{-8}	1.10 10^{-5}	1.33 10^{-7}	2.60 10^{-5}
U-236	4.70 10^{-8}	8.70 10^{-6}	7.00 10^{-8}	1.10 10^{-5}	1.30 10^{-7}	2.70 10^{-5}
U-238	4.84 10^{-8}	8.01 10^{-6}	7.54 10^{-8}	1.00 10^{-5}	1.45 10^{-7}	2.50 10^{-5}
Np-237	1.11 10^{-7}	5.00 10^{-5}	1.12 10^{-7}	5.00 10^{-5}	2.16 10^{-7}	9.30 10^{-5}
Pu-238	2.30 10^{-7}	1.10 10^{-4}	2.40 10^{-7}	1.10 10^{-4}	4.00 10^{-7}	1.90 10^{-4}

Radionuclide	Ingestion - adult (Sv Bq^{-1})	Ingestion - child (Sv Bq^{-1})	Ingestion - infant (Sv Bq^{-1})	Inhalation - adult (Sv Bq^{-1})	Inhalation - child (Sv Bq^{-1})	Inhalation - infant (Sv Bq^{-1})
Pu-239	$2.50\ 10^{-7}$	$1.20\ 10^{-4}$	$2.70\ 10^{-7}$	$1.20\ 10^{-4}$	$4.20\ 10^{-7}$	$2.00\ 10^{-4}$
Pu-240	$2.50\ 10^{-7}$	$1.20\ 10^{-4}$	$2.70\ 10^{-7}$	$1.20\ 10^{-4}$	$4.20\ 10^{-7}$	$2.00\ 10^{-4}$
Pu-241	$4.80\ 10^{-9}$	$2.30\ 10^{-6}$	$5.10\ 10^{-9}$	$2.40\ 10^{-6}$	$5.70\ 10^{-9}$	$2.90\ 10^{-6}$
Pu-242	$2.40\ 10^{-7}$	$1.10\ 10^{-4}$	$2.60\ 10^{-7}$	$1.20\ 10^{-4}$	$4.00\ 10^{-7}$	$1.90\ 10^{-4}$
Pu-244	$2.41\ 10^{-7}$	$1.10\ 10^{-4}$	$2.62\ 10^{-7}$	$1.20\ 10^{-4}$	$4.18\ 10^{-7}$	$1.90\ 10^{-4}$
Am-241	$2.00\ 10^{-7}$	$9.60\ 10^{-5}$	$2.20\ 10^{-7}$	$1.00\ 10^{-4}$	$3.70\ 10^{-7}$	$1.80\ 10^{-4}$
Am-242m	$2.42\ 10^{-7}$	$1.16\ 10^{-4}$	$2.65\ 10^{-7}$	$1.21\ 10^{-4}$	$4.34\ 10^{-7}$	$2.00\ 10^{-4}$
Am-243	$2.01\ 10^{-7}$	$9.60\ 10^{-5}$	$2.22\ 10^{-7}$	$1.00\ 10^{-4}$	$3.76\ 10^{-7}$	$1.70\ 10^{-4}$
Cm-242	$1.20\ 10^{-8}$	$5.90\ 10^{-6}$	$2.40\ 10^{-8}$	$8.20\ 10^{-6}$	$7.60\ 10^{-8}$	$2.10\ 10^{-5}$
Cm-243	$1.51\ 10^{-7}$	$6.93\ 10^{-5}$	$1.61\ 10^{-7}$	$7.33\ 10^{-5}$	$3.31\ 10^{-7}$	$1.50\ 10^{-4}$
Cm-244	$1.20\ 10^{-7}$	$5.70\ 10^{-5}$	$1.40\ 10^{-7}$	$6.10\ 10^{-5}$	$2.90\ 10^{-7}$	$1.30\ 10^{-4}$
Cm-245	$2.10\ 10^{-7}$	$9.90\ 10^{-5}$	$2.30\ 10^{-7}$	$1.00\ 10^{-4}$	$3.70\ 10^{-7}$	$1.80\ 10^{-4}$
Cm-246	$2.10\ 10^{-7}$	$9.80\ 10^{-5}$	$2.20\ 10^{-7}$	$1.00\ 10^{-4}$	$3.70\ 10^{-7}$	$1.80\ 10^{-4}$
Cm-248	$7.70\ 10^{-7}$	$3.60\ 10^{-4}$	$8.40\ 10^{-7}$	$3.70\ 10^{-4}$	$1.40\ 10^{-6}$	$6.50\ 10^{-4}$

Note: Ingestion and Inhalation doses from (ICRP, 2012). External Irradiation doses from (US EPA, 2018)

Table 226 Radionuclide dose coefficients for cloud immersion and external dose from a slab

Radionuclide	Irradiation cloudshine (adult) (Sv h^{-1} Bq^{-1} m^{3})	Irradiation cloudshine (child) (Sv h^{-1} Bq^{-1} m^{3})	Irradiation cloudshine (infant) (Sv h^{-1} Bq^{-1} m^{3})	Irradiation slab (adult) (Sv y^{-1} Bq^{-1} kg)	Irradiation slab (child) (Sv y^{-1} Bq^{-1} kg)	Irradiation slab (infant) (Sv y^{-1} Bq^{-1} kg)
H-3	1.37 10^{-16}	1.54 10^{-16}	1.70 10^{-16}	1.72 10^{-12}	1.90 10^{-12}	2.12 10^{-12}
C-14	1.39 10^{-13}	1.55 10^{-13}	1.71 10^{-13}	1.59 10^{-9}	1.75 10^{-9}	1.95 10^{-9}
Cl-36	2.32 10^{-12}	2.54 10^{-12}	2.76 10^{-12}	2.13 10^{-8}	2.34 10^{-8}	2.61 10^{-8}
Ca-41	0	0	0	0	0	0
Mn-54	1.36 10^{-10}	1.54 10^{-10}	1.71 10^{-10}	1.31 10^{-6}	1.44 10^{-6}	1.62 10^{-6}
Fe-55	2.35 10^{-20}	2.73 10^{-20}	3.10 10^{-20}	1.70 10^{-16}	1.92 10^{-16}	2.19 10^{-16}
Co-60	4.25 10^{-10}	4.75 10^{-10}	5.22 10^{-10}	4.17 10^{-6}	4.58 10^{-6}	5.10 10^{-6}
Ni-59	2.46 10^{-15}	2.80 10^{-15}	3.11 10^{-15}	2.28 10^{-11}	2.53 10^{-11}	2.85 10^{-11}
Ni-63	1.66 10^{-14}	1.87 10^{-14}	2.07 10^{-14}	2.07 10^{-10}	2.28 10^{-10}	2.54 10^{-10}
Zn-65	9.68 10^{-11}	1.09 10^{-10}	1.20 10^{-10}	9.44 10^{-7}	1.04 10^{-6}	1.16 10^{-6}
Se-79	1.56 10^{-13}	1.74 10^{-13}	1.91 10^{-13}	1.76 10^{-9}	1.94 10^{-9}	2.17 10^{-9}
Sr-90	1.29 10^{-11}	1.42 10^{-11}	1.54 10^{-11}	1.27 10^{-7}	1.39 10^{-7}	1.55 10^{-7}
Mo-93	4.46 10^{-14}	9.90 10^{-14}	1.34 10^{-13}	8.58 10^{-11}	2.07 10^{-10}	2.64 10^{-10}
Zr-93	1.97 10^{-14}	2.21 10^{-14}	2.46 10^{-14}	2.44 10^{-10}	2.70 10^{-10}	3.00 10^{-10}
Nb-93m	7.99 10^{-15}	1.77 10^{-14}	2.40 10^{-14}	1.53 10^{-11}	3.69 10^{-11}	4.71 10^{-11}
Nb-94	2.55 10^{-10}	2.88 10^{-10}	3.20 10^{-10}	2.43 10^{-6}	2.69 10^{-6}	3.01 10^{-6}
Tc-99	5.26 10^{-13}	5.76 10^{-13}	6.30 10^{-13}	5.10 10^{-9}	5.66 10^{-9}	6.26 10^{-9}
Ru-106	5.29 10^{-11}	5.90 10^{-11}	6.52 10^{-11}	5.10 10^{-7}	5.66 10^{-7}	6.31 10^{-7}
Ag-108m	2.57 10^{-10}	2.92 10^{-10}	3.24 10^{-10}	2.41 10^{-6}	2.67 10^{-6}	3.00 10^{-6}
Ag-110m	4.57 10^{-10}	5.11 10^{-10}	5.69 10^{-10}	4.38 10^{-6}	4.84 10^{-6}	5.40 10^{-6}
Cd-109	6.48 10^{-13}	9.43 10^{-13}	1.16 10^{-12}	3.23 10^{-9}	4.05 10^{-9}	4.86 10^{-9}
Sb-125	6.79 10^{-11}	7.74 10^{-11}	8.61 10^{-11}	6.22 10^{-7}	6.93 10^{-7}	7.79 10^{-7}
Sn-119m	2.35 10^{-13}	3.92 10^{-13}	5.08 10^{-13}	5.81 10^{-10}	8.99 10^{-10}	1.27 10^{-9}
Sn-123	6.59 10^{-12}	7.27 10^{-12}	7.92 10^{-12}	6.31 10^{-8}	6.97 10^{-8}	7.73 10^{-8}
Sn-126	3.23 10^{-10}	3.68 10^{-10}	4.09 10^{-10}	3.03 10^{-6}	3.36 10^{-6}	3.77 10^{-6}
Te-127m	3.43 10^{-13}	5.00 10^{-13}	6.30 10^{-13}	1.44 10^{-9}	1.82 10^{-9}	2.35 10^{-9}
I-129	9.14 10^{-13}	1.31 10^{-12}	1.69 10^{-12}	3.98 10^{-9}	4.99 10^{-9}	6.51 10^{-9}
Ba-133	5.62 10^{-11}	6.48 10^{-11}	7.34 10^{-11}	4.86 10^{-7}	5.45 10^{-7}	6.16 10^{-7}

Radionuclide	Irradiation cloudshine (adult) (Sv h^{-1} Bq^{-1} m^3)	Irradiation cloudshine (child) (Sv h^{-1} Bq^{-1} m^3)	Irradiation cloudshine (infant) (Sv h^{-1} Bq^{-1} m^3)	Irradiation slab (adult) (Sv y^{-1} Bq^{-1} kg)	Irradiation slab (child) (Sv y^{-1} Bq^{-1} kg)	Irradiation slab (infant) (Sv y^{-1} Bq^{-1} kg)
Cs-134	$2.53\ 10^{-10}$	$2.86\ 10^{-10}$	$3.18\ 10^{-10}$	$2.40\ 10^{-6}$	$2.66\ 10^{-6}$	$2.98\ 10^{-6}$
Cs-135	$4.28\ 10^{-13}$	$4.72\ 10^{-13}$	$5.15\ 10^{-13}$	$4.25\ 10^{-9}$	$4.68\ 10^{-9}$	$5.20\ 10^{-9}$
Cs-137	$9.18\ 10^{-11}$	$1.04\ 10^{-10}$	$1.16\ 10^{-10}$	$8.66\ 10^{-7}$	$9.58\ 10^{-7}$	$1.08\ 10^{-6}$
Ce-144	$2.84\ 10^{-12}$	$3.33\ 10^{-12}$	$3.78\ 10^{-12}$	$2.13\ 10^{-8}$	$2.41\ 10^{-8}$	$2.75\ 10^{-8}$
Pm-147	$2.30\ 10^{-13}$	$2.55\ 10^{-13}$	$2.79\ 10^{-13}$	$2.43\ 10^{-9}$	$2.68\ 10^{-9}$	$2.98\ 10^{-9}$
Sm-147	0	0	0	0	0	0
Sm-151	$2.26\ 10^{-14}$	$2.55\ 10^{-14}$	$2.83\ 10^{-14}$	$2.79\ 10^{-10}$	$3.08\ 10^{-10}$	$3.43\ 10^{-10}$
Eu-152	$1.92\ 10^{-10}$	$2.16\ 10^{-10}$	$2.39\ 10^{-10}$	$1.82\ 10^{-6}$	$2.01\ 10^{-6}$	$2.24\ 10^{-6}$
Eu-154	$2.07\ 10^{-10}$	$2.33\ 10^{-10}$	$2.58\ 10^{-10}$	$1.98\ 10^{-6}$	$2.19\ 10^{-6}$	$2.44\ 10^{-6}$
Eu-155	$7.13\ 10^{-12}$	$8.78\ 10^{-12}$	$1.03\ 10^{-11}$	$4.78\ 10^{-8}$	$5.50\ 10^{-8}$	$6.36\ 10^{-8}$
Gd-153	$9.97\ 10^{-12}$	$1.24\ 10^{-11}$	$1.51\ 10^{-11}$	$5.96\ 10^{-8}$	$6.97\ 10^{-8}$	$8.23\ 10^{-8}$
Pb-210	$3.84\ 10^{-12}$	$4.26\ 10^{-12}$	$4.64\ 10^{-12}$	$3.54\ 10^{-8}$	$3.90\ 10^{-8}$	$4.35\ 10^{-8}$
Po-210	$1.58\ 10^{-15}$	$1.79\ 10^{-15}$	$1.99\ 10^{-15}$	$1.51\ 10^{-11}$	$1.68\ 10^{-11}$	$1.88\ 10^{-11}$
Ra-226	$7.87\ 10^{-10}$	$8.76\ 10^{-10}$	$9.68\ 10^{-10}$	$7.61\ 10^{-6}$	$8.38\ 10^{-6}$	$9.28\ 10^{-6}$
Ra-228	$4.09\ 10^{-10}$	$4.54\ 10^{-10}$	$4.99\ 10^{-10}$	$3.95\ 10^{-6}$	$4.33\ 10^{-6}$	$4.78\ 10^{-6}$
Ac-227	$6.70\ 10^{-11}$	$7.71\ 10^{-11}$	$8.72\ 10^{-11}$	$5.76\ 10^{-7}$	$6.43\ 10^{-7}$	$7.23\ 10^{-7}$
Th-228	$2.63\ 10^{-10}$	$2.90\ 10^{-10}$	$3.17\ 10^{-10}$	$2.55\ 10^{-6}$	$2.80\ 10^{-6}$	$3.07\ 10^{-6}$
Th-229	$5.17\ 10^{-11}$	$5.95\ 10^{-11}$	$6.70\ 10^{-11}$	$4.47\ 10^{-7}$	$5.00\ 10^{-7}$	$5.62\ 10^{-7}$
Th-230	$4.50\ 10^{-14}$	$6.30\ 10^{-14}$	$7.49\ 10^{-14}$	$3.14\ 10^{-10}$	$3.72\ 10^{-10}$	$4.31\ 10^{-10}$
Th-232	$4.09\ 10^{-10}$	$4.54\ 10^{-10}$	$4.99\ 10^{-10}$	$3.95\ 10^{-6}$	$4.34\ 10^{-6}$	$4.78\ 10^{-6}$
Pa-231	$5.04\ 10^{-12}$	$5.83\ 10^{-12}$	$6.62\ 10^{-12}$	$4.29\ 10^{-8}$	$4.81\ 10^{-8}$	$5.40\ 10^{-8}$
U-232	$6.51\ 10^{-10}$	$7.15\ 10^{-10}$	$7.79\ 10^{-10}$	$6.37\ 10^{-6}$	$6.97\ 10^{-6}$	$7.63\ 10^{-6}$
U-233	$3.49\ 10^{-14}$	$4.46\ 10^{-14}$	$5.33\ 10^{-14}$	$2.49\ 10^{-10}$	$2.89\ 10^{-10}$	$3.32\ 10^{-10}$
U-234	$1.85\ 10^{-14}$	$2.90\ 10^{-14}$	$3.71\ 10^{-14}$	$9.49\ 10^{-11}$	$1.23\ 10^{-10}$	$1.48\ 10^{-10}$
U-235	$2.57\ 10^{-11}$	$2.98\ 10^{-11}$	$3.39\ 10^{-11}$	$2.04\ 10^{-7}$	$2.30\ 10^{-7}$	$2.59\ 10^{-7}$
U-236	$1.11\ 10^{-14}$	$1.92\ 10^{-14}$	$2.52\ 10^{-14}$	$4.71\ 10^{-11}$	$6.66\ 10^{-11}$	$8.18\ 10^{-11}$
U-238	$1.38\ 10^{-11}$	$1.54\ 10^{-11}$	$1.70\ 10^{-11}$	$1.32\ 10^{-7}$	$1.46\ 10^{-7}$	$1.62\ 10^{-7}$
Np-237	$3.54\ 10^{-11}$	$4.09\ 10^{-11}$	$4.65\ 10^{-11}$	$2.95\ 10^{-7}$	$3.30\ 10^{-7}$	$3.72\ 10^{-7}$
Pu-238	$9.18\ 10^{-15}$	$1.83\ 10^{-14}$	$2.46\ 10^{-14}$	$2.67\ 10^{-11}$	$4.68\ 10^{-11}$	$5.96\ 10^{-11}$

