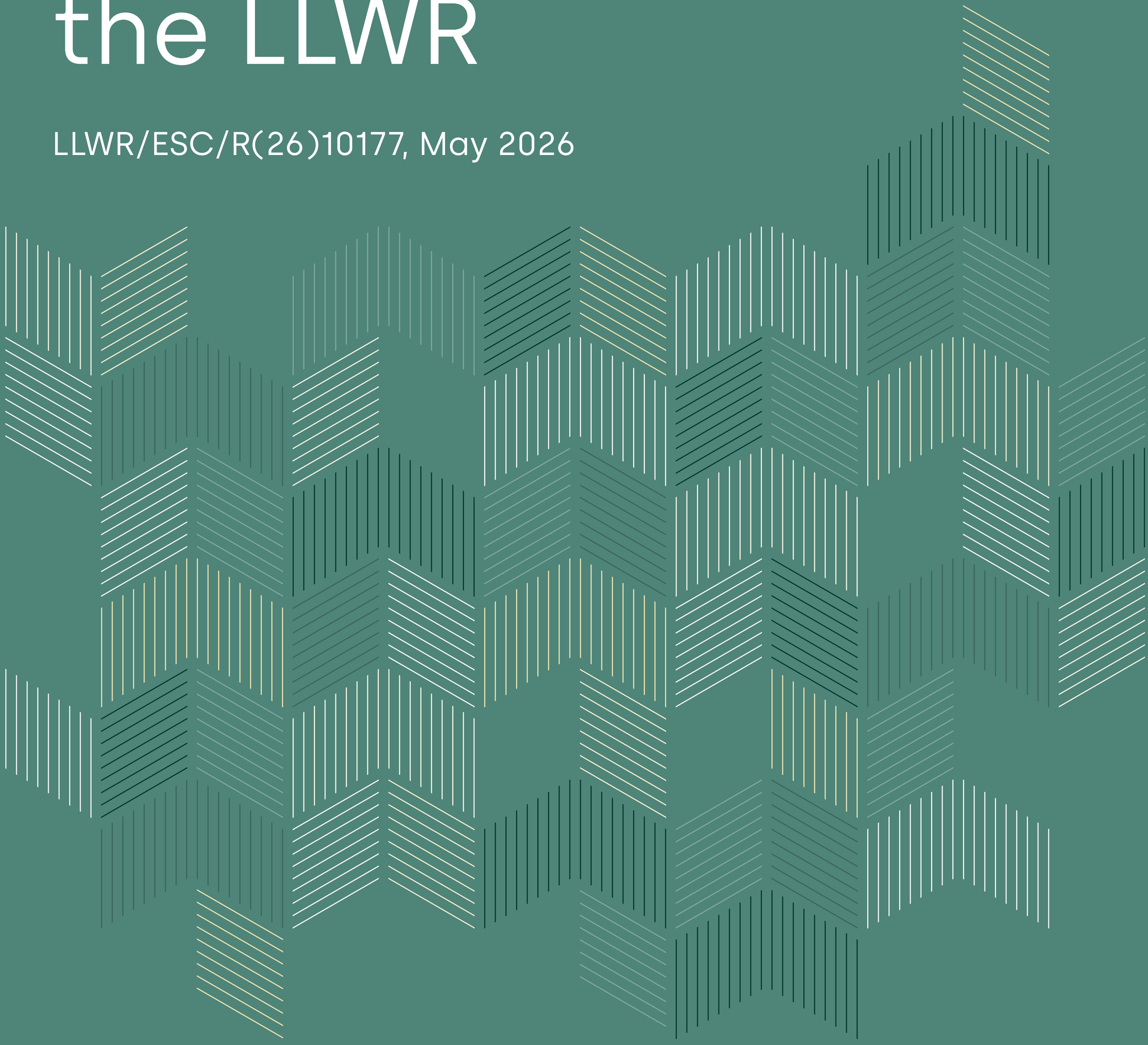
Nuclear Waste Services

SAFETY FUNCTIONS

2026 Environmental Safety Case for the LLWR

LLWR/ESC/R(26)10177, May 2026



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Preface

The Low Level Waste Repository (LLWR) is the United Kingdom's principal facility for the disposal of solid Low Level Waste (LLW). It is a near-surface disposal facility in which waste was disposed in trenches and is now being disposed in vaults excavated into the ground surface. The LLWR is owned by the Nuclear Decommissioning Authority (NDA) and operated on their behalf by a wholly-owned subsidiary division, Nuclear Waste Services Ltd.

We, Nuclear Waste Services, are committed to operating the LLWR as a safe and efficient facility that provides a continuing option for the disposal of LLW in the United Kingdom. This will be achieved consistent with good practice for the near-surface disposal of radioactive waste, in accordance with environmental, health and safety, and security regulation and guidance, and in compliance with the terms of our Nuclear Site Licence and Permit to dispose of radioactive waste. We are also committed to working with the NDA to ensure optimal use is made of the LLWR to support the NDA's mission, in accordance with government policy. This may involve the disposal of a broader range of wastes than just LLW as currently defined in the United Kingdom[1].

One of the means we use to operate the LLWR safely is to maintain and implement an Environmental Safety Case for the site. This is one of the reports presenting the 2026 Environmental Safety Case for the LLWR – the 2026 ESC. The 2026 ESC is a major update based on a comprehensive review of our previous 2011 ESC and subsequent developments. The 2026 ESC addresses both the environmental safety of the disposal facility and the rest of the site. It considers the disposal of both LLW and some less-hazardous Intermediate Level Waste (ILW). Assessing the disposal of some less-hazardous ILW does not imply any decision has been made to dispose of such waste at the LLWR. The work has been undertaken to understand the safety implications if such a decision were made and hence support consideration of the option by the NDA.

The 2026 ESC is issued under the authority of the Nuclear Waste Services' Executive Director of Sites and Operations.

The 2026 ESC consists of documents at two levels:

- A single 'Level 1' report outlines the plan for the development of the LLWR and the main arguments concerning environmental safety and how it is achieved.
- A series of 'Level 2' reports present the evidence that underpins our safety arguments, including descriptions of our management framework, system understanding, design and management choices, assessments and implementation.

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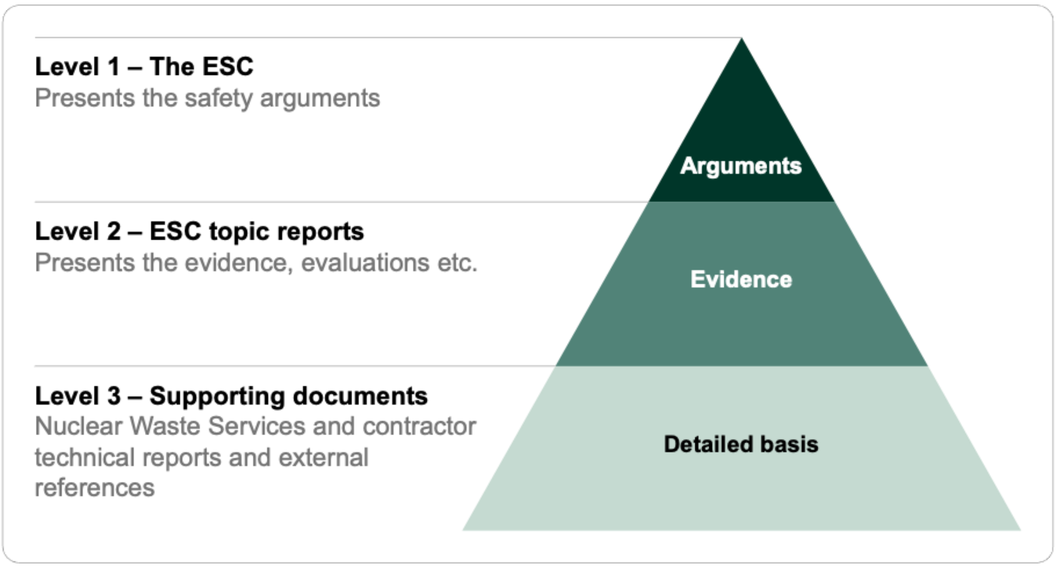
[1] In government policy, LLW is defined as radioactive waste having a radioactive content not exceeding four gigabecquerels per tonne (GBq t^{-1}) of alpha or 12 GBq t^{-1} of beta/gamma activity.