Radionuclide	Irradiation cloudshine (adult) (Sv h^{-1} Bq^{-1} m^3)	Irradiation cloudshine (child) (Sv h^{-1} Bq^{-1} m^3)	Irradiation cloudshine (infant) (Sv h^{-1} Bq^{-1} m^3)	Irradiation slab (adult) (Sv y^{-1} Bq^{-1} kg)	Irradiation slab (child) (Sv y^{-1} Bq^{-1} kg)	Irradiation slab (infant) (Sv y^{-1} Bq^{-1} kg)
Pu-239	$1.19\ 10^{-14}$	$1.71\ 10^{-14}$	$2.12\ 10^{-14}$	$7.42\ 10^{-11}$	$9.09\ 10^{-11}$	$1.06\ 10^{-10}$
Pu-240	$9.07\ 10^{-15}$	$1.77\ 10^{-14}$	$2.38\ 10^{-14}$	$2.76\ 10^{-11}$	$4.69\ 10^{-11}$	$5.96\ 10^{-11}$
Pu-241	$3.96\ 10^{-16}$	$4.57\ 10^{-16}$	$5.18\ 10^{-16}$	$3.79\ 10^{-12}$	$4.24\ 10^{-12}$	$4.76\ 10^{-12}$
Pu-242	$2.11\ 10^{-14}$	$3.00\ 10^{-14}$	$3.64\ 10^{-14}$	$1.56\ 10^{-10}$	$1.85\ 10^{-10}$	$2.10\ 10^{-10}$
Pu-244	$6.33\ 10^{-11}$	$7.15\ 10^{-11}$	$7.88\ 10^{-11}$	$5.99\ 10^{-7}$	$6.64\ 10^{-7}$	$7.40\ 10^{-7}$
Am-241	$1.80\ 10^{-12}$	$2.57\ 10^{-12}$	$3.15\ 10^{-12}$	$1.11\ 10^{-8}$	$1.34\ 10^{-8}$	$1.61\ 10^{-8}$
Am-242m	$3.52\ 10^{-12}$	$4.07\ 10^{-12}$	$4.61\ 10^{-12}$	$2.79\ 10^{-8}$	$3.13\ 10^{-8}$	$3.53\ 10^{-8}$
Am-243	$3.15\ 10^{-11}$	$3.75\ 10^{-11}$	$4.31\ 10^{-11}$	$2.41\ 10^{-7}$	$2.73\ 10^{-7}$	$3.10\ 10^{-7}$
Cm-242	$1.04\ 10^{-14}$	$2.01\ 10^{-14}$	$2.68\ 10^{-14}$	$2.99\ 10^{-11}$	$5.20\ 10^{-11}$	$6.56\ 10^{-11}$
Cm-243	$1.86\ 10^{-11}$	$2.14\ 10^{-11}$	$2.45\ 10^{-11}$	$1.46\ 10^{-7}$	$1.64\ 10^{-7}$	$1.84\ 10^{-7}$
Cm-244	$1.14\ 10^{-14}$	$1.99\ 10^{-14}$	$2.59\ 10^{-14}$	$5.05\ 10^{-11}$	$7.17\ 10^{-11}$	$8.63\ 10^{-11}$
Cm-245	$1.39\ 10^{-11}$	$1.62\ 10^{-11}$	$1.87\ 10^{-11}$	$9.80\ 10^{-8}$	$1.11\ 10^{-7}$	$1.26\ 10^{-7}$
Cm-246	$6.55\ 10^{-13}$	$7.31\ 10^{-13}$	$8.03\ 10^{-13}$	$6.31\ 10^{-9}$	$6.92\ 10^{-9}$	$7.67\ 10^{-9}$
Cm-248	$2.37\ 10^{-10}$	$2.62\ 10^{-10}$	$2.87\ 10^{-10}$	$2.30\ 10^{-6}$	$2.52\ 10^{-6}$	$2.78\ 10^{-6}$

Note: Cloudshine and External Irradiation doses for a slab from (US EPA, 2018)

Table 227 Radionuclide external dose coefficients and attenuation coefficients for soil

Radionuclide	Gamma skin dose (7 mg cm^{-2}) (Sv h^{-1} Bq^{-1} cm^{2})	Beta skin dose (4 mg cm-2) (Sv h^{-1} Bq^{-1} cm^{2})	Beta skin dose (40 mg cm-2) (Sv h^{-1} Bq^{-1} cm^{2})	Attenuation coefficient (m^{-1})*
H-3	0	0	0	0
C-14	0	9.02 10^{-7}	0	-5.59 10^{1}
Cl-36	1.10 10^{-11}	2.51 10^{-6}	5.37 10^{-7}	-2.04 10^{1}
Ca-41	0	0	0	0
Mn-54	6.10 10^{-8}	0	0	-1.36 10^{1}
Fe-55	1.60 10^{-8}	0	0	0
Co-60	1.30 10^{-7}	1.83 10^{-6}	2.85 10^{-8}	-1.20 10^{1}
Ni-59	6.39 10^{-8}	0	0	0
Ni-63	0	1.83 10^{-8}	0	0
Zn-65	5.00 10^{-8}	3.77 10^{-8}	1.14 10^{-9}	-1.26 10^{1}
Se-79	0	1.14 10^{-6}	0	-5.40 10^{1}
Sr-90	2.40 10^{-12}	5.14 10^{-6}	1.76 10^{-6}	-1.85 10^{1}
Mo-93	2.13 10^{-8}	0	0	0
Zr-93	1.51 10^{-10}	4.80 10^{-7}	0	0
Nb-93m	3.69 10^{-9}	0	0	0
Nb-94	1.00 10^{-7}	2.17 10^{-6}	1.83 10^{-7}	-1.38 10^{1}
Tc-99	3.49 10^{-14}	1.60 10^{-6}	1.37 10^{-8}	-3.85 10^{1}
Ru-106	1.20 10^{-8}	2.85 10^{-6}	1.60 10^{-6}	-1.47 10^{1}
Ag-108m	1.28 10^{-7}	2.76 10^{-7}	1.15 10^{-7}	-1.49 10^{1}
Ag-110m	1.50 10^{-7}	8.24 10^{-7}	8.22 10^{-6}	-1.32 10^{1}
Cd-109	1.70 10^{-8}	2.05 10^{-6}	0	-4.13 10^{1}
Sb-125	3.51 10^{-8}	1.73 10^{-6}	8.45 10^{-8}	-1.54 10^{1}
Sn-119m	7.20 10^{-9}	8.56 10^{-7}	0	-3.47 10^{2}
Sn-123	0	0	0	-1.33 10^{1}
Sn-126	1.33 10^{-7}	4.54 10^{-6}	1.43 10^{-6}	-1.46 10^{1}
Te-127m	6.72 10^{-10}	1.83 10^{-6}	1.07 10^{-8}	-3.05 10^{1}
I-129	9.70 10^{-9}	6.51 10^{-7}	0	-1.31 10^{2}
Ba-133	0	0	0	-1.79 10^{1}

Radionuclide	Gamma skin dose (7 mg cm^{-2}) ($Sv\ h^{-1}\ Bq^{-1}\ cm^2$)	Beta skin dose (4 mg cm-2) ($Sv\ h^{-1}\ Bq^{-1}\ cm^2$)	Beta skin dose (40 mg cm-2) ($Sv\ h^{-1}\ Bq^{-1}\ cm^2$)	Attenuation coefficient (m^{-1})*
Cs-134	$8.80\ 10^{-8}$	$1.83\ 10^{-6}$	$3.08\ 10^{-7}$	$-1.42\ 10^{1}$
Cs-135	0	$1.10\ 10^{-6}$	$5.71\ 10^{-11}$	$-4.65\ 10^{1}$
Cs-137	$3.31\ 10^{-8}$	$2.54\ 10^{-6}$	$3.92\ 10^{-7}$	$-1.45\ 10^{1}$
Ce-144	$4.10\ 10^{-9}$	$4.45\ 10^{-6}$	$1.50\ 10^{-6}$	$-2.77\ 10^{1}$
Pm-147	$4.90\ 10^{-13}$	$1.26\ 10^{-6}$	$4.11\ 10^{-10}$	$-3.73\ 10^{1}$
Sm-147	0	0	0	0
Sm-151	$6.40\ 10^{-12}$	$2.85\ 10^{-8}$	0	$-4.66\ 10^{2}$
Eu-152	$1.18\ 10^{-7}$	$1.60\ 10^{-6}$	$1.71\ 10^{-7}$	$-1.30\ 10^{1}$
Eu-154	$9.02\ 10^{-8}$	$3.42\ 10^{-6}$	$3.77\ 10^{-7}$	$-1.29\ 10^{1}$
Eu-155	$1.77\ 10^{-8}$	$8.68\ 10^{-7}$	$3.20\ 10^{-10}$	$-3.37\ 10^{1}$
Gd-153	$6.30\ 10^{-9}$	$4.00\ 10^{-7}$	0	$-3.57\ 10^{1}$
Pb-210	$8.30\ 10^{-9}$	$2.63\ 10^{-6}$	$8.45\ 10^{-7}$	$-1.39\ 10^{1}$
Po-210	$4.80\ 10^{-13}$	0	0	$-1.39\ 10^{1}$
Ra-226	$1.64\ 10^{-7}$	$8.53\ 10^{-6}$	$2.49\ 10^{-6}$	$-1.18\ 10^{1}$
Ra-228	$5.78\ 10^{-8}$	$3.08\ 10^{-6}$	$7.19\ 10^{-7}$	$-1.03\ 10^{1}$
Ac-227	$3.81\ 10^{-8}$	$6.59\ 10^{-6}$	$2.00\ 10^{-6}$	$-1.47\ 10^{1}$
Th-228	$1.06\ 10^{-7}$	$6.34\ 10^{-6}$	$1.22\ 10^{-6}$	$-1.03\ 10^{1}$
Th-229	$7.31\ 10^{-8}$	$8.56\ 10^{-6}$	$1.36\ 10^{-6}$	$-1.21\ 10^{1}$
Th-230	$3.83\ 10^{-9}$	$1.04\ 10^{-7}$	0	$-2.93\ 10^{1}$
Th-232	$1.65\ 10^{-7}$	$9.46\ 10^{-8}$	$1.94\ 10^{-6}$	$-1.03\ 10^{1}$
Pa-231	$6.27\ 10^{-8}$	$1.48\ 10^{-7}$	$5.14\ 10^{-9}$	$-1.91\ 10^{1}$
U-232	$9.36\ 10^{-8}$	$6.38\ 10^{-6}$	$1.22\ 10^{-6}$	$-1.03\ 10^{1}$
U-233	$1.70\ 10^{-9}$	$5.25\ 10^{-7}$	0	$-2.29\ 10^{1}$
U-234	$2.70\ 10^{-9}$	$7.42\ 10^{-9}$	0	$-3.58\ 10^{1}$
U-235	$5.31\ 10^{-8}$	$2.52\ 10^{-6}$	$1.09\ 10^{-8}$	$-2.32\ 10^{1}$
U-236	$3.55\ 10^{-9}$	$4.57\ 10^{-9}$	0	$-3.16\ 10^{1}$
U-238	$9.70\ 10^{-9}$	$3.82\ 10^{-6}$	$1.26\ 10^{-6}$	$-1.36\ 10^{1}$
Np-237	$5.50\ 10^{-8}$	$3.46\ 10^{-6}$	$9.93\ 10^{-8}$	$-1.93\ 10^{1}$
Pu-238	$2.70\ 10^{-9}$	$1.06\ 10^{-7}$	0	$-3.73\ 10^{1}$

Radionuclide	Gamma skin dose (7 mg cm^{-2}) ($Sv\ h^{-1}\ Bq^{-1}\ cm^2$)	Beta skin dose (4 mg cm-2) ($Sv\ h^{-1}\ Bq^{-1}\ cm^2$)	Beta skin dose (40 mg cm-2) ($Sv\ h^{-1}\ Bq^{-1}\ cm^2$)	Attenuation coefficient (m^{-1})*
Pu-239	$1.00\ 10^{-9}$	$4.34\ 10^{-10}$	0	$-2.18\ 10^{1}$
Pu-240	$2.60\ 10^{-9}$	0	0	$-4.44\ 10^{1}$
Pu-241	$3.30\ 10^{-12}$	0	0	$-2.96\ 10^{1}$
Pu-242	$3.07\ 10^{-9}$	0	0	$-5.58\ 10^{1}$
Pu-244	$1.70\ 10^{-8}$	$2.64\ 10^{-6}$	$1.06\ 10^{-6}$	$-1.41\ 10^{1}$
Am-241	$1.70\ 10^{-8}$	$5.48\ 10^{-8}$	0	$-5.37\ 10^{1}$
Am-242m	$1.95\ 10^{-8}$	$1.94\ 10^{-6}$	$2.97\ 10^{-7}$	$-1.30\ 10^{1}$
Am-243	$4.60\ 10^{-8}$	$4.24\ 10^{-6}$	$1.37\ 10^{-7}$	$-2.29\ 10^{1}$
Cm-242	$2.40\ 10^{-9}$	0	0	$-3.16\ 10^{1}$
Cm-243	$2.75\ 10^{-8}$	$1.94\ 10^{-6}$	$3.42\ 10^{-8}$	$-2.29\ 10^{1}$
Cm-244	$2.20\ 10^{-9}$	0	0	$-3.52\ 10^{2}$
Cm-245	$9.55\ 10^{-8}$	$9.82\ 10^{-7}$	0	$-2.79\ 10^{1}$
Cm-246	$2.52\ 10^{-9}$	0	0	$-1.29\ 10^{2}$
Cm-248	$2.32\ 10^{-9}$	0	0	$-3.26\ 10^{2}$

Table 228 External dose coefficients for different thicknesses of contamination in a semi-infinite slab

Radionuclide	Point Source air kerma$ (mSv h-1 per Bq)	Semi-infinite slab dose coefficients (mSv h^{-1} per Bq kg^{-1} at 1600 kg/m^3)			
		Top 1 cm	Top 5 cm	Top 15 cm	Uniform
Am-241	2.14 10^{-12}	5.72 10^{-10}	1.16 10^{-9}	1.27 10^{-9}	1.27 10^{-9}
Pu-241	2.54 10^{-16}	9.62 10^{-14}	2.71 10^{-13}	3.95 10^{-13}	4.33 10^{-13}
Pu-239	1.63 10^{-14}	2.74 10^{-12}	6.16 10^{-12}	8.12 10^{-12}	8.47 10^{-12}
Eu-152	1.15 10^{-10}	3.92 10^{-8}	1.14 10^{-7}	1.80 10^{-7}	2.08 10^{-7}
Cs-137+Ba-137m	6.65 10^{-11}	1.97 10^{-8}	5.68 10^{-8}	8.83 10^{-8}	9.88 10^{-8}
Sr-90+Y-90	3.82 10^{-11}	3.09 10^{-9}	7.96 10^{-9}	1.24 10^{-8}	1.45 10^{-8}
Ni-63	0	4.35 10^{-12}	1.27 10^{-11}	2.03 10^{-11}	2.36 10^{-11}
Co-60	2.71 10^{-10}	8.41 10^{-8}	2.48 10^{-7}	3.99 10^{-7}	4.75 10^{-7}
Fe-55	1.51 10^{-13}	5.04 10^{-18}	1.42 10^{-17}	1.92 10^{-17}	1.94 10^{-17}
C-14	0	3.34 10^{-11}	9.79 10^{-11}	1.56 10^{-10}	1.81 10^{-10}
H-3	0	3.63 10^{-14}	1.07 10^{-13}	1.69 10^{-13}	1.96 10^{-13}

$ RP65 (European Commission, 1993) others from (US EPA, 2018).