This is the Level 2 report *'Safety Functions'*. The ESC Level 1 and 2 reports are listed in the table below, which also shows for the Level 2 reports the set of arguments for which each report mainly provides evidence. A brief description of the contents of each Level 2 report is also given. The ESC is supported by a large number of technical and scientific reports and references that we refer to as 'Level 3' documents. We have also produced a Guide to Key Points of the ESC, to help a wider group of stakeholders understand its nature, conclusions and implications.



Level 1	
Main Report [1]	
Level 2	
Management and dialogue	
Management and Dialogue [2]	Describes our environmental management systems and interactions with regulators and stakeholders
System characterisation and understanding	
Site History and Description [3]	Provides a history and description of the site
Disposal Facility Inventory [4]	Describes the wastes already disposed and wastes that may be disposed at the facility
Engineering Design [5]	Presents the engineering design of the current facility and proposed changes as further disposal vaults are built and the disposal facility is closed

Near Field [6]	Describes our understanding of the chemical and physical evolution of the engineered disposal system
Hydrogeology [7]	Describes our understanding of the geology and hydrogeology of the site
Site Evolution [8]	Describes our understanding of how the site will evolve, with a focus on coastal erosion
Monitoring [9]	Presents our programme of environmental monitoring supporting the ESC
Optimisation and Site Development Plan	
Optimisation and Site Development Plan [10]	Describes our approach to optimising the design and management of the disposal facility and wider site, and sets out our Site Development Plan
Waste Management Plan [11]	Presents our plans for managing the wastes produced by previous uses and operation of the site
Assessments	
Safety Functions (this report)	Presents our understanding of how the different aspects of the repository system and its management contribute to the safety of the facility
Engineering Performance Assessment [12]	Presents our analysis of how the various components of the engineered disposal system will perform, which is an input into our impact assessments
Environmental Safety During the Period of Authorisation [13]	Presents evidence that the LLWR is currently being operated safely and will continue to be so during the period that the facility is permitted
Assessment of Long-term Radiological Impacts [14]	Presents evidence that, if the LLWR is managed in accordance with the Site Development Plan, the site will remain safe in the long term
Hydrogeological Risk Assessment [15]	Presents evidence that the disposal facility protects groundwater from both radiological and non-radiological contaminants in the disposed wastes now and will continue to do so in the future

Assessment of Radiological Impacts on Non-human Biota [16]	Presents evidence that the LLWR does not have adverse consequences for non-human biota populations now and will not in the future
Implementation	
Implementation [17]	Sets out how we use the ESC to manage the site, including setting Waste Acceptance Criteria and other controls on the types and quantities of waste accepted for disposal
Audit	
Addressing Regulatory Requirements and Feedback [18]	Provides a cross-reference between the contents of the ESC and regulatory guidance and feedback

Executive Summary

The Environmental Safety Case (ESC) for the Low Level Waste Repository (LLWR) presents a set of claims concerning the environmental safety of disposals of solid radioactive waste, substantiated by a structured collection of arguments and evidence. We present these claims, arguments and evidence in various ways and at various levels of detail in a comprehensive set of documents. The detail is necessary to show with confidence that members of the public and the environment will be adequately protected from the potential radiological hazards.

The volume of information that is contained in the ESC can mean that the key features of the LLWR's disposal system that provide environmental safety cannot be easily explained as a whole. This issue is recognised in national and international guidance, which introduces the concept of 'safety functions' to provide a means of distilling the key mechanisms by which a disposal system delivers its safety performance.

In our approach to ensuring the environmental safety of the LLWR and its wastes, safety functions are provided by the 'controls' that are applied by the disposal system and the way it is operated. The environment within which the LLWR sits also provides natural controls on the potential exposures of people and non-human biota, and these are relevant to consider and document. The safety functions that correspond to the various controls describe the various ways in which the components contribute to environmental safety.

The controls and their safety functions address the specific pathways by which a radiological hazard could be presented to people and the environment:

- Radionuclide migration in groundwater;
- Releases of radionuclides as gases and vapour;
- Discharges of radionuclides to surface water;
- External irradiation;
- Coastal erosion; and
- Inadvertent human intrusion into the disposal facility.

As the nature of the release, the characteristics of the radiological hazard and the timescale over which it is relevant differs for each pathway, so the controls and safety functions differ. In some cases, specific disposal system components provide the control, e.g. the system for managing leachate during operations. In other cases, a component provides many different safety functions, e.g. the grout added to waste containers stabilises the wastes, provides alkaline conditions that retard radionuclides, provides a barrier to radon gas release, etc. Some controls are a consequence of addressing other issues - e.g. the grout added to stabilise the wastes also provides some additional radiation shielding of the wastes as well as other benefits. Others are simply an intrinsic part of the environmental setting, e.g. the retardation of contaminants that occurs by sorption to geological materials along transport pathways in groundwater. The relationship between the controls placed on the hazards posed by the wastes, the associated safety functions, the components that deliver them, and the pathways involved, is therefore complex. The whole of the LLWR is subject to ongoing optimisation of its controls, both managerial and engineered, to enhance its environmental safety. This is informed by extensive research and operational experience.

There is no universally agreed method for determining safety functions, but generally two approaches have been used: an analysis that starts with the disposal system components and systematically asks what safety functions they perform; or an approach that starts with high-level safety objectives, and examines how these are fulfilled by the disposal system. While the first approach is methodical, it is not well suited to the LLWR, for which the disposal concept has changed over time. It may therefore overlook safety functions provided collectively by various system components, incidental benefits, and aspects of the environment that are important to environmental safety.

The LLWR has evolved over more than 65 years and it is composed of a range of different engineered barriers, some of which have been introduced to supplement those originally present. The second approach, of starting with the high-level safety objectives and safety functions, is therefore best suited to describing the safety functions of the LLWR. This method was used in the 2011 ESC to communicate how our Environmental Safety Strategy will be delivered through a range of controls that apply to various aspects of the disposal system. For the 2026 ESC, we have sought to develop the detail in which we describe the controls and associated safety functions. To do this, we have made use of the ongoing process of optimisation of the disposal system and drawn on our initial work to develop a Disposal System Specification, which captures the requirements for vaults and other engineered features. We have used judgement based on our knowledge of the disposal system and its performance to identify the key controls and safety functions presented here. In each case, we have explicitly stated the safety function(s) that each control provides and characterised its effect, making use of information from assessments and other studies where relevant.

The key controls, associated safety functions, and the components involved in providing the environmental safety of the LLWR, are summarised below. As the hazards differ for each potential pathway by which people and the environment can be exposed, the relevant controls and safety functions are presented for each, along with simple indications of their effectiveness.

An overarching form of control that applies to all pathways is the control over the wastes that are accepted for disposal in the future. We use Waste Acceptance Criteria (WAC) to control the concentrations and amounts of radiological and non-radiological hazardous materials, the physical characteristics of the waste, and its biogeochemical characteristics. We use our understanding of the LLWR and its performance, developed through the ESC and other work, to define the requirements which must be met by waste consignors. The WAC provide the primary method by which we ensure that the waste accepted for disposal is consistent with the ESC and the requirements at the facility for transporting and handling it.

Main controls and safety functions for release in groundwater

Controls on	Safety function	Main components	Function and its effectiveness
Waste characteristics	Ensures groundwater releases do not lead to unacceptable risks	Site management	We control the radionuclide inventory that will be disposed to ensure compliance with the regulatory criteria for radiation dose and risk. We also place requirements on the physical and chemical properties of the waste if such controls are required to promote appropriate system performance.
Waste contact with water	Reduce leachate generation Reduce grout leaching rate Manage leachate migration	Containers, CPUs[2], warehouses, cut-off wall, interim cap, final cap	Water contacting waste can generate radioactive leachate. The main source of water is precipitation. In the operational period, trench wastes are covered with an interim cap, vault wastes are in containers which in the future will be covered, and leachate is collected. Once the LLWR is closed, the key features are the low permeability layers in the caps. As an indication of the effectiveness of the final cap, over 99% of I-129 (a long-lived, mobile radionuclide) is retained in Vault 8 over the assessment timeframe. For more strongly sorbing radionuclides, an even lower proportion would be released from the vaults.
Wasteform integrity	Protect engineered barriers Support the function of other engineered barriers	Grout, containers, void fill, CPUs, vault structures	The final cap will be thick and so will place a considerable load on the wastes. Slumping or compression of wastes could degrade the low permeability layers in the cap, so voids are filled. In vaults and the trenches and existing vault wastes will be surcharged before the final cap is emplaced to ensure that the structural performance of the engineering is assured. The reference assessed cap performance leads to risks a factor