Table 229 Radionuclide dose coefficients from IAEA SR44 for landfill workers

Radionuclide	Worker on a landfill (Sv y^{-1} Bq^{-1} g)$	Worker handling a load (Sv y^{-1} Bq^{-1} g)$
H-3	0	0
C-14	0	0
Cl-36	0	0
Ca-41	0	0
Mn-54	1.48 10^{-1}	3.59 10^{-2}
Fe-55	0	0
Co-60	4.65 10^{-1}	1.13 10^{-1}
Ni-59	0	0
Ni-63	0	0
Zn-65	1.06 10^{-1}	2.59 10^{-2}
Se-79	nd	nd
Sr-90	0	0
Mo-93	4.13 10^{-9}	0
Zr-93	6.22 10^{-10}	0
Nb-93m	6.27 10^{-10}	0
Nb-94	2.77 10^{-1}	6.71 10^{-2}
Tc-99	4.31 10^{-8}	2.13 10^{-10}
Ru-106	2.24 10^{-2}	5.29 10^{-3}
Ag-108m	2.71 10^{-1}	6.43 10^{-2}
Ag-110m	4.87 10^{-1}	1.18 10^{-1}
Cd-109	2.87 10^{-4}	1.22 10^{-6}
Sb-125	6.86 10^{-2}	1.59 10^{-2}
Sn-119m	nd	nd
Sn-123	nd	nd
Sn-126	3.35 10^{-1}	7.90 10^{-2}
Te-127m	7.70 10^{-4}	1.64 10^{-4}
I-129	7.15 10^{-5}	0

Radionuclide	Worker on a landfill (Sv y^{-1} Bq^{-1} g)$	Worker handling a load (Sv y^{-1} Bq^{-1} g)$
Ba-133	$5.15\ 10^{-2}$	$1.04\ 10^{-2}$
Cs-134	$2.69\ 10^{-1}$	$6.48\ 10^{-2}$
Cs-135	0	0
Cs-137	$1.02\ 10^{-1}$	$2.45\ 10^{-2}$
Ce-144	$7.35\ 10^{-3}$	$1.44\ 10^{-3}$
Pm-147	$3.66\ 10^{-7}$	$1.71\ 10^{-8}$
Sm-147	nd	nd
Sm-151	$1.60\ 10^{-9}$	0
Eu-152	$1.98\ 10^{-1}$	$4.67\ 10^{-2}$
Eu-154	$2.21\ 10^{-1}$	$5.24\ 10^{-2}$
Eu-155	$4.34\ 10^{-3}$	$4.95\ 10^{-5}$
Gd-153	$5.70\ 10^{-3}$	$5.34\ 10^{-5}$
Pb-210	nd	nd
Po-210	nd	nd
Ra-226	nd	nd
Ra-228	nd	nd
Ac-227	nd	nd
Th-228	nd	nd
Th-229	$4.20\ 10^{-2}$	$7.73\ 10^{-3}$
Th-230	nd	nd
Th-232	nd	nd
Pa-231	nd	nd
U-232	$2.56\ 10^{-1}$	$5.78\ 10^{-2}$
U-233	$4.14\ 10^{-4}$	$7.31\ 10^{-5}$
U-234	nd	nd
U-235	nd	nd
U-236	$4.20\ 10^{-6}$	$1.22\ 10^{-9}$
U-238	nd	nd
Np-237	$3.10\ 10^{-2}$	$5.36\ 10^{-3}$
Pu-238	$9.18\ 10^{-7}$	$4.77\ 10^{-11}$
Pu-239	$5.32\ 10^{-6}$	$1.84\ 10^{-7}$
Pu-240	$9.51\ 10^{-7}$	$1.31\ 10^{-13}$
Pu-241	$2.64\ 10^{-5}$	$7.11\ 10^{-11}$
Pu-242	$9.25\ 10^{-7}$	$1.67\ 10^{-13}$
Pu-244	$4.26\ 10^{-2}$	$1.02\ 10^{-2}$
Am-241	$8.93\ 10^{-4}$	$2.40\ 10^{-9}$
Am-242m	$1.69\ 10^{-3}$	$1.36\ 10^{-4}$
Am-243	$2.28\ 10^{-2}$	$2.38\ 10^{-3}$
Cm-242	$9.42\ 10^{-7}$	$2.07\ 10^{-13}$
Cm-243	$1.51\ 10^{-2}$	$1.92\ 10^{-3}$
Cm-244	$6.10\ 10^{-7}$	$1.14\ 10^{-13}$
Cm-245	$6.95\ 10^{-3}$	$3.05\ 10^{-4}$
Cm-246	$2.20\ 10^{-7}$	$3.65\ 10^{-17}$
Cm-248	$5.37\ 10^{-7}$	$9.42\ 10^{-14}$

$ Dose conversion factors account for short-lived daughters [see (IAEA, 2005)].

E.9.4. Crop and animal transfer parameters

Table 230 Uptake factors for various crops (Bq kg^{-1} fresh crop per Bq kg^{-1} soil)

Element	Grain	Green Vegetables	Root Vegetables	Pasture
H	$1.00\ 10^{-2}$	$5.00\ 10^{0}$	$5.00\ 10^{0}$	$5.00\ 10^{0}$
C	$1.60\ 10^{-1}$	$1.00\ 10^{-1}$	$1.00\ 10^{-1}$	$1.00\ 10^{-1}$
Cl	$8.80\ 10^{-2}$	$5.00\ 10^{0}$	$5.00\ 10^{0}$	$5.00\ 10^{0}$
Ca	$8.00\ 10^{-2}$	$5.00\ 10^{-1}$	$5.00\ 10^{-1}$	$5.00\ 10^{-1}$
Mn	$2.44\ 10^{-1}$	$4.10\ 10^{-2}$	$8.40\ 10^{-2}$	$1.92\ 10^{-1}$
Fe	$1.74\ 10^{-4}$	$1.00\ 10^{-4}$	$2.00\ 10^{-4}$	$6.00\ 10^{-4}$
Co	$8.70\ 10^{-3}$	$1.70\ 10^{-2}$	$2.20\ 10^{-2}$	$2.31\ 10^{-2}$
Ni	$2.35\ 10^{-2}$	$3.00\ 10^{-2}$	$3.00\ 10^{-2}$	$5.10\ 10^{-2}$
Zn	$1.57\ 10^{0}$	$2.40\ 10^{-1}$	$6.00\ 10^{-2}$	$3.00\ 10^{-1}$
Se	$1.00\ 10^{0}$	$1.00\ 10^{0}$	$1.00\ 10^{0}$	$1.00\ 10^{0}$
Sr	$2.78\ 10^{-1}$	$7.60\ 10^{-2}$	$1.44\ 10^{-1}$	$2.73\ 10^{-1}$
Mo	$6.96\ 10^{-1}$	$5.10\ 10^{-2}$	$6.40\ 10^{-2}$	$5.40\ 10^{0}$
Zr	$8.70\ 10^{-4}$	$4.00\ 10^{-4}$	$8.00\ 10^{-4}$	$3.00\ 10^{-3}$
Nb	$1.22\ 10^{-2}$	$1.70\ 10^{-3}$	$3.40\ 10^{-3}$	$6.00\ 10^{-3}$
Tc	$1.00\ 10^{1}$	$1.00\ 10^{1}$	$1.00\ 10^{1}$	$1.00\ 10^{1}$
Ru	$2.61\ 10^{-3}$	$9.00\ 10^{-3}$	$2.00\ 10^{-3}$	$4.00\ 10^{-2}$
Ag	$8.80\ 10^{-2}$	$1.80\ 10^{-5}$	$2.60\ 10^{-4}$	$1.50\ 10^{-1}$
Cd	$7.66\ 10^{-1}$	$5.50\ 10^{-1}$	$3.00\ 10^{-1}$	$2.10\ 10^{0}$
Sb	$1.57\ 10^{-3}$	$9.40\ 10^{-6}$	$1.24\ 10^{-4}$	$1.00\ 10^{-2}$
Sn	$2.00\ 10^{-1}$	$1.00\ 10^{-1}$	$1.00\ 10^{-1}$	$2.00\ 10^{-1}$
Te	$8.70\ 10^{-2}$	$3.00\ 10^{-2}$	$6.00\ 10^{-2}$	$3.00\ 10^{-1}$
I	$5.48\ 10^{-4}$	$6.50\ 10^{-4}$	$2.00\ 10^{-2}$	$1.11\ 10^{-3}$
Ba	$8.70\ 10^{-4}$	$5.00\ 10^{-4}$	$1.00\ 10^{-3}$	$6.00\ 10^{-1}$
Cs	$2.87\ 10^{-2}$	$6.00\ 10^{-3}$	$1.12\ 10^{-2}$	$1.89\ 10^{-2}$
Ce	$2.70\ 10^{-3}$	$6.00\ 10^{-4}$	$1.20\ 10^{-3}$	$6.00\ 10^{-3}$
Pm	$1.22\ 10^{-2}$	$3.00\ 10^{-3}$	$8.40\ 10^{-3}$	$3.00\ 10^{-3}$
Sm	$4.80\ 10^{-2}$	$2.00\ 10^{-3}$	$2.00\ 10^{-3}$	$2.00\ 10^{-3}$
Eu	$4.80\ 10^{-2}$	$3.00\ 10^{-3}$	$3.00\ 10^{-3}$	$3.00\ 10^{-3}$
Gd	$4.80\ 10^{-2}$	$1.00\ 10^{-3}$	$6.00\ 10^{-4}$	$2.00\ 10^{-2}$
Pb	$9.57\ 10^{-3}$	$8.00\ 10^{-3}$	$3.00\ 10^{-3}$	$9.30\ 10^{-2}$
Po	$2.09\ 10^{-4}$	$7.40\ 10^{-4}$	$1.16\ 10^{-3}$	$3.60\ 10^{-2}$
Ra	$1.48\ 10^{-2}$	$9.10\ 10^{-3}$	$1.40\ 10^{-2}$	$3.90\ 10^{-2}$
Ac	$1.00\ 10^{-3}$	$1.00\ 10^{-3}$	$1.00\ 10^{-3}$	$1.00\ 10^{-3}$
Th	$1.83\ 10^{-3}$	$1.20\ 10^{-4}$	$1.60\ 10^{-4}$	$1.26\ 10^{-2}$
Pa	$4.00\ 10^{-2}$	$4.00\ 10^{-2}$	$4.00\ 10^{-2}$	$4.00\ 10^{-2}$
U	$1.31\ 10^{-2}$	$2.00\ 10^{-3}$	$1.68\ 10^{-3}$	$5.10\ 10^{-3}$
Np	$4.18\ 10^{-3}$	$2.70\ 10^{-3}$	$4.40\ 10^{-3}$	$9.30\ 10^{-3}$
Pu	$8.27\ 10^{-6}$	$8.30\ 10^{-6}$	$7.80\ 10^{-5}$	$4.80\ 10^{-5}$
Am	$1.91\ 10^{-5}$	$2.70\ 10^{-5}$	$1.34\ 10^{-4}$	$9.90\ 10^{-3}$
Cm	$2.00\ 10^{-5}$	$1.40\ 10^{-4}$	$1.70\ 10^{-4}$	$3.00\ 10^{-4}$

Shaded values from TRS 472 (IAEA, 2010), others from (Eden NE, 2023) based on (Augean, 2009a). Gd based on Ce values in (SNIFFER, 2006).

Table 231 Transfer factors for animal produce

	Transfer factor		
Element	Meat (d kg^{-1})	Milk (d kg^{-1})	Fish (m^3 kg^{-1})
H	2.90 10^{-2}	1.00 10^{-2}	1.00 10^{-3}
C	1.20 10^{-1}	1.00 10^{-2}	9.00 10^{0}
Cl	1.70 10^{-2}	1.70 10^{-2}	9.50 10^{-2}
Ca	1.30 10^{-2}	1.00 10^{-2}	1.00 10^{0}
Mn	6.00 10^{-4}	4.10 10^{-5}	4.50 10^{-1}
Fe	1.40 10^{-2}	3.50 10^{-5}	1.40 10^{-1}
Co	4.30 10^{-4}	1.10 10^{-4}	4.00 10^{-1}
Ni	5.00 10^{-3}	9.50 10^{-4}	7.10 10^{-2}
Zn	1.60 10^{-1}	2.70 10^{-3}	4.70 10^{0}
Se	7.00 10^{-3}	4.00 10^{-3}	6.90 10^{0}
Sr	1.30 10^{-3}	1.30 10^{-3}	1.90 10^{-1}
Mo	1.00 10^{-3}	1.10 10^{-3}	2.70 10^{-2}
Zr	1.20 10^{-6}	3.60 10^{-6}	9.50 10^{-2}
Nb	2.60 10^{-7}	4.10 10^{-7}	3.00 10^{-1}
Tc	1.00 10^{-4}	2.30 10^{-5}	2.00 10^{-2}
Ru	3.30 10^{-3}	9.40 10^{-6}	1.00 10^{-2}
Ag	3.00 10^{-5}	5.00 10^{-5}	1.10 10^{-1}
Cd	5.80 10^{-3}	1.90 10^{-4}	1.00 10^{-1}
Sb	1.20 10^{-3}	3.80 10^{-5}	7.10 10^{-2}
Sn	1.90 10^{-3}	1.00 10^{-3}	1.00 10^{0}
Te	7.00 10^{-3}	3.40 10^{-4}	4.20 10^{-1}
I	6.70 10^{-3}	5.40 10^{-3}	6.50 10^{-1}
Ba	1.40 10^{-4}	1.60 10^{-4}	4.70 10^{-2}
Cs	2.20 10^{-2}	4.60 10^{-3}	3.00 10^{0}
Ce	2.00 10^{-5}	2.00 10^{-5}	1.20 10^{-2}
Pm	5.00 10^{-3}	2.00 10^{-5}	3.00 10^{-2}
Sm	5.10 10^{-4}	2.00 10^{-5}	3.00 10^{-2}
Eu	4.70 10^{-4}	5.00 10^{-5}	1.50 10^{-1}
Gd	2.00 10^{-5}	3.00 10^{-5}	3.00 10^{-2}
Pb	7.00 10^{-4}	1.90 10^{-4}	3.70 10^{-1}
Po	5.00 10^{-3}	2.10 10^{-4}	5.00 10^{-2}
Ra	1.70 10^{-3}	3.80 10^{-4}	2.10 10^{-1}
Ac	1.60 10^{-4}	4.00 10^{-7}	3.00 10^{-2}
Th	2.30 10^{-4}	5.00 10^{-6}	1.90 10^{-1}
Pa	5.00 10^{-5}	5.00 10^{-6}	1.00 10^{-2}
U	3.90 10^{-4}	2.00 10^{-4}	2.40 10^{-3}
Np	1.00 10^{-3}	5.00 10^{-6}	1.00 10^{-2}
Pu	1.10 10^{-6}	1.00 10^{-5}	4.00 10^{-3}
Am	5.00 10^{-4}	4.20 10^{-7}	3.00 10^{-2}
Cm	4.00 10^{-5}	1.50 10^{-6}	8.00 10^{-1}

* Shaded values from IAEA 472 (IAEA, 2010), others from (Eden NE, 2023) Gd based on Ce values in (SNIFFER, 2006).

Appendix F. Description of the GNU Octave model

APPENDIX F. DESCRIPTION OF THE GNU OCTAVE MODEL 565
F.1. CL-36 MODEL 567
F.1.1. RESULTS AND COMPARISON WITH GOLDSIM MODEL 570
F.2. RA-226 MODEL 571
F.2.1. RESULTS AND COMPARISON WITH GOLDSIM MODEL 575

1. GNU Octave (an open source multi-purpose maths analysis programme) comes with a numerical solver for a set of coupled linear ordinary differential equations (lsode).

$$\frac{d\bar{x}}{dt} = f(\bar{x}, t)$$

Where: $\bar{x}$ is a vector with elements x_1, x_2, … x_n.

2. Our confidence building model is based on some simplified assumptions:

- Cap and liner are not taken into account. Flow rates (sub-vertical $q_{leachate}$, subhorizontal $q_{aquifer}$ and overtopping $q_{breakout}$) are constant in time and modelled for two periods: before bathtubbing and during bathtubbing.
- One radionuclide (and if applicable its daughter) is modelled at a time. The models are for disposals of unit inventory (1 MBq) of each (parent) radionuclide.
- The model parameters used were those for the northern area of the proposed western extension (phases 12 to 14).

3. It is possible to refine this model further, for example by using time dependent flow or modelling migration through the aquifer. However, this was not within the scope of the confidence building exercise. Parameter values have been taken from the GoldSim model.