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[2] Container Protection Units are steel-reinforced concrete slabs added to the top of waste container stacks, primarily intended to protect them from loading by the final cap.

Controls on	Safety function	Main components	Function and its effectiveness
			of 10 lower than a variant case considering poorer than expected cap performance.
Chemical conditions	Reduce corrosion Reduce biodegradation Reduce mobility by sorption	Grout, CPUs, warehouses, cut-off wall, interim cap, final cap	Cementitious grout which is added for void fill and stability will also condition water to high pH. Vault structures limit rainwater ingress thus minimising the leaching of grout and thus help maintain the alkalinity. The alkaline conditions reduce corrosion (which degrades containers leading to release of contaminants), reduce contaminant mobility in groundwater and inhibit biodegradation (which generates voidage). For example, corrosion rates of steel are a factor of six lower in the expected pH 12.5 conditions in vault containers than in a pH 10-11 environment.
Groundwater concentrations	Reduce migration by sorption Dilution and dispersion	Geology	The characteristics of the geology beneath the LLWR extend the time contaminants take to migrate to the surface, providing time for radioactive decay, and reduce the concentrations released to the surface by dilution and dispersion. Radionuclide amounts are reduced by at least a factor of 100 between the base of the LLWR and release to the surface environment.
Environmental concentrations	Dilution and dispersion	Surface water and marine environment	The majority of the groundwater flowing from the LLWR will discharge to the highly dispersive marine environment. Assessed concentrations in the local coastal waters are a factor of 100,000 times lower than those in the groundwater due to natural dilution and dispersion.

Controls on	Safety function	Main components	Function and its effectiveness
Land use restrictions	Control use of surrounding land during PoA	Site management	The region between the LLWR facility and the coastline constitutes part of a site of special scientific interest (SSSI). NDA has a 999-year lease on this land. This ensures that we have control over future development on the SSSI, including installation of groundwater abstraction wells. This is important because assessed doses from groundwater wells in this region are a factor of 10,000 higher than doses from groundwater releases to the marine environment.

Main controls and safety functions for gas release

Controls on	Safety function	Main components	Function and its effectiveness
Waste characteristics	Ensures gas releases do not lead to unacceptable risks	Site management	We control the radionuclide inventory that will be disposed to ensure compliance with the regulatory criteria for radiation dose and risk. We also place requirements on the physical and chemical properties of the waste if such controls are required to promote appropriate system performance.
Gas generation and release from waste	Reduce corrosion Reduce biodegradation Reduce gas release	Grout, containers, CPUs, warehouses, cut-off wall, interim cap, final cap	The alkaline conditions generated by the grout reduce corrosion and biodegradation, both of which generate gas. C-14 released from waste in inorganic form may also react with cement minerals in the grout and form carbonate, reducing the proportion of C-14 released as gas. The grout and containers also act as a barrier for radon gas migration (increasing the transport path length, which increases decay of radon before it is released). Less than 15% of the radon generated is released, and less than 5% of the C-14 from graphite and irradiated steels is released within the assessment timeframe. Release of C-14 is reduced by limiting water contact with waste and minimising steel corrosion rates through high pH conditions.
Gas transport and release to air	Manage gas movement Manage gas pressure	Waste placement, final cap	Managing the rate of bulk gas transport and release prevents pressurisation which could damage the final cap. The cap includes a gas collection layer and it will be vented for a period to limit the peak pressure. The amount of radon, which has a short half-life, that is released is affected by the time it is takes to be transported by bulk gas. The total thickness of the cap and profile material, the number of defects in the

Controls on	Safety function	Main components	Function and its effectiveness
			geomembrane, and the use of the vent, all affect this. Waste placement can also be used to control the time it takes for of radon to be released.
Environmental concentrations	Limit site access during PoA Dilution and dispersion	Site management (access controls), atmosphere	Gas is released to air where it is dispersed rapidly. Concentrations are highest on-site, so access will be controlled during operations and when the site is closed but the vent is open. Concentrations of tritium and C-14 in foods are 50 times lower at an off-site farm during PoA than they would be on-site. Radon concentrations outdoors are three to four orders of magnitude lower than in a house situated on the cap.

Main controls and safety functions for managing liquid discharges during the Period of Authorisation

Controls on	Safety function	Main components involved	Function and its effectiveness
Waste characteristics	Ensures liquid discharges do not lead to unacceptable doses	Site management	We control the radionuclide inventory that will be disposed to ensure compliance with the regulatory criteria for radiation dose and risk. We also place requirements on the physical and chemical properties of the waste if such controls are required to promote appropriate system performance.
Waste contact with water	Reduce leachate generation Manage leachate migration	Grout, containers, CPUs, warehouses, cut-off wall, interim cap, final cap	Precipitation contacting waste can generate radioactive leachate. In the operational period, trench wastes are covered with an interim cap and vault wastes are in containers which in the future will be covered. Emplacement of the final cap is expected to reduce infiltration rates to below 1 mm per year, resulting in no significant leachate generation.
Leachate management	Collect leachate Prevent release to groundwater Prevent release to surface Dilution and dispersion	Vault structures, drainage system, cut-off wall site management, marine environment	Leachate is collected by a drainage network. The low permeability vault bases and walls prevent leakage to the surface or to groundwater. A clay layer in the base of the trenches limits releases and a cut-off wall prevents lateral leakage. Collected leachate is monitored and subject to controlled discharge through a pipeline to the sea, where it is rapidly dispersed. Measured concentrations in the marine environment and modelled doses are very low.

Main controls and safety Functions for managing external irradiation during the Period of Authorisation

Controls on	Safety function	Main components involved	Function and its effectiveness
Waste characteristics	Ensures that public doses from direct and scattered radiation are not unacceptable	Site management	We control the radionuclide inventory that will be disposed to ensure compliance with the regulatory criteria for radiation dose and risk. We also place requirements on the physical and chemical properties of the waste if such controls are required to promote appropriate system performance.
External dose rate	Waste placement Shielding of wastes Limit site access	Site management, grout, containers, CPUs, warehouses, cut-off wall, interim cap, final cap	The wasteform and structures provide radiation shielding and access controls during operations keep the public at a distance, where dose rates are lower. The final cap will provide essentially complete shielding. Currently, dose rates at the site boundary that are attributable to the LLWR are typically about one tenth of background, and at most about a third. Shielding by less than 20 cm of concrete will attenuate fluxes by an order of magnitude.

Main Controls and safety functions that reduce the consequences of coastal erosion

Controls on	Safety function	Main components involved	Function and its effectiveness
Waste characteristics	Ensures that coastal erosion does not lead to unacceptable doses or risks	Site management	We control the radionuclide inventory that will be disposed to ensure compliance with the regulatory criteria for radiation dose and risk. This includes controls on the presence of particles and the activity of sealed sources and discrete items that could be exposed during coastal erosion (and human intrusion, see below). We also place requirements on the physical and chemical properties of the waste if such controls are required to promote appropriate system performance.
Concentration in eroded waste	Timing of erosion Reduce waste concentrations Dilution and dispersion	Site management (placement of wastes), grout, hinterland, marine environment	Coastal erosion is inevitable, but the land between the LLWR and coast may delay the onset of erosion for over 1,000 years, during which time the total activity in the wastes reduces by a factor of six. The grout mixed with the waste reduces the effective concentrations that could expose people. Eroded waste will be broken up and dispersed into marine sediment when it will be diluted. An emplacement strategy of distributing the most hazardous waste across the vaults can spread their erosion over the largest possible time, minimising fluxes to the coastal environment.