4. The flow rates (q, $m^3\ y^{-1}$) driving advective transport are:

$$q_{leachate} = A_{basal} \cdot K_{Clay} \cdot \frac{h}{d_{barrier}}$$

$$q_{aquifer} = W_{Aquifer} \cdot d_{Aquifer} \cdot K_{limestone} \cdot Grad$$

$$q_{breakout} = A_{surface} \cdot P_{grassland} - q_{leachate}$$

with:

- A_{basal} the basal area of the landfill (m^2);
- K_{clay} the hydraulic conductivity of clay ($m\ y^{-1}$);
- h the head of water in the waste cells (m) (taken to be 1 m before bathtubbing and 4 m during bathtubbing);

- $d_{barrier}$ the thickness of the clay barrier (m);
- $W_{Aquifer}$ the width of the aquifer strip (m);
- $d_{Aquifer}$ the thickness of the aquifer (m);
- $K_{limestone}$ the hydraulic conductivity of limestone (m y^{-1})
- *Grad* the hydraulic gradient (dimensionless);
- $A_{surface}$ the surface area of the landfill (m^2); and,
- $P_{grassland}$ the rate of infiltration to grassland (m y^{-1}).

5. The time at which bathtubbing and breakout occur (t_{bt}) is calculated independently of GoldSim. It is the time at which the volume of leachate in the landfill is equal to the pore volume in the waste cell below the top of the clay barrier.

6. It is given by integrating the change in volume of water in the repository with respect to time to derive an expression that gives the time at which a specified leachate volume is reached:

$$\int_0^t \frac{dV}{dt}dt = \int_0^t F - kV\,dt = \frac{F}{k}(1 - e^{-k \cdot t}) = A_{basal} \cdot d_t \cdot \varepsilon$$

which gives:

$$t = \frac{\ln(1 - k \cdot A_{basal} \cdot d_t \cdot \varepsilon / F)}{-k}$$

where:

- t is time (y);
- V is the volume of water in the waste cell (m^3);
- F is the rate of inflow into the landfill (cap design infiltration multiplied by cap surface area) (m^3 y^{-1});
- k is a simplifying constant, given by $K_{clay}/(d_{barrier} \cdot \varepsilon)$ (y^{-1});
- K_{clay} is the hydraulic conductivity of clay (m y^{-1});
- $d_{barrier}$ is the thickness of the clay barrier (m);
- ε is the porosity of the waste cell (considering both waste and soil) (dimensionless);
- A_{basal} is the basal area of the landfill (m^2);
- d_t is the head of leachate at time t (m).

7. The expression in paragraph 6 is then used to calculate:

- the time at which overtopping would occur without the period of active management (t_{bt0}) (d_t is the height of the low-permeability basin);
- the time that would be taken to reach to reach the managed head level (if less than the duration of management – 60 y) (t_{mh}) (d_t is the managed leachate head).

8. The time at which bathtubbing and breakout occur (t_{bt}, y) is then given by:

$$t_{bt} = t_{bt0} - t_{mh} + t_{PoA}$$

where:

- t_{bt0} is the time that bathtubbing would occur without any period of active management (y);
- t_{mh} is the time taken for the leachate head in the landfill to reach the managed head level (y) (or 0 y if $t_{mh} > t_{PoA}$);
- t_{PoA} is the duration of active leachate management (60 y) (or 0 y if $t_{mh} > t_{PoA}$)

9. The integration in paragraph 6 may be done using integrating factors (Boas, 2006) (Stroud & Booth, 2007).

F.1. Cl-36 model

10. The Cl-36 activity in the waste cell, $A_{cell}(^{36}Cl)$, varies according to the following equation:

$$\frac{dA_{cell}(^{36}Cl)}{dt} = -\left(r_{cell}(^{36}Cl) + r_{breakout}(^{36}Cl) + \lambda(^{36}Cl)\right) \cdot A_{cell}(^{36}Cl)$$

with loss terms for leaching, breakout and radioactive decay.

11. Leaching is described by:

$$-r_{cell}(^{36}Cl) \cdot A_{cell}(^{36}Cl) = -\frac{q_{leachate}}{V_{cell} \cdot ((1 - f_{soil,cell}) \cdot \varepsilon_{cell} + f_{soil,cell} \cdot \varepsilon_{soil}) + V_{cell} \cdot \rho_{soil} \cdot f_{soil,cell} \cdot k_{d,soil}(Cl)} \cdot A_{cell}(^{36}Cl)$$

with:

- $r_{cell}(^{36}Cl)$ the waste cell leaching rate (y^{-1});
- V_{cell} the volume of the waste cells (m^3);
- $f_{soil,cell}$ the volume fraction of soil and inert waste in the waste cell (dimensionless);
- ε_{cell} the porosity of the waste (dimensionless);
- ε_{soil} the porosity of the soil and inert waste (dimensionless);
- ρ_{soil} the density of soil ($kg\ m^{-3}$);
- $k_{d,soil(Cl)}$ the distribution coefficient of soil relative to water for chlorine ($m^3\ kg^{-1}$).

12. Radioactive decay is described by:

$$-\lambda(^{36}Cl) \cdot A_{cell}(^{36}Cl) = -\frac{ln(2)}{t_{1/2}(^{36}Cl)} \cdot A_{cell}(^{36}Cl)$$

with:

- $\lambda(^{36}Cl)$ the decay constant of Cl-36; and,
- $t_{1/2}(^{36}Cl)$ the half-life of Cl-36.

13. Breakout, when applied, is described by:

$$-r_{breakout}(^{36}Cl) \cdot A_{cell}(^{36}Cl) = -\frac{q_{breakout}}{V_{cell} \cdot ((1 - f_{soil,cell}) \cdot \varepsilon_{cell} + f_{soil,cell} \cdot \varepsilon_{soil}) + V_{cell} \cdot \rho_{soil} \cdot f_{soil,cell} \cdot k_{d,soil}(Cl)} \cdot A_{cell}(^{36}Cl)$$

and is 0 when not applied.

14. The Cl-36 activity in the clay barrier (A_B) varies according to the following equation:

$$\frac{dA_B(^{36}Cl)}{dt} = r_{cell}(^{36}Cl) \cdot A_{cell}(^{36}Cl) - \left(r_B(^{36}Cl) + \lambda(^{36}Cl)\right) \cdot A_B(^{36}Cl)$$

with source term $r_{cell}(^{36}Cl) \cdot A_{cell}(^{36}Cl)$ (as given in paragraph 11),:

and with loss terms (B = Barrier):

$$-r_B(^{36}Cl) \cdot A_B(^{36}Cl) = -\frac{q_{leachate}}{V_B \cdot \varepsilon_B + V_B \cdot \rho_{clay} \cdot k_{d,clay}(Cl)} \cdot A_B(^{36}Cl)$$

and

$$-\lambda(^{36}Cl) \cdot A_B(^{36}Cl) = -\frac{ln(2)}{t_{1/2}(^{36}Cl)} \cdot A_B(^{36}Cl)$$

15. The Cl-36 activity in the unsaturated zone (A_{Unsat}) varies according to the following equation:

$$\frac{dA_{Unsat}(^{36}Cl)}{dt} = r_B(^{36}Cl) \cdot A_B(^{36}Cl) - \left(r_{Unsat}(^{36}Cl) + \lambda(^{36}Cl)\right) \cdot A_{Unsat}(^{36}Cl)$$

with source term:

$$r_B(^{36}Cl) \cdot A_B(^{36}Cl) = \frac{q_{leachate}}{V_B \cdot \varepsilon_B + V_B \cdot \rho_{clay} \cdot k_{d,clay}(Cl)} \cdot A_B(^{36}Cl)$$

and, with loss terms:

$$-r_{Unsat}(^{36}Cl) \cdot A_{Unsat}(^{36}Cl) = -\frac{q_{leachate}}{V_{Unsat} \cdot \varepsilon_{Unsat} + V_{Unsat} \cdot \rho_{MadeGround} \cdot k_{d,soil}(Cl)} \cdot A_{Unsat}(^{36}Cl)$$

and

$$-\lambda(^{36}Cl) \cdot A_{Unsat}(^{36}Cl) = -\frac{ln(2)}{t_{1/2}(^{36}Cl)} \cdot A_{Unsat}(^{36}Cl)$$

16. The Cl-36 activity in the saturated zone below the landfill, A_{sat}, varies according to the following equation:

$$\frac{dA_{sat}(^{36}Cl)}{dt} = r_{Unsat}(^{36}Cl) \cdot A_{Unsat}(^{36}Cl) - \left(r_{sat}(^{36}Cl) + \lambda(^{36}Cl)\right) \cdot A_{sat}(^{36}Cl)$$

with source term:

$$r_{Unsat}(^{36}Cl) \cdot A_{Unsat}(^{36}Cl) = \frac{q_{leachate}}{V_{Unsat} \cdot \varepsilon_{Unsat} + V_{Unsat} \cdot \rho_{MadeGround} \cdot k_{d,soil}(Cl)} \cdot A_{Unsat}(^{36}Cl)$$

and, with loss terms:

$$-r_{sat}(^{36}Cl) \cdot A_{sat}(^{36}Cl) = -\frac{q_{leachate}}{V_{sat} \cdot \varepsilon_{sat} + V_{sat} \cdot \rho_{MadeGround} \cdot k_{d,soil}(Cl)} \cdot A_{sat}(^{36}Cl)$$

and

$$-\lambda(^{36}Cl) \cdot A_{sat}(^{36}Cl) = -\frac{ln(2)}{t_{1/2}(^{36}Cl)} \cdot A_{sat}(^{36}Cl)$$

17. The Cl-36 activity in the aquifer, $A_{aquifer}$ varies according to the following equation:

$$\frac{dA_{aquifer}(^{36}Cl)}{dt} = r_{sat}(^{36}Cl) \cdot A_{sat}(^{36}Cl) - \left(r_{aquifer}(^{36}Cl) + \lambda(^{36}Cl)\right) \cdot A_{aquifer}(^{36}Cl)$$

with source term:

$$r_{sat}(^{36}Cl) \cdot A_{sat}(^{36}Cl) = \frac{q_{leachate}}{V_{sat} \cdot \varepsilon_{sat} + V_{sat} \cdot \rho_{MadeGround} \cdot k_{d,soil}(Cl)} \cdot A_{sat}(^{36}Cl)$$

and, with loss terms:

$$-r_{aquifer}(^{36}Cl) \cdot A_{aquifer}(^{36}Cl) = -\frac{q_{aquifer}}{V_{aquifer} \cdot \varepsilon_{aquifer} + V_{aquifer} \cdot \rho_{alluvium} \cdot k_{d,soil}(Cl)} \cdot A_{aquifer}(^{36}Cl)$$

$$-\lambda(^{36}Cl) \cdot A_{aquifer}(^{36}Cl) = -\frac{ln(2)}{t_{1/2}(^{36}Cl)} \cdot A_{aquifer}(^{36}Cl)$$

18. Boundary conditions at t=0 are:

- 1 MBq of Cl-36 in the waste cell;
- 0 MBq of Cl-36 in the barrier
- 0 MBq of Cl-36 in the unsaturated zone;
- 0 MBq of Cl-36 in the saturated zone;
- 0 MBq of Cl-36 is the aquifer.

19. The model is run in steps of 1 year. It is run up to t_{bt} years (see paragraph 8) without applying breakout and then with breakout applied until 100,000 y have elapsed. The finishing conditions of the first run are the starting conditions for the second.

20. After the model run activity values can be translated into activity concentrations in the water fractions using the following equations:

$$C_{cell}(^{36}Cl) = \frac{A_{cell}(^{36}Cl)}{V_{cell} \cdot ((1 - f_{soil,cell}) \cdot (\varepsilon_{cell} - Cap_{cell}) + f_{soil,cell} \cdot \varepsilon_{soil}) + V_{cell} \cdot \rho_{soil} \cdot f_{soil,cell} \cdot k_{d,soil}(Cl)}$$

$$C_B(^{36}Cl) = \frac{A_B(^{36}Cl)}{V_B \cdot \varepsilon_B + V_B \cdot \rho_{clay} \cdot k_{d,clay}(Cl)}$$

$$C_{Unsat}(^{36}Cl) = \frac{A_{Unsat}(^{36}Cl)}{V_{Unsat} \cdot \varepsilon_{Unsat} + V_{Unsat} \cdot \rho_{madeground} \cdot k_{d,soil}(Cl)}$$

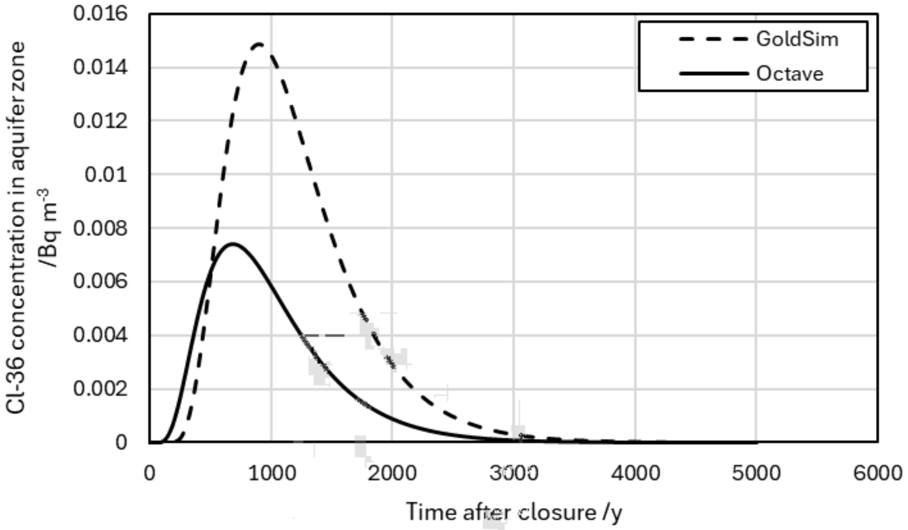
$$C_{sat}(^{36}Cl) = \frac{A_{sat}(^{36}Cl)}{V_{sat} \cdot \varepsilon_{sat} + V_{sat} \cdot \rho_{madeground} \cdot k_{d,soil}(Cl)}$$

$$C_{aquifer}(^{36}Cl) = \frac{A_{aquifer}(^{36}Cl)}{V_{aquifer} \cdot \varepsilon_{aquifer} + V_{aquifer} \cdot \rho_{alluvium} \cdot k_{d,soil}(Cl)}$$

F.1.1. Results and comparison with GoldSim model

21. Figure 40 compares the result of the GNU Octave GoldSim models.

Figure 40 Comparison of GNU Octave (solid) and GoldSim (dashed) estimations of Cl-36 activity concentration in the saturated zone (per MBq disposed Cl-36)



22. The GNU Octave model has a peak concentration of just over half that of the GoldSim model. The time of peak concentration is slightly earlier in the GNU Octave model than in the GoldSim model. The differences between the curves are because the GNU

Octave model does not represent any reduction in infiltration arising from the cap nor any reduction in leaching arising from the landfill liner, whereas the GoldSim model does. This has the following effects:

- As the GNU Octave model does not represent the basal liner, the rate of leaching of Cl-36 is initially higher in the GNU Octave model than in the GoldSim model. This leads to greater flow rates through the saturated and unsaturated zones, transferring more leached Cl-36 to the aquifer more quickly. This will be particularly pronounced after the time of bathtubbing (which occurs while the basal liner is still functioning), when the leachate head (and therefore leaching flow rate) in the GNU Octave model increases instantaneously.[3]
- As the GNU Octave model doesn't represent the cap, it assumes that the rate of infiltration into the waste cell is the same as for grassland. After the onset of bathtubbing, the breakout flow is the balance between leaching rate and infiltration. At the onset of bathtubbing, the cap is performing to its design specification, limiting the infiltration rate to be somewhat below that for grassland. Therefore, for around the first 1000 y of bathtubbing, the GNU Octave model has a significantly higher breakout flow than the GoldSim model. This leads to a more rapid loss of mobile radionuclides (such as Cl-36) from the waste cell in the GNU Octave model than in the GoldSim model. This reduces the activity available to leach to the aquifer and, therefore, aquifer concentrations, and causes the leaching rate to peak earlier than it otherwise would.

F.2. Ra-226 model

23. The main difference between Cl-36 and Ra-226 is the ingrowth of Pb-210. This process is included in the model. Equations are described for nuclei count (N) rather than activity for each radionuclide k.

$$A(k) = \lambda(k) \cdot N(k)$$

24. The Ra-226 and Pb-210 nuclei counts in the waste cell ($N_{cell}(^{226}Ra)$ and $N_{cell}(^{210}Pb)$) vary according to the following equation:

$$\frac{dN_{cell}(^{226}Ra)}{dt} = -\left(r_{cell}(^{226}Ra) + r_{breakout}(^{226}Ra) + \lambda(^{226}Ra)\right) \cdot N_{cell}(^{226}Ra)$$

$$\frac{dN_{cell}(^{210}Pb)}{dt} = \lambda(^{226}Ra) \cdot N_{cell}(^{226}Ra) - \left(r_{cell}(^{210}Pb) + r_{breakout}(^{226}Ra) + \lambda(^{210}Pb)\right) \cdot N_{cell}(^{210}Pb)$$

with loss terms for leaching, breakout and radioactive decay and a source term for ingrowth of Pb-210.

25. Leaching of Ra-226 and Pb-210 is described by:

[3] However, during the period between the end of active leachate management and the onset of bathtubbing, the GoldSim model could show greater leaching flow rates if the greater head in the GoldSim model during this time were sufficient to exceed the reduction in flow rate because of the basal liner.

$$-r_{cell}(^{226}Ra) \cdot N_{cell}(^{226}Ra) = -\frac{q_{leachate}}{V_{cell} \cdot ((1 - f_{soil,cell}) \cdot \varepsilon_{cell} + f_{soil,cell} \cdot \varepsilon_{soil}) + V_{cell} \cdot \rho_{soil} \cdot f_{soil,cell} \cdot k_{d,soil}(Ra)} \cdot N_{cell}(^{226}Ra)$$

$$-r_{cell}(^{210}Pb) \cdot N_{cell}(^{210}Pb) = -\frac{q_{leachate}}{V_{cell} \cdot ((1 - f_{soil,cell}) \cdot \varepsilon_{cell} + f_{soil,cell} \cdot \varepsilon_{soil}) + V_{cell} \cdot \rho_{soil} \cdot f_{soil,cell} \cdot k_{d,soil}(Pb)} \cdot N_{cell}(^{210}Pb)$$

with:

- r_{wc} the leaching rate ($r_{cell}(^{226}Ra)$ or $r_{cell}(^{210}Pb)$) (y^{-1});
- V_{cell} the volume of the waste cells (m^3);
- $f_{soil,cell}$ the volume fraction of soil and inert waste in the waste cells (dimensionless);
- ε_{cell} the porosity of the waste (dimensionless);
- ε_{soil} the porosity of the soil and inert waste (dimensionless);
- ρ_{soil} the density of soil (kg m^{-3}); and,
- $k_{d,soil}$ the distribution coefficient of soil relative to water for radium/lead ($k_{d,soil}$(Ra) or $k_{d,soil}$(Pb)) (m^3 kg^{-1}).

26. Radioactive decay of Ra-226 and Pb-210 is described by:

$$-\lambda(^{226}Ra) \cdot N_{cell}(^{226}Ra) = -\frac{ln(2)}{t_{1/2}(^{226}Ra)} \cdot N_{cell}(^{226}Ra)$$

$$-\lambda(^{210}Pb) \cdot N_{cell}(^{210}Pb) = -\frac{ln(2)}{t_{1/2}(^{210}Pb)} \cdot N_{cell}(^{210}Pb)$$

with:

- $t_{1/2}$ the half-life ($t_{1/2}(^{226}Ra)$ or $t_{1/2}(^{210}Pb)$)

27. Ingrowth of Pb-210 from radioactive decay of Ra-226 is described by:

$$\lambda(^{226}Ra) \cdot N_{cell}(^{226}Ra) = \frac{ln(2)}{t_{1/2}(^{226}Ra)} \cdot N_{cell}(^{226}Ra)$$

$$\lambda(^{226}Ra) \cdot N_{cell}(^{226}Ra) = \frac{ln(2)}{t_{1/2}(^{226}Ra)} \cdot N_{cell}(^{226}Ra)$$

28. Breakout, when applied, is described by:

$$-r_{breakout}\left({}^{226}Ra\right)\cdot N_{cell}\left({}^{226}Ra\right) = -\frac{q_{breakout}}{V_{cell}\cdot\left(\left(1-f_{soil,cell}\right)\cdot\varepsilon_{cell}+f_{soil,cell}\cdot\varepsilon_{soil}\right)+V_{cell}\cdot\rho_{soil}\cdot f_{soil,cell}\cdot k_{d,soil}(Ra)}\cdot N_{cell}\left({}^{226}Ra\right)$$

$$-r_{breakout}\left({}^{210}Pb\right)\cdot A_{cell}\left({}^{210}Pb\right) = -\frac{q_{breakout}}{V_{cell}\cdot\left(\left(1-f_{soil,cell}\right)\cdot\varepsilon_{cell}+f_{soil,cell}\cdot\varepsilon_{soil}\right)+V_{cell}\cdot\rho_{soil}\cdot f_{soil,cell}\cdot k_{d,soil}(Pb)}\cdot N_{cell}\left({}^{210}Pb\right)$$

29. The Ra-226 and Pb-210 nuclei counts in the clay barrier ($N_B({}^{226}Ra)$, $N_B({}^{210}Pb)$) vary according to the following equations:

$$\frac{dN_B\left({}^{226}Ra\right)}{dt} = r_{cell}\left({}^{226}Ra\right)\cdot N_{cell}\left({}^{226}Ra\right) - \left(r_B\left({}^{226}Ra\right)+\lambda\left({}^{226}Ra\right)\right)\cdot N_B\left({}^{226}Ra\right)$$

$$\frac{dN_B\left({}^{210}Pb\right)}{dt} = r_{cell}\left({}^{210}Pb\right)\cdot N_{cell}\left({}^{210}Pb\right) + \lambda\left({}^{226}Ra\right)\cdot N_B\left({}^{226}Ra\right) - \left(r_B\left({}^{210}Pb\right)+\lambda\left({}^{210}Pb\right)\right)\cdot N_B\left({}^{210}Pb\right)$$

with source, loss and ingrowth terms defined similar to Cl-36 above.

30. The Ra-226 and Pb-210 nuclei counts in the unsaturated zone ($N_{Unsat}({}^{226}Ra)$, $N_{Unsat}({}^{210}Pb)$) vary according to the following equations:

$$\frac{dN_{Unsat}\left({}^{226}Ra\right)}{dt} = r_B\left({}^{226}Ra\right)\cdot N_B\left({}^{226}Ra\right) - \left(r_{Unsat}\left({}^{226}Ra\right)+\lambda\left({}^{226}Ra\right)\right)\cdot N_{Unsat}\left({}^{226}Ra\right)$$

$$\frac{dN_{Unsat}\left({}^{210}Pb\right)}{dt} = r_B\left({}^{210}Pb\right)\cdot N_B\left({}^{210}Pb\right) + \lambda\left({}^{226}Ra\right)\cdot N_{Unsat}\left({}^{226}Ra\right) - \left(r_{Unsat}\left({}^{210}Pb\right)+\lambda\left({}^{210}Pb\right)\right)\cdot N_{Unsat}\left({}^{210}Pb\right)$$

with source, loss and ingrowth terms defined similar to Cl-36 above.

31. The Ra-226 and Pb-210 nuclei counts in the saturated zone below the landfill ($N_{sat}({}^{226}Ra)$, $N_{sat}({}^{210}Pb)$) vary according to the following equations:

$$\frac{dN_{sat}\left({}^{226}Ra\right)}{dt} = r_{Unsat}\left({}^{226}Ra\right)\cdot N_{Unsat}\left({}^{226}Ra\right) - \left(r_{sat}\left({}^{226}Ra\right)+\lambda\left({}^{226}Ra\right)\right)\cdot N_{sat}\left({}^{226}Ra\right)$$

$$\frac{dN_{sat}\left({}^{210}Pb\right)}{dt} = r_{Unsat}\left({}^{210}Pb\right)\cdot N_{Unsat}\left({}^{210}Pb\right) + \lambda\left({}^{226}Ra\right)\cdot N_{sat}\left({}^{226}Ra\right) - \left(r_{sat}\left({}^{210}Pb\right)+\lambda\left({}^{210}Pb\right)\right)\cdot N_{sat}\left({}^{210}Pb\right)$$

with source, loss and ingrowth terms defined similar to Cl-36 above.

32. The Ra-226 and Pb-210 nuclei counts in the aquifer ($N_{aquifer}(^{226}Ra)$ and $N_{aquifer}(^{210}Pb)$) vary according to the following equation:

$$\frac{dN_{aquifer}(^{226}Ra)}{dt} = r_{sat}(^{226}Ra) \cdot N_{sat}(^{226}Ra) - \left(r_{aquifer}(^{226}Ra) + \lambda(^{226}Ra)\right) \cdot N_{aquifer}(^{226}Ra)$$

$$\frac{dN_{aquifer}(^{210}Pb)}{dt} = r_{sat}(^{210}Pb) \cdot N_{sat}(^{210}Pb) + \lambda(^{226}Ra) \cdot N_{aquifer}(^{226}Ra) - \left(r_{aquifer}(^{210}Pb) + \lambda(^{210}Pb)\right) \cdot N_{aquifer}(^{210}Pb)$$

with source, loss and ingrowth terms defined similar to above.

33. Boundary conditions at t=0 are:

- 1 MBq of Ra-226 and 0 MBq of Pb-210 in the waste cell;
- 0 MBq of Ra-226 and 0 MBq of Pb-210 in the barrier
- 0 MBq of Ra-226 and 0 MBq of Pb-210 in the unsaturated zone;
- 0 MBq of Ra-226 and 0 MBq of Pb-210 in the saturated zone;
- 0 MBq of Ra-226 and 0 MBq of Pb-210 is the aquifer.

34. The model is run in steps of 1 year. It is run up to t_{bt} years (see paragraph 8) without applying breakout and then with breakout applied until 100,000 y have elapsed. The finishing conditions of the first run are the starting conditions for the second.

35. After the model run, nuclei counts can be translated into activity concentrations in the water fractions.

$$C_{cell}(^{226}Ra) = \frac{N_{cell}(^{226}Ra) \cdot \lambda(^{226}Ra)}{V_{cell} \cdot ((1 - f_{soil,cell}) \cdot \varepsilon_{cell} + f_{soil,cell} \cdot \varepsilon_{soil}) + V_{cell} \cdot \rho_{soil} \cdot f_{soil,cell} \cdot k_{d,soil}(Ra)}$$

$$C_B(^{226}Ra) = \frac{N_B(^{226}Ra) \cdot \lambda(^{226}Ra)}{V_B \cdot \varepsilon_B + V_B \cdot \rho_{clay} \cdot k_{d,clay}(Ra)}$$

$$C_{Unsat}(^{226}Ra) = \frac{N_{Unsat}(^{226}Ra) \cdot \lambda(^{226}Ra)}{V_{Unsat} \cdot \varepsilon_{Unsat} + V_{Unsat} \cdot \rho_{madeground} \cdot k_{d,soil}(Ra)}$$

$$C_{sat}(^{226}Ra) = \frac{N_{sat}(^{226}Ra) \cdot \lambda(^{226}Ra)}{V_{sat} \cdot \varepsilon_{sat} + V_{sat} \cdot \rho_{madeground} \cdot k_{d,soil}(Ra)}$$

$$C_{aquifer}\left({}^{226}Ra\right) = \frac{N_{aquifer}\left({}^{226}Ra\right) \cdot \lambda\left({}^{226}Ra\right)}{V_{aquifer} \cdot \varepsilon_{aquifer} + V_{aquifer} \cdot d_{alluvium} \cdot k_{d,soil}(Ra)}$$

$$C_{cell}\left({}^{210}Pb\right) = \frac{N_{cell}\left({}^{210}Pb\right) \cdot \lambda\left({}^{210}Pb\right)}{V_{cell} \cdot \left((1 - f_{soil,cell}) \cdot \varepsilon_{cell} + f_{soil,cell} \cdot \varepsilon_{soil}\right) + V_{cell} \cdot \rho_{soil} \cdot f_{soil,cell} \cdot k_{d,soil}(Pb)}$$

$$C_{B}\left({}^{210}Pb\right) = \frac{N_{B}\left({}^{210}Pb\right) \cdot \lambda\left({}^{210}Pb\right)}{V_{B} \cdot \varepsilon_{B} + V_{B} \cdot \rho_{clay} \cdot k_{d,clay}(Pb)}$$

$$C_{Unsat}\left({}^{210}Pb\right) = \frac{N_{Unsat}\left({}^{210}Pb\right) \cdot \lambda\left({}^{210}Pb\right)}{V_{Unsat} \cdot \varepsilon_{Unsat} + V_{Unsat} \cdot \rho_{madeground} \cdot k_{d,soil}(Pb)}$$

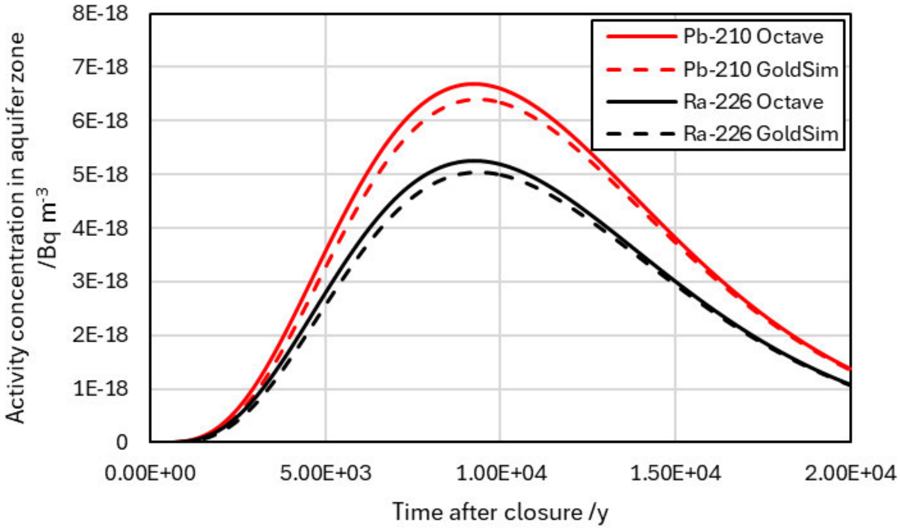
$$C_{sat}\left({}^{210}Pb\right) = \frac{N_{sat}\left({}^{210}Pb\right) \cdot \lambda\left({}^{210}Pb\right)}{V_{sat} \cdot \varepsilon_{sat} + V_{sat} \cdot \rho_{madeground} \cdot k_{d,soil}(Pb)}$$

$$C_{aquifer}\left({}^{210}Pb\right) = \frac{N_{aquifer}\left({}^{210}Pb\right) \cdot \lambda\left({}^{210}Pb\right)}{V_{aquifer} \cdot \varepsilon_{aquifer} + V_{aquifer} \cdot d_{alluvium} \cdot k_{d,soil}(Pb)}$$

F.2.1. Results and comparison with GoldSim model

36. Figure 41 compares the modelling results for Ra-226 and its daughter Pb-210 using the GNU Octave and GoldSim models.

Figure 41 Comparison of GNU Octave (solid) and GoldSim (dashed) estimates of Ra-226 (black) and daughter Pb-210 (red) activity concentrations in the aquifer zone (per MBq disposed Ra-226)

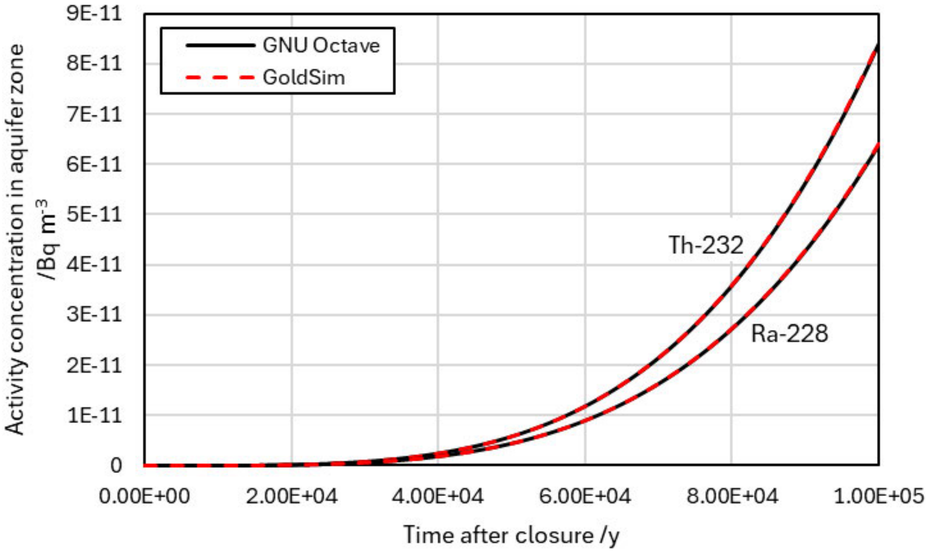


37. In 0, the agreement between the GNU Octave model (solid lines) and the GoldSim model (dashed lines) is close. The two model results are significantly more similar than the results for Cl-36 are (0).