Main controls and safety functions for limiting the likelihood and consequence of human intrusion

Controls on	Safety function	Main components involved	Function and its effectiveness
Waste characteristics	Ensures that human intrusion would not lead to unacceptable doses	Site management	We control the radionuclide inventory that will be disposed to ensure compliance with the regulatory criteria for radiation dose and risk. This includes controls on the presence of particles and the activity of sealed sources and discrete items that could be exposed during human intrusion (and coastal erosion, see above). We also place requirements on the physical and chemical properties of the waste if such controls are required to promote appropriate system performance.
Likelihood of encountering waste	Limit access during PoA Limit scope for waste disturbance	Site management (access controls), final engineered cap, retention of knowledge and records	While the site is being managed after it is closed, access controls will prevent waste being disturbed. The total activity reduces by a factor of two during the planned period of control. Access controls cannot be guaranteed indefinitely, therefore the cap is four to five m thick to ensure that unintentional excavation is unlikely to encounter waste. Records will be retained and, although they cannot be relied upon indefinitely, can be expected to reduce the likelihood of inadvertent intrusion.
Concentrations in the waste	Immobilisation of waste Reduce concentrations	Grout, final engineered cap	If waste were excavated, the concentrations that could expose people would be reduced by the uncontaminated material that would need to be excavated to reach the waste. For example, an average of 45% of the vault container volumes is filled with waste and the remainder with grout, providing a factor of two dilution.

Table of Contents

List of Tables

1 Introduction

1.1 Objectives

The Environmental Safety Case (ESC) for the Low Level Waste Repository (LLWR) presents a set of claims concerning the environmental safety of disposals of solid radioactive waste, substantiated by a structured collection of arguments and evidence. These demonstrate that members of the public and the environment are adequately protected and address the specific principles and requirements of the environment agencies’ Guidance on Requirements for Authorisation (GRA) [19].

The GRA states that the ESC should convey how the different components of the disposal system contribute to meeting these requirements. These are referred to as 'environmental safety functions' (shortened to simply 'safety functions' hereafter). There are varying definitions of safety functions, but the GRA describes them as

> *“The various ways in which components of the disposal system may contribute towards environmental safety, e.g. the host rock may provide a physical barrier function and may also have chemical properties that help to retard the migration of radionuclides.”*

The GRA requires that safety functions be presented and described in the ESC. In our approach to ensuring the environmental safety of the LLWR and its wastes, safety functions correspond to the optimised 'controls' that are applied to the disposal system and its operation. The concept of controls is central to our Environmental Safety Strategy. We define these controls as follows.

> *Controls are the measures provided by the disposal system that ensure that its impact on environmental safety is acceptably low. We determine the need for controls through a process of developing understanding and assessing performance, and use optimisation to identify our preferred set of controls.*

Controls are provided by the components of the disposal system.

> *The disposal system is considered to be the wastes, the wasteform and containers, the engineered structures of the LLWR and the surrounding environment (including ground and groundwater) that may be affected by the contaminants in the wastes.*

The components of the disposal system provide safety functions.

> *Safety functions describe various ways in which the components of the disposal system may contribute to environmental safety. Safety functions can involve controlling the wastes, isolating the hazard, containing it and/or*

> *managing residual releases. Multiple safety functions are employed by the disposal system to ensure that environmental safety is not overly dependent on any one.*

Controls can be provided by a single component or a range of different components, acting together to reduce the hazard posed to people or the environment. A given component can also provide several different controls and associated safety functions.

The purpose of this document is to present the controls, and the safety functions they provide through the various components of the LLWR disposal system, describing the way they act separately and together to manage the hazards to people and the environment.

1.2 Scope

Within the ESC, safety has been assessed in terms of the main pathways that could lead to the exposure of people and/or the environment to radioactivity associated with the LLWR. In the ESC, we use the term 'pathways' to refer to the routes or mechanisms by which contaminants may be released from the LLWR and give rise to exposure to humans or non-human biota. The pathways are:

- Radionuclide migration in groundwater;
- Releases of radionuclides as gases and vapour;
- Managed release of leachate;
- External irradiation;
- Coastal erosion;
- Inadvertent human intrusion into the disposal facility.