38. Ra-226 and Pb-210 are significantly more sorbing than Cl-36. This means that early releases are much lower for Ra-226 and Pb-210 than for Cl-36 and, therefore, the lack of representation of the low-permeability liner in the GNU Octave model has much less effect on the results for these radionuclides.

39. The results of a similar model for Th-232 and its daughter Ra-228 are shown in Figure 42. Like Ra-226 and Pb-210, Th-232 and Ra-228 are more sorbing than Cl-36 and the agreement between the two models is very good.

Figure 42 Comparison of GNU Octave (solid, black) and GoldSim (dashed, red) estimates of Th-232 (top) and daughter Ra-228 (bottom) activity concentrations in the aquifer zone (per MBq disposed Th-232).



Appendix G. Major uncertainties in the ESC

Theme	Description of Uncertainty	How minimised	Remaining Bias	Relative importance
1 Landfill engineering	**Barrier performance**. The landfill design includes several barriers. There is uncertainty regarding operating life and rate of deterioration of some of these barriers.	It is cautiously assumed that the cap will degrade between 250 years and 1000 years after construction, although this comprises a geosynthetic clay layer. (see ESC Appendix E, Section E.1.3.1) Gradual deterioration of the HDPE waste cell liner (see ESC Appendix E, Section E.4.3) is included. The basal clay layer (an engineered geological barrier) will not degrade.	Conservative assumptions lead to overestimation of rain infiltration into landfill and hence increase possibility of bathtubbing and inundation.	Low
	Settlement. Settlement is expected, which will result in a change in the shape of the landfill. Settlement may not be uniform and could affect the final gradient of the landfill	The landfill is designed based on the assumption settlement will occur and it is operated to minimise uneven settlement. It is assumed that cap materials are able to cope with the expected settlement without it causing damage. A stability risk assessment has been undertaken (MJCA, 2019c). Voidage in wastes is minimised through WAC.	The aftercare period will address any differential settling evident at the restored surface. Settlement after the period of authorisation not expected but covered by degradation of cap.	Low

Theme	Description of Uncertainty	How minimised	Remaining Bias	Relative importance
2 Waste properties	**Heterogeneous activity distribution in landfill**. Many disposed wastes are heterogeneous in terms of the distribution of activity within packaged material. The activity will also vary across the landfill as different wastes are disposed over time.	Heterogenous wastes are considered explicitly in ESC for scenarios where this impacts the doses (e.g. intrusion scenarios). (see ESC Section E6). Heterogeneity is not important for other scenarios (e.g. leaching and groundwater migration). Conservative assumptions are applied in calculating risks and doses. Activity concentrations constrained by doses from heterogenous wastes and by setting limits e.g. for discrete items and particles to ensure dose and risk criteria are met.	Characterisation of wastes by the consignor will not be perfect but most waste types suitable for disposal at the site are expected to be covered by the cases considered.	Low
	Waste form. It is not possible prior to near the time of receipt of the wastes to describe the specific form, amounts or types of wastes	ESC has considered waste streams sent to similar landfill sites to understand likely wastes. Package requirements are specified in the WAC. Loose tipping of some wastes has been considered explicitly. Radiological capacity of site for each radionuclide determined and sum of fractions used to ensure dose and risk criteria will be met. Hence exact waste form, amount or type of waste not required for ESC but will be required prior to acceptance for disposal. Estimates of radiological impact based on 'illustrative inventories' for waste streams that might be typical of those contributing to the total impact from disposals at the facility have been produced. These estimates are presented in the ESC (Appendix E).	Limit of 5% LLW in void reduces maximum inventory of some radionuclides to below the radiological capacity, reducing radiological impact. Consignment specific disposability assessments will be undertaken (as done at the ENRMF) where it is unclear that a waste type conforms to ESC assumptions.	Low

Theme	Description of Uncertainty	How minimised	Remaining Bias	Relative importance
	Sorption in waste materials. As the waste form is uncertain, the sorption properties of the waste are also uncertain.	ESC calculations do not take into account sorption within waste materials, i.e. all radionuclides are assumed to be readily soluble. This is a cautious approach as in reality radionuclides will be bound to sorption sites within waste for some radionuclides.	None. Overestimating leachate concentrations.	Low
	Gas generation rates. The impact of recreational users of the site after closure as a result of exposure from gases released from the waste is assessed using assumed gas generation rates.	A 20 year timescale for gas generation has been applied to the period after closure using the value recommended by IAEA (IAEA, 2003). A shorter period is used for assessments during the operational period (10 years). Sensitivity of dose to a recreational user to the gas generation rate is considered in the ESC (Section E.8.1.6).	The assumptions concerning gas release in this period are cautious and this results in overstating gas doses to recreational users of the site.	Low
3 Pathways and Receptors	**Leachate spillage and use of contaminated water for irrigation.** A scenario is considered in which leachate spillage results in contamination of a water body. Contamination of a water body is difficult to remediate. It is assumed that farmland next to the contaminated water body also becomes contaminated due to irrigation and that the farming family use the water body for fishing and consume fish they catch.	The leachate spillage pathway is highly uncertain, both in terms of the possibility of occurring and duration. It is conservative to assume irrigation occurs with the contaminated water since after a spillage there would be mitigating actions. Conservative parameter values are used for irrigation pathway. Sensitivity to the pathway is considered by calculating capacity if the pathway is excluded (see ESC Section E.8.1.5). For most radionuclides, the radiological capacity would increase by at least five orders of magnitude if exposure as a result of irrigation did not occur. The exceptions are Ba- 133, Eu-155 and Ac-227, for which the increase is smaller.	The scenario is very conservative and will overestimate the doses. It is a scenario used in the sum of fractions so including the irrigation pathway will reduce the radiological capacity for some radionuclides.	Medium

Theme	Description of Uncertainty	How minimised	Remaining Bias	Relative importance
	Volume of water body into which leachate is spilled.	This is an uncertain scenario. It was assumed that the volume of the water body into which leachate is spilled was 2,000,000 m^3. The sensitivity of dose to this volume was investigated by varying it by a factor of 1.5, see ESC Section E.8.1.5.	It is uncertain whether this scenario would occur and, if it did, the actual circumstances would determine the mitigating actions.	Low
	Presence of a well.	The abstraction of potable water is not known to occur from the aquifer beneath the Port Clarence site. The groundwater is not potable due to saline intrusion and would also not be suitable for irrigation or livestock. This scenario is therefore considered as a 'what if' scenario in the ESC and is not used to limit the radiological capacity because water cannot be used for irrigation or animal consumption.	None.	None
	Impact of tide on groundwater. It is likely that groundwater flow in the alluvium is affected by tidal influences of the River Tees.	It is assumed that the tide has no effect on groundwater in the ESC models. Tidal effects on groundwater flow in the estuary would be complex but assuming the groundwater flow rate is driven by the groundwater head will overestimate the release to the estuary. The salinity could affect the sorption characteristics of the aquifer but sorption in the aquifer is not included in the model. This is conservative.	Assessment is conservative and overestimates release to estuary.	Low
	Sorption parameter (Kd) for Tc in saturated zone	Mobile value adopted – low Kd. This will overestimate release to the aquifer and result in an earlier time of peak release. A higher Kd value would result in a higher radiological capacity for the groundwater scenario.	Assessment is conservative and overestimates release to estuary.	Medium

Theme	Description of Uncertainty	How minimised	Remaining Bias	Relative importance
	Sorption parameter (Kd) for Cl in saturated sone	Mobile value adopted – low Kd. This will overestimate release to the aquifer and result in an earlier time of peak release. . A higher Kd value would result in a higher radiological capacity for the groundwater scenario.	Assessment is conservative and overestimates release to estuary.	Medium
	Proportion of radionuclides in root zone of plants following bathtubbing. Bathtubbing may result in leachate seeping over the top of the basal liner at the sides where the cap and basal liners join. A proportion of any release is expected to accumulate in the rooting zone of plants and the remainder will drain to groundwater.	A value of 1% was adopted in the ESC for all radionuclides based on experimental values for Tc-99 and Cl-36 (Shaw, et al., 2004) (Wheater, et al., 2007). This is probably a realistic value for the very mobile radionuclides Tc-99 and Cl-36, but conservative for sorbed radionuclides. Values are now scaled on the basis of kd. This scenario is used in the sum of fractions calculation.	None.	Medium

Theme	Description of Uncertainty	How minimised	Remaining Bias	Relative importance
	Leachate management. Radionuclides in leachate could exceed relevant exemption levels and a permit variation would be required for disposal to a facility with appropriate permits in place.	Concentrations in leachate for the maximum inventory have been compared with relevant exemption levels for liquids. The radiological impact of treatment off-site has been assessed using cautious assumptions and the dose constraint used to limit disposals. The composition of leachate has been considered using the ENRMF fingerprint as representative of the inventory that could be disposed at Port Clarence. This indicates off-site leachate disposal is unlikely to require permitting. Monitoring programme for measuring key radionuclides in leachate has been proposed. Alternative management options are available at the WRP for on-site treatment of leachate.	None.	Low
	Missing radionuclides from EA IRAT. The leachate treatment scenario uses the EA IRAT to assess impacts to a treatment worker. EA IRAT does not include all of the radionuclides considered in the Port Clarence ESC.	The updated models use chemical analogues to fill in the gaps in the assessment. The analogues scope the potential impact of missing radionuclides.	None.	Low

Theme	Description of Uncertainty	How minimised	Remaining Bias	Relative importance
	Behaviour of burrowing mammals. There is uncertainty as to whether burrowing mammals could break through the cap of the landfill and, if they could, how much time would be spent in burrows that are located in waste rather than clean material.	An assessment of dose rates to mammals burrowing into the waste 60 y after closure is carried out. It is assumed that the burrowing mammal spends 100% of its time in the soil, however in practice it will spend some of its time outside the burrow. The granular layer in the cap will deter burrowing animals at least for a few hundred years, until it is naturally broken down and mixes with soil. LLW in containers would also deter direct contact with the waste. A whole population of burrowing mammals would not burrow into waste. However, the scenario is cautiously used to assess radiological capacity for radionuclides where an individual burrowing mammal may be exposed to a dose rate higher than 40 µGy/h (see ESC Section E.8.1.7).	Using this scenario in the sum of fractions will reduce the radiological capacity of the site for some radionuclides. Waste containing these radionuclides could be disposed of below the burrowing depth.	Low

Theme	Description of Uncertainty	How minimised	Remaining Bias	Relative importance
4 Site evolution	**Evolution of the estuary.** The estuary is expected to accumulate sediment and there is no information to support erosion of the estuary banks. It is possible that local or national policies for maintaining shipping access and management of local flood defences could change and impact the future evolution of the estuary. If dredging activities stopped there would be accumulation of sediments and development of salt marshes and mudflats in the estuary. There is evidence of sediment deposits to the south of the landfill. The sediment deposits and sea level rise could lead to tidal erosion at the Port Clarence site from the seaward side.	Bangor University (Bangor University, 2023) have provided advice on the evolution of the estuary and possible erosion rates. Erosion of the landfill has been assessed using cautious assumptions. Two assessments are carried out assuming that the facility will be eroded: • coastal walker/beach user • exposure from releases of leachate from the eroding site into the marine environment The coastal walker/beach user is assumed to be present once erosion begins, even though access to the site may be restricted once erosion begins due to low lying land surrounding the site becoming tidally inundated. Sensitivity to exposure time and erosion rate is assessed in ESC Section E.8.1.3. The erosion scenarios are used in the sum of fractions to limit radiological capacity. A sensitivity analysis was carried out to demonstrate the change in capacity if erosion is not considered because it is assumed that it does not occur (see ESC Section E.8.1.4). For all radionuclides limited by coastal erosion, the radiological capacity increases by at least one order of magnitude if the coastal erosion scenario is not considered.	It is very cautious to assume the facility will be eroded sometime in the future and to perform an assessment using the inventory calculated at 60 years after closure. The erosion scenarios constrain the radiological capacity for many radionuclides.	Low

Theme	Description of Uncertainty	How minimised	Remaining Bias	Relative importance
	Timing and form of erosion. The rate of erosion is influenced by several factors, including human actions, estuary behaviours, sea level, wave characteristics and storminess.	The timing of erosion is unknown and there are no models available that would be able to predict whether it would occur in the future. It is cautiously assumed that once erosion begins the inventory used is based on the time at which the site is released from regulatory control (60 years after closure). It is also assumed that, when erosion starts, the landfill is on the coast rather than being sheltered in an estuary. The erosion rate adopted is based on work performed by Bangor University (Bangor University, 2023).	ESC approach is now very cautious.	Low
	Shape of the coastline if erosion did occur. An assessment is carried out considering exposure from releases of leachate from the eroding site into the marine environment. Erosion is considered unlikely to occur, and if it did happen, it is not known what shape the estuary or coastline might be at the time of erosion.	The assessment uses the default local marine compartment values recommended in PC CREAM08. There are no models that can model the evolution of the coast on the timescales that are relevant to a radiological assessment (100s of years or more). Erosion leading to a release to the marine environment is a scenario used in the sum of fractions to limit disposals to the site.	The concentration in the local compartment depends on the exchange rate between the local compartment and the regional compartment. A straight coastline would lead to higher exchange rates and an indented coastline would lead to lower exchange rates. The scenario is used in the sum of fractions and limits disposals for a few radionuclides.	Low

Appendix H. Assessment of Transboundary Radioactive Contamination

APPENDIX H. ASSESSMENT OF TRANSBOUNDARY RADIOACTIVE CONTAMINATION 586
H.1. INTRODUCTION 586
H.2. NAME AND LOCATION OF THE FACILITY CONCERNED: 587
H.3. BRIEF DESCRIPTION OF THE FACILITY: 587
H.4. AUTHORISED DISCHARGE LIMITS, AND OTHER RELEVANT CONDITIONS: 590
H.4.1. GASEOUS EFFLUENTS: 590
H.4.2. LIQUID EFFLUENTS: 590
H.4.3. SOLID WASTE: 591
H.5. CONSEQUENCES IN RELATION TO THE DISPOSAL OF SOLID WASTE: LOCAL TO SITE 593
H.6. IMPACT ON OTHER COUNTRIES 595
H.6.1. CONSEQUENCES IN RELATION TO THE EXPECTED SCENARIOS 596
H.6.1.1. LEACHATE PROCESSING OFF-SITE: TREATMENT WORKER 597
H.6.1.2. RELEASE TO ATMOSPHERE 597
H.6.1.3. RELEASE TO THE ESTUARY 598
H.6.2. CONSEQUENCES IN RELATION TO THE REFERENCE ACCIDENTS AND UNLIKELY EVENTS 598
H.6.2.1. LANDFILL FIRE IMPACT: 598
H.6.2.2. SMALLHOLDER AND RESIDENT: 599
H.7. IMPLICATIONS IN RELATION TO THE CURRENT EMERGENCY PLANS AND THE CURRENT ENVIRONMENTAL MONITORING: 599

H.1. Introduction

40. Augean Ltd operates an integrated waste management facility at Port Clarence, Stockton-on-Tees in the north east of England. The facility comprises an operational landfill and an adjacent associated Waste Recovery Park (WRP) providing a range of specialist waste treatment and management activities for the recycling, recovery and disposal of primarily industrial wastes including hazardous and non-hazardous waste. The landfill receives wastes directly from local, regional and national businesses. The majority of the residues from the treatment processes in the WRP that are not suitable for recycling or reuse are deposited in the landfill. The facility serves local, regional and national markets and is part of the nationally significant waste management infrastructure.

41. The site comprises land that was reclaimed from salt marshes and mudflats using waste from iron, steel and coke works and a tar distillation plant (from the 1800s to the 1960s). The site is close to the River Tees.

42. The Port Clarence landfill sites were granted planning permission in September 1996 (planning application reference TDC/94/065) for use as a waste disposal site (see planning reference 94/1049) and the most recent planning variation (planning reference 14/3135/VARY) for the site was granted by Stockton-on-Tees Borough Council in June 2015. This extended the operational life of the non-hazardous and hazardous waste landfill sites beyond 2016 with no fixed completion date. The two landfill sites are the subject of separate Environmental Permits which are regulated by the Environment Agency and control the engineering of the containment systems as well as the waste acceptance and management procedures (EPR/BV1399IT -

hazardous waste, EPR/BV1402IC - non-hazardous waste). Further Environmental Permits are in place for the WRP located to the south of the landfill sites (EPR/YP3234XR, EPR/UB3694DU).

43. A radioactive waste permit application has been submitted to the Environment Agency and this appendix assesses the potential transboundary impacts associated with disposal of LLW to the hazardous and non-hazardous waste landfills. The Transboundary Radioactive Contamination (England) Direction 2020 requires that a Transboundary Impact Assessment be provided to the Environment Agency so they can consider whether plans to dispose of radioactive waste are liable to result in the radioactive contamination, significant from the point of view of health, of water, soil or airspace of notifiable countries.

44. This document represents the Transboundary Impact Assessment for the site and demonstrates that the proposal to dispose of LLW does not impact EU Member States and/or Norway. The Environmental Safety Case (ESC) developed to support the radioactive waste permit application has demonstrated that the Port Clarence site will not have a significant impact locally. The ESC assessments have formed the basis of this submission to demonstrate there will be no wider impact as a consequence of the proposed disposals to the site.

45. Previous Article 37 submissions relating to the ENRMF (a landfill site also operated by Augean) have indicated that there are no transboundary impacts from the disposal of LLW at that site (Augean, 2010; Eden NE, 2015c; Eden NE, 2023) as noted in the published opinion of the European Commission (European Commission, 2011). Similar operational procedures will be used at Port Clarence and the radiological assessments performed for Port Clarence indicate there are no transboundary impacts. The main difference between the Port Clarence site and the ENRMF is the location of the Port Clarence site close to an estuary which introduces the potential for radioactivity to enter the marine environment if erosion of the site occurs at some point in the future.

H.2. Name and location of the facility concerned:

46. The Port Clarence site is located near Middlesbrough, United Kingdom: the centre of the hazardous waste landfill site lies approximately at OS Grid Reference NZ 51841 22242, 54.5927º N 1.1992º W and the centre of the non-hazardous landfill site lies at approximately at OS Grid Reference NZ 51785 22505).

47. The nearest area under the jurisdiction of another European Economic Area (EEA) State is in Ireland, at a distance of 320 km on a bearing of 261 degrees (to the west). The closest EEA State bordering the North Sea is the Netherlands, at a distance of 425 km on a bearing of 111 degrees (to the east)

H.3. Brief description of the facility:

48. There are two existing landfill sites at Port Clarence, one for hazardous waste and one for non-hazardous waste. The consented design of the two landfills (MJCA, 2018) allocates 44% of the void to disposal of hazardous waste, 54% to non-hazardous waste and the remainder (2%) to an engineered separation bund constructed from specified hazardous waste. The hazardous waste landfill area is approximately 19.5 ha and the

non-hazardous waste landfill area is approximately 20.3 ha (MJCA, 2019a). The void remaining at the site is 4.3 10^6 m^3 (September 2024).

49. Annual disposal limits are specified in the environmental permits (see Table 232).

Table 232 Annual hazardous and non-hazardous waste disposal limits specified in the permits

Category	Non-hazardous permit (BV/1402IC) Table S1.4	Hazardous permit (BV/1399IT) Table S1.4
Hazardous waste (tpa)	-	500,000
Non-hazardous waste (tpa)	995,000	-
Inert waste (tpa)	50,000	100,000(1)
Asbestos waste(2) (tpa)	150,000	-

Note: 1) For cover. 2) Including construction material containing asbestos.

50. The non-radioactive wastes accepted at the Port Clarence landfills cover a broad spectrum of waste but exclude explosive, flammable, corrosive and infectious materials. Those defined as hazardous under the European Waste Catalogue are subject to the hazardous waste acceptance criteria under the Landfill Directive (European Commission, 1999) as defined in Council Decision 2003/33/EC (European Communities, 2003). Wastes that will not be accepted for disposal include liquid wastes, corrosive wastes, flammable wastes, wastes that are classified as oxidising, and hazardous wastes with leachable components above statutory thresholds

51. Very low-level naturally occurring radioactive waste (NORM) has been disposed at the Port Clarence site since 2016 under an exemption from the need for a Permit for Type 2 NORM. Hence, Type 2 NORM waste with concentrations between 1 and 2 Bq g^{-1} is disposed at Port Clarence through compliance with Paragraphs 18 and 19 in Section 6 of Part 6 to Schedule 23 of the EPR2016. Type 2 exemption was required because the total annual activity for disposal exceeded the limit for Type 1 NORM exemption. Augean completed a radiological assessment of the exposure to the public and workers before disposals started and used this to calculate the tonnage that could be buried in accordance with the specified dose limit for these wastes (Jones, et al., 2014).

52. The ESC for Port Clarence provides a radiological assessment for the operation and post closure period of the landfill sites and determines both the maximum total quantity of radionuclides for disposal and the activity concentration of waste based on a sum of fractions approach. In addition, the ESC assumes that no more than 5% of the remaining capacity of either landfill, on a mass basis, will be used for the disposal of LLW.

53. A Port Clarence site plan is shown in Figure 43 and the plan for the restored landfill site is shown in Figure 44.

Figure 43 Current boundary of Port Clarence and design

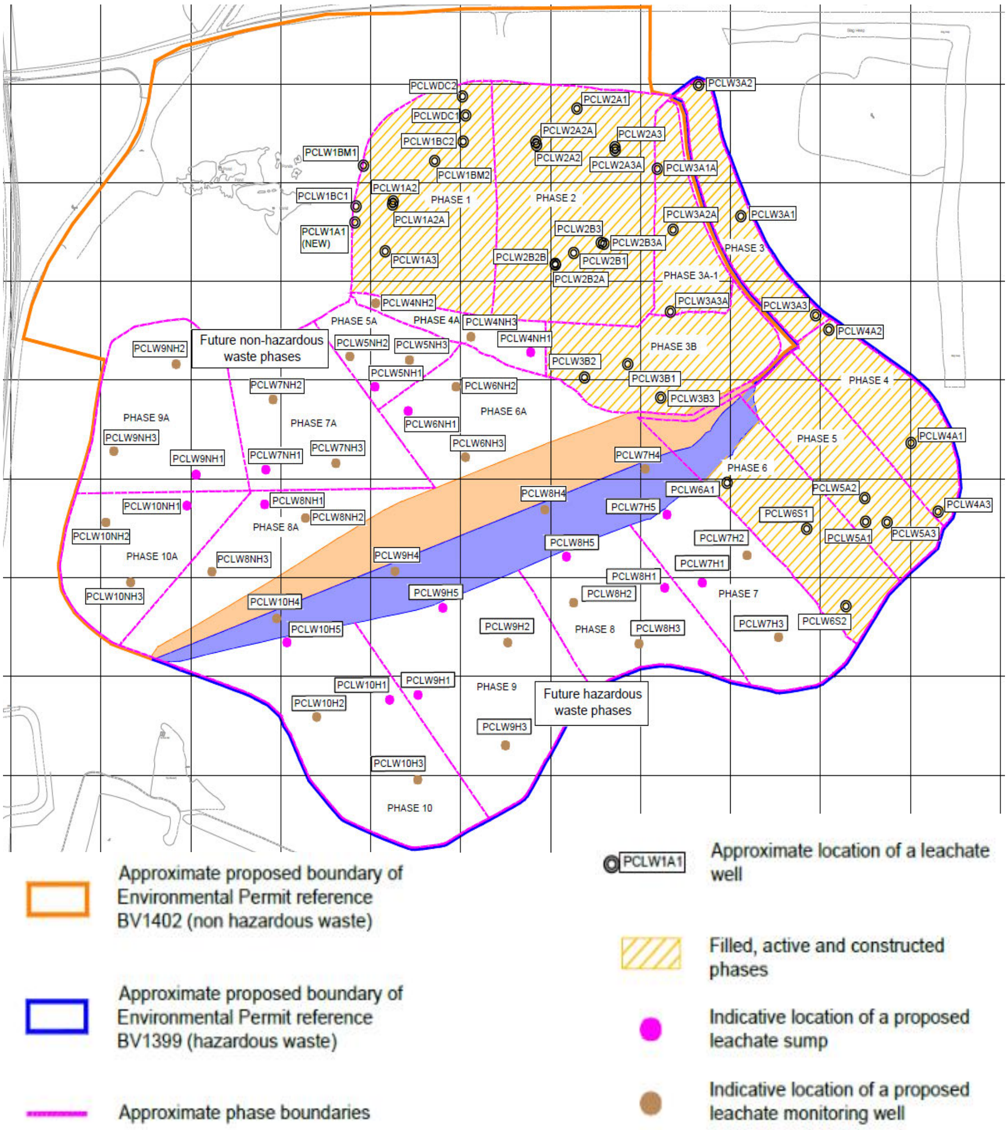
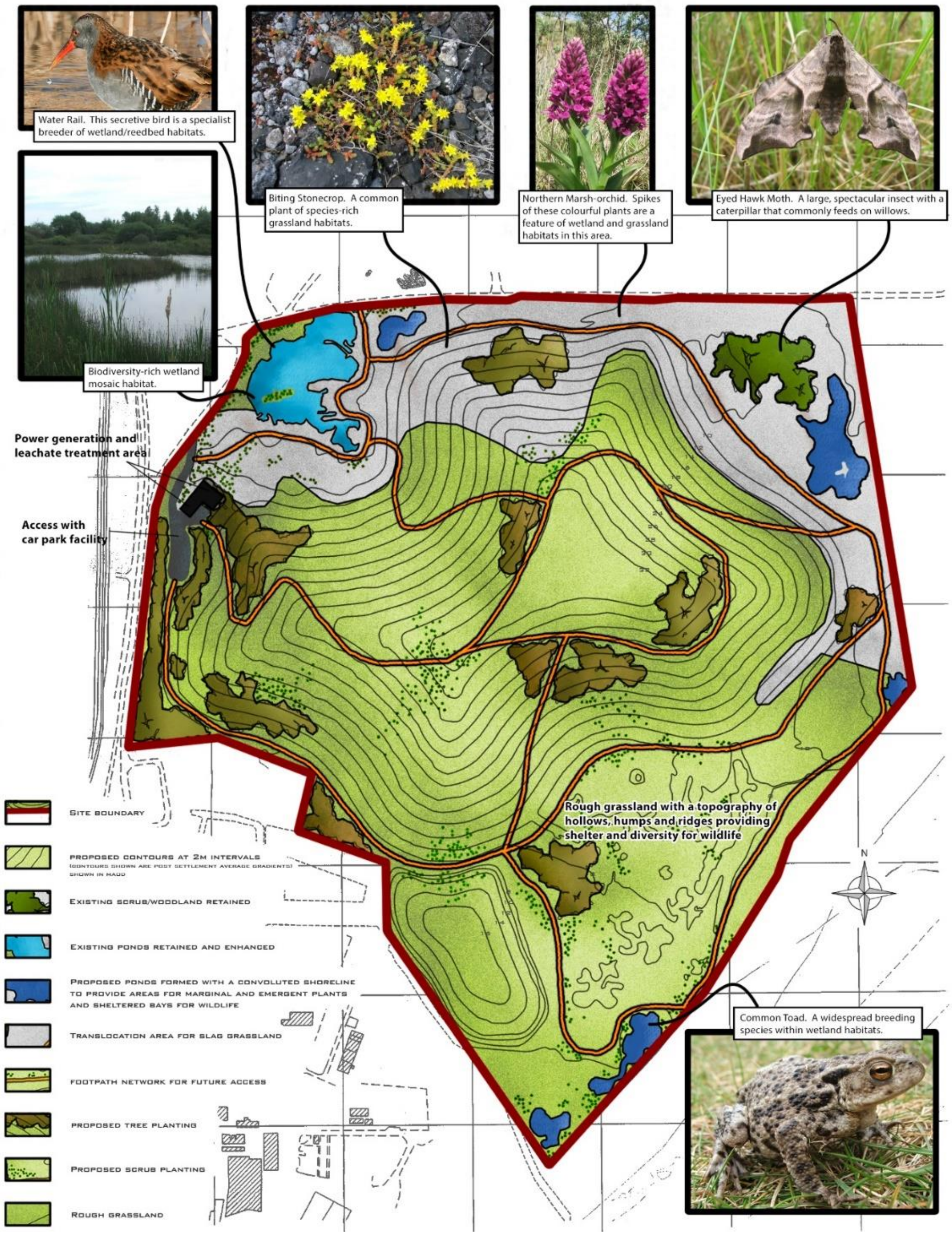


Figure 44 Restored profile of Port Clarence site



H.4. Authorised discharge limits, and other relevant conditions:

H.4.1. Gaseous effluents:

54. It is not envisaged there will be authorised discharges to atmosphere under the permit.

H.4.2. Liquid effluents:

55. Leachate collects in the leachate drainage blanket in the base of the landfill. In the event that the leachate exceeds 1 m in depth the leachate is extracted through vertical

wells located in the waste. The leachate is used in the on-site waste treatment facility and any excess is exported from the site by tanker to an effluent treatment works. Once the site is capped the need to extract leachate will be rare.

56. The radioactivity of the leachate is monitored quarterly. In the unlikely event that significant radioactivity is detected in the leachate the need to authorise transfer of the leachate to a treatment or disposal site will be determined. Alternatively, subject to the conditions in the permit for the waste treatment facility, the leachate is used in the treatment of fly ash and returned to the landfill.

H.4.3. Solid waste:

57. The proposed waste acceptance criteria for disposal require that:

a) waste is solid low level radioactive waste up to (radionuclide specific) maximum specific activities shown in Table 233 (per consignment or successive 10 t, whichever is the smaller);

b) the non-radioactive properties of the waste mean that it is inert or non-hazardous or of a type which would be acceptable for disposal under the current variation of environmental permit EPR/BV1399IT (hazardous waste) and EPR/BV1402IC (non-hazardous waste);

c) all the relevant waste acceptance procedures have been completed based on the non-radioactive properties of the waste (inert or non-hazardous or subject to the current environmental permits);

d) the non-radioactive properties of the waste satisfy the relevant waste acceptance criteria or basic characterisation requirements; and,

e) it has not been diluted or mixed for the purpose of meeting condition (a) or (d).

58. The disposal limits (radiological capacity values) of radionuclides are shown below (Table 233) and are used in a sum of fractions approach to limit disposals. This ensures that the relevant dose criteria are met. The values shown in the second column are the minimum value from the set of scenarios that will be used to control disposals at the site. A further limit is applied to the non-hazardous landfill to account for the unlikely event of a landfill fire in this part of the site. These values are shown below alongside the proposed specific activity limits for each radionuclide for each radionuclide averaged over a 10 t consignment and for a single package within a larger consignment (that when averaged over the consignment also meets the consignment limit). The sum of fractions approach is also used for the specific activity limits to limit disposals and ensure the relevant dose criteria are met. An upper limit of 2000 Bq g^{-1} for a consignment fingerprint is also applied. The value for the alpha emitter Cm-242 was lowered 200 Bq g^{-1}.

Table 233 Radionuclide radiological capacity and specific activity limits

Radionuclide	Minimum radiological capacity limit from scenarios relevant to both landfills (TBq)	Radiological capacity: fire scenario for non-hazardous landfill (TBq)	Maximum specific activity in a consignment ($Bq\ g^{-1}$)	Single package specific activity limit ($Bq\ g^{-1}$)
H-3	$1.88\ 10^{2}$	$3.83\ 10^{4}$	5,000	5,000
C-14	$1.19\ 10^{2}$	$1.82\ 10^{3}$	5,000	5,000
Cl-36	$5.08\ 10^{-1}$	$1.44\ 10^{3}$	5,000	5,000
Ca-41	$1.05\ 10^{3}$	$4.42\ 10^{7}$	5,000	5,000
Mn-54	$3.10\ 10^{5}$	$5.70\ 10^{6}$	5,000	5,000
Fe-55	$1.96\ 10^{7}$	$1.04\ 10^{7}$	5,000	5,000
Co-60	$2.09\ 10^{4}$	$3.36\ 10^{5}$	200	1,000
Ni-59	$3.44\ 10^{4}$	$2.40\ 10^{7}$	5,000	5,000
Ni-63	$3.86\ 10^{3}$	$8.11\ 10^{6}$	5,000	5,000
Zn-65	$2.48\ 10^{5}$	$3.73\ 10^{4}$	5,000	5,000
Se-79	$8.58\ 10^{2}$	$1.55\ 10^{3}$	2,000	3,000
Sr-90	$9.61\ 10^{2}$	$6.53\ 10^{4}$	200	1,000
Mo-93	$5.95\ 10^{1}$	$4.58\ 10^{6}$	5,000	5,000
Zr-93	$3.27\ 10^{3}$	$4.22\ 10^{5}$	5,000	5,000
Nb-93m	$2.08\ 10^{4}$	$5.83\ 10^{6}$	5,000	5,000
Nb-94	$7.83\ 10^{1}$	$2.14\ 10^{5}$	100	500
Tc-99	$1.73\ 10^{1}$	$8.11\ 10^{5}$	200	1,000
Ru-106	$1.59\ 10^{5}$	$1.60\ 10^{3}$	5,000	5,000
Ag-108m	$2.89\ 10^{2}$	$2.83\ 10^{4}$	100	500
Ag-110m	$3.48\ 10^{4}$	$7.87\ 10^{4}$	2,000	3,000
Cd-109	$1.39\ 10^{6}$	$1.04\ 10^{6}$	5,000	5,000
Sb-125	$2.04\ 10^{4}$	$8.10\ 10^{3}$	5,000	5,000
Sn-119m	$1.05\ 10^{7}$	$4.70\ 10^{6}$	5,000	5,000
Sn-123	$3.71\ 10^{6}$	$1.21\ 10^{6}$	5,000	5,000
Sn-126	$1.37\ 10^{2}$	$3.46\ 10^{5}$	50	250
Te-127m	$2.80\ 10^{6}$	$1.04\ 10^{4}$	5,000	5,000
I-129	$9.36\ 10^{1}$	$2.17\ 10^{2}$	200	1,000
Ba-133	$2.12\ 10^{2}$	$1.05\ 10^{6}$	5,000	5,000
Cs-134	$8.46\ 10^{4}$	$5.15\ 10^{3}$	5,000	5,000
Cs-135	$1.43\ 10^{3}$	$1.23\ 10^{4}$	5,000	5,000
Cs-137	$1.08\ 10^{3}$	$2.70\ 10^{3}$	200	1,000
Ce-144	$8.89\ 10^{6}$	$1.54\ 10^{5}$	5,000	5,000
Pm-147	$3.05\ 10^{7}$	$2.08\ 10^{6}$	5,000	5,000
Sm-147	$3.83\ 10^{1}$	$1.10\ 10^{3}$	200	1,000
Sm-151	$5.90\ 10^{4}$	$2.63\ 10^{6}$	5,000	5,000
Eu-152	$6.69\ 10^{3}$	$2.50\ 10^{5}$	2,000	3,000
Eu-154	$2.08\ 10^{4}$	$1.98\ 10^{5}$	5,000	5,000
Eu-155	$9.23\ 10^{5}$	$1.53\ 10^{6}$	5,000	5,000
Gd-153	$3.38\ 10^{6}$	$3.45\ 10^{6}$	5,000	5,000
Pb-210	$7.84\ 10^{0}$	$2.11\ 10^{0}$	50	250
Po-210	$8.57\ 10^{3}$	$2.45\ 10^{3}$	2,000	3,000
Ra-226	$1.39\ 10^{0}$	$5.40\ 10^{2}$	10	50
Ra-228	$4.80\ 10^{3}$	$1.77\ 10^{2}$	200	1,000
Ac-227	$3.06\ 10^{1}$	$1.85\ 10^{1}$	50	250
Th-228	$8.11\ 10^{4}$	$2.42\ 10^{2}$	200	1,000
Th-229	$4.27\ 10^{0}$	$4.11\ 10^{1}$	20	100
Th-230	$2.03\ 10^{0}$	$1.05\ 10^{2}$	100	500
Th-232	$2.16\ 10^{0}$	$6.21\ 10^{1}$	10	50

Radionuclide	Minimum radiological capacity limit from scenarios relevant to both landfills (TBq)	Radiological capacity: fire scenario for non-hazardous landfill (TBq)	Maximum specific activity in a consignment (Bq g^{-1})	Single package specific activity limit (Bq g^{-1})
Pa-231	$7.73\ 10^{-1}$	$7.53\ 10^{1}$	10	50
U-232	$2.12\ 10^{1}$	$1.31\ 10^{2}$	50	250
U-233	$2.52\ 10^{-1}$	$1.10\ 10^{3}$	200	1,000
U-234	$1.55\ 10^{0}$	$1.12\ 10^{3}$	200	1,000
U-235	$2.09\ 10^{-1}$	$1.24\ 10^{3}$	200	1,000
U-236	$4.24\ 10^{0}$	$1.21\ 10^{3}$	200	1,000
U-238	$4.17\ 10^{0}$	$1.32\ 10^{3}$	200	1,000
Np-237	$7.47\ 10^{-2}$	$2.11\ 10^{2}$	200	1,000
Pu-238	$7.47\ 10^{1}$	$9.58\ 10^{1}$	200	1,000
Pu-239	$3.89\ 10^{0}$	$8.78\ 10^{1}$	100	500
Pu-240	$5.98\ 10^{0}$	$8.78\ 10^{1}$	200	1,000
Pu-241	$1.66\ 10^{3}$	$4.58\ 10^{3}$	5,000	5,000
Pu-242	$3.41\ 10^{0}$	$9.58\ 10^{1}$	200	1,000
Pu-244	$1.80\ 10^{0}$	$9.58\ 10^{1}$	200	1,000
Am-241	$5.51\ 10^{1}$	$1.10\ 10^{2}$	100	500
Am-242m	$4.14\ 10^{1}$	$9.10\ 10^{1}$	100	500
Am-243	$7.73\ 10^{0}$	$1.10\ 10^{2}$	200	1,000
Cm-242	$1.46\ 10^{4}$	$1.78\ 10^{3}$	200	1,000
Cm-243	$2.36\ 10^{2}$	$1.52\ 10^{2}$	200	1,000
Cm-244	$6.24\ 10^{2}$	$1.85\ 10^{2}$	200	1,000
Cm-245	$1.45\ 10^{1}$	$1.06\ 10^{2}$	200	1,000
Cm-246	$4.78\ 10^{1}$	$1.08\ 10^{2}$	200	1,000
Cm-248	$1.25\ 10^{0}$	$2.93\ 10^{1}$	50	250
Any other radionuclide	$7.47\ 10^{-2}$	$2.11\ 10^{0}$	10	50

H.5. Consequences in relation to the disposal of solid waste: local to site

59. The concentrations and exposure levels are addressed in the radiological assessment (summarised in Section 6 of the main report and detailed in Appendix E).

60. The scenarios considered in the ESC for the period of authorisation and the highest doses per radionuclide disposed of at the maximum inventory (the inventory that meets the radiological capacity and the constraint of 5% of the void is LLW) are listed in Table 234 (doses to site workers are not reported here as they are not relevant to the impact on other countries).

Table 234 Highest dose from disposal of the maximum inventory obtained in the scenarios for members of the public in the vicinity of the site during the period of authorisation

Scenario	Section of ESC	Exposed group	Highest dose from maximum inventory* (µSv y^{-1})
Period of Authorisation – likely to occur			
Direct exposure during emplacement	6.1.1.1	Member of public	12 (at a distance of 50 m) 3 (at a distance of 100m)
Leachate processing off-site	App E.3.7 Table 99	Treatment worker	23
		Farming family	0.7
		Fishing family	0.01
Inadvertent release to atmosphere	6.1.1.5 Table 12	Member of public	13 (H-3) 247 (C-14) 5 (Radon from Ra-226 disposal)
Landfill gas	6.1.1.5	Member of public	<0.01 (H-3) 3 (C-14)
Period of Authorisation – unlikely to occur			
Leachate spillage	6.1.2.3 Table 14	Farming family	48
Dropped load	6.1.2.1 Table 13	Member of Public	6.5
Landfill fire	6.1.2.4 Table 15	Member of Public	<10

* Dose is calculated for each radionuclide at the maximum inventory. The highest value is presented. The sum of fractions will be applied to limit the inventory of each radionuclide disposed of.

61. The scenarios considered in the ESC for the period after the period of authorisation and the highest doses per radionuclide disposed of at the maximum inventory are listed in Table 235.

Table 235 Highest doses to members of the public in the vicinity of the site from disposal of the maximum inventory after the period of authorisation

Scenario	Section of ESC	Exposed group	Highest dose from the maximum inventory (µSv y^{-1})
After the Period of Authorisation – likely to occur			
Recreational user	6.2.1.1 Table 17	Member of public	20
Groundwater to estuary	6.2.1.3 Table 20	Family on estuary	0.738
Dog walker after erosion*	6.2.1.2 Table 18	Member of public	13 (increasing to 20 after in-growth)
Erosion to coast*	6.2.1.2 Table 19	Member of public	20
Inundation from sea	6.2.1.4 Table 21	Farming family	20
After the Period of Authorisation – unlikely to occur			
Water abstraction at site boundary	6.2.2.1 Table 22	Farming family	8.88
Bathtubbing	6.2.2.2 Table 23	Farming family	20
After the period of authorisation – intrusion scenarios			
Borehole drill operative	6.3.2 Table 25	Worker	116
Material recovery	6.3.2 Table 25	Worker	133
Resident (cap intact)	6.3.3 Table 26	Site resident	1480
Housing	6.3.4 Table 27	Resident	1480
Smallholder	6.3.4 Table 27	Farming family	1255
Road construction	6.3.2 Table 25	Worker	0.15
Large heterogeneous items	6.4	Resident	1630

* Erosion of the site in the future is assumed to occur for the ESC. This limits the disposal of some radionuclides

62. The assessments show that disposal at Port Clarence meets the radiological criteria specified by the Environment Agency in their guidance (Environment Agencies, 2009). Hence, there is no unacceptable risk of exposures to operatives or the public at the site or in the vicinity of the site.

H.6. Impact on other countries

63. Discharges from the site (leachate, groundwater, dust and gases) have the potential to carry radioactivity and may therefore result in migration of contamination across borders. Also, site erosion and inundation by the sea may lead to radioactivity in coastal waters. The location of the site is shown in Figure 45 and Table 236 summarises the neighbouring countries of the UK. The nearest country is Ireland but Denmark is in the direction of prevailing winds.

Table 236 Notifiable countries closest to the UK

Country	Distance from Port Clarence (km)	Bearing (degrees)	Population (Eurostat, 2024)
Ireland	325	235	$5.34\ 10^{6}$
France	450	153	$6.84\ 10^{7}$
Belgium	464	120	$1.18\ 10^{7}$
Netherlands	425	111	$1.79\ 10^{7}$
Germany	525	99	$8.34\ 10^{7}$
Denmark	600	76	$5.96\ 10^{6}$
Sweden	870	56	$1.05\ 10^{7}$

Figure 45 Location of Port Clarence in relation to other notifiable countries

H.6.1. Consequences in relation to the expected scenarios

64. Doses received by the members of the public in the vicinity of the site are expected to be higher than those received by notifiable countries due to the dilution caused by the increased distance from the site. There are no identified special pathways from the site to other countries. In theory the sewage sludge from the leachate processing treatment

works could be exported, resulting in impacts to the soils or agricultural community of other notifiable countries but in this case the doses to farmers using the sludge would be expected to be no higher than the doses to local farmers using the sludge (0.83 µSv y^{-1}).

65. The doses from some expected scenarios for the site are larger than 10 µSv y^{-1} for some members of the exposed group close to the site, and therefore doses to neighbouring EU Member States have been assessed for these scenarios. Although the dose to a member of the public at 50 m from the site for emplacement is above 12 µSv y^{-1}, the dose at a distance of 100 m is 3 µSv y^{-1} and therefore the dose to a member of a notifiable country would be insignificant.

66. The expected scenarios assessed for the period of authorisation are:

- Leachate processing off-site: treatment worker
- Inadvertent release to atmosphere
- Landfill gas

67. The expected scenario assessed for after the period of authorisation is:

- Recreational user
- Dog walker after erosion
- Release to estuary from groundwater or erosion

H.6.1.1. Leachate processing off-site: treatment worker

68. The treatment worker receives external exposure from radioactivity in sewage media and internal exposure via inadvertent ingestion and inhalation of sewage media. There is no potential for transboundary impact in relation to this pathway, as the treatment works will always be situated in the UK, and it is likely to be local to the site.

H.6.1.2. Release to atmosphere

69. This scenario considers the inadvertent release of gases during and after operations leading to the exposure of public at some distance from the source and considers radioactive carbon, tritium and radon. Radon has a short half-life and therefore radon gas from the site will decay before it reaches other countries. Hence, only H-3 and C-14 are considered here.

70. The individual dose to a member of the public in Denmark can be estimated from the individual dose to a member of the public 100 m from the source by applying the ratio of the dispersion factors for the different distances. $F_{Dispersion,Denmark}$ (Bq m^{-3} per Bq y^{-1}), the dispersion factor for Denmark, was calculated using PC-CREAM 08 (HPA, 2015) for a distance of 600 km (65% category D and 10% rain in C and D) and $F_{Dispersion,Local}$ was calculated a distance of 100 m (65% category D and 10% rain in C and D). The ratio of the dispersion factor for Denmark to that for the local member of the public is 1.08 10^{-5}.

71. The greatest dose was to a child in Denmark, and this dose from H-3 or C-14 release for the maximum inventory would be less than 3 nSv y^{-1} for all scenarios (Recreational user, Landfill gas and Inadvertent release to atmosphere).

H.6.1.3. Release to the estuary

72. A walker passing close to the eroded waste will receive a dose from the exposed bank. The doses received by members of the public in the vicinity of the site from direct exposure and inhalation or ingestion of soil particles will not occur for members of the public in neighbouring countries due to the distances involved.

73. The relevant pathway for transboundary radioactive contamination is release to the estuary from groundwater migration or erosion of the site and leaching of the eroded wastes. Releases to the estuary following groundwater migration and or to the coast following erosion of materials and leaching with subsequent dispersion in the North Sea are considered and are used to limit disposal at Port Clarence. Protection of local members of the public by limiting doses to less than 20 µSv y^{-1} (based on concentrations in the local marine environment) ensures that doses in neighbouring States would be very low considering the large dilution in the North Sea (the volume of the relevant regional marine compartment is several orders of magnitude greater than the volume of the local marine compartment).

H.6.2. Consequences in relation to the reference accidents and unlikely events

74. Doses received by members of the public in the vicinity of the site are expected to be higher than those received by notifiable countries due to the dilution caused by the increased distance from the site. There are no identified special pathways to neighbouring countries. The relevant pathway for transboundary radioactive contamination is inhalation of gaseous releases or dust as the dilution in the aquatic pathway would be very large. The potential impacts of the reference accidents and unlikely events are sufficiently low as to be within national and international guidance and limits.

75. The doses received by a worker (Borehole drill operative, Material recovery) or a member of the public exposed to large heterogeneous items consider inhalation exposure pathways. If it is assumed that the maximum doses are due only to dust or gaseous releases, the resulting doses in neighbouring States are all less than 20 nSv y^{-1}.

76. The reference accidents and unlikely events potentially leading to a dose of 1 mSv or greater are considered for transboundary effects. For the period of authorisation the following scenario is considered:

- Landfill fire
- Intrusion scenario (Smallholder and Resident)

H.6.2.1. Landfill fire impact:

77. In the extremely unlikely event of a landfill fire in the non-hazardous waste landfill the maximum calculated dose to an individual in proximity to the fire (250 m) is

approximately 1.1 mSv y^{-1} from inhalation of dust based on the maximum inventory that applies to the non-hazardous waste landfill. The controls placed on disposals to the non-hazardous site will limit exposure in the unlikely event of a landfill fire in the non-hazardous waste landfill to 0.3 mSv y^{-1}. This is a very cautious assessment as it assumes that the same person is exposed to 2 fires in a year and there are no additional controls applied to the non-hazardous waste disposals.

78. Hence, the maximum doses due to dispersion of dust or gaseous releases to neighbouring states is less than 20 nSv y^{-1} due to the additional dispersion over the increased distance.

H.6.2.2. Smallholder and Resident:

79. The highest dose from the maximum inventory comes from C-14 (dose to adult resident on the site of 1.4 mSv y^{-1}). The dose to the smallholder or resident is the dose to a person living on the site and is therefore not relevant to the impact on other countries. The only pathway that could lead to off-site exposure is inhalation of dust suspended by the smallholder/resident or gas released from the site. However, it is not credible that significant levels of suspended dust would reach other countries from farming a smallholding. Therefore, the impact on other countries would be negligible due to the additional dispersion that would occur over the increased distance (dose would be less than 20 nSv y^{-1}).

H.7. Implications in relation to the current emergency plans and the current environmental monitoring:

80. On-site operations and working procedures will be similar to those used at the ENRMF that has been operating as a LLW disposal site since 2015. These are local actions and there are no implications for transboundary responses.

81. Environmental monitoring will be undertaken at the site boundary.

Eden Nuclear and Environment Ltd registered address:
Unit 1 Mereside,
Greenbank Road,
Eden Business Park,
Penrith,
Cumbria
CA11 9FB

Eden
Nuclear and Environment

ISOQAR
REGISTERED
UKAS
MANAGEMENT
SYSTEMS
0026

Certificate Number 12469
ISO 9001

Company No 6314579, registered in England and Wales