The nature of the release, the characteristics of the radiological hazard and timescale over which it is relevant differs for each pathway. The controls and safety functions that are required therefore differ significantly and can act through different components. In some cases, several disposal system components act together to provide a particular safety function. A single component may also provide a number of controls over different pathways simultaneously. An example is "control of the chemical environment of the waste". A control of the chemical environment is provided by the grout added to the waste containers. This delivers various safety functions, such as reducing the mobility of some key radioelements in groundwater and reducing the biodegradation rate which can lead to the evolution of some radioactive gases.

Controls, and the associated safety functions, are central to our overarching Environmental Safety Strategy for ensuring that the LLWR is safe. The strategy involves using our understanding of the disposal system and the hazards posed by the waste to inform its design and development so that it provides the controls that will ensure environmental safety. The LLWR is unusual in that the disposal concept and design have evolved over the more than 65 years that the facility has been operated. As it has developed, we have followed an approach of optimising the design of the facility to ensure it provides the required safety and environmental performance.

In this document, we gather together, organise and summarise the main controls on environmental safety and the related safety functions. The intention is to explain them and show our understanding of how they control the performance of the disposal system. We have not sought to identify exhaustively all potential safety functions nor to explain how the controls have been derived. Rather, we identify those that are central to describing how the disposal system will deliver the required performance. We have then characterised the safety functions in various ways:

- Where the behaviour and performance of the disposal system can be described with numerical modelling, information from safety assessments provide a means of quantifying the effects on safety of the controls that comprise the disposal system;
- Where aspects of the disposal system provide safety by other means (such as reducing the probability that a person could inadvertently be exposed to radioactive material), a qualitative description of how the controls contribute is more relevant.

Evidence is drawn mainly from the safety assessments and from the work to develop and optimise the disposal system to provide the required controls.

1.3 Structure

The GRA is not prescriptive about how safety functions are identified and described. Furthermore, different waste management organisations have taken different approaches to identifying and presenting safety functions.

Controls and their safety functions concern the disposal system, how it is managed and is expected to behave, therefore Section 2 provides a summary of the disposal system to which safety functions relate. We then describe our approach to identifying controls and related safety functions in Section 3, and explain the reasons it is appropriate to the unique characteristics of the LLWR. In Section 4, we present the key controls and safety functions of the disposal system that have been identified. The controls and safety functions are then described and characterised in Section 5.

2 Overview of Disposal System

The LLWR has received radioactive waste for more than 65 years. Since disposal operations commenced, in 1959, scientific understanding of radiation risks, the behaviour of engineered structures, and the environmental transport of contaminants, has increased considerably. Correspondingly, techniques for managing radioactive wastes and disposing of them safely have evolved substantially, as have the regulations surrounding the practice.

The LLWR disposal system is therefore unusual in that it does not have a single disposal concept (the suite of barriers intended to prevent or restrict contaminant release). Furthermore, the historical method of disposal reflects the knowledge of radiological risk, engineering and the environment held at the time.

This section provides a brief description of the disposal system as a whole: its historical components, more recent features, and future plans. This provides important context for the way in which controls can be applied to the LLWR and the safety functions that are provided.

2.1 Trenches

This section provides a brief description of the trenches and their engineering and associated engineered components and geology. The information is taken from NWS [5], where more details may be found.

The trench wastes were loose tipped into seven trenches of differing depths and sizes (see Figure 2.1 and Figure 2.2). They were constructed and filled in sequence from 1959 to 1995 and they have now been closed for many years. The trenches range from about 3.5 to 6.5 m in terms of the thickness (depth) of waste as disposed, with side slopes typically at 1 in 1 (see Table 2.1). The bases typically had a fall to the south of around 1 in 500 to facilitate leachate collection, the leachate being directed to the leachate management system. Most of the trenches were excavated into clay and those that were not (Trenches 5, 6 and 7) had bentonite rotavated into their bases. The status of the trenches from a design perspective is summarised in Table 2.1.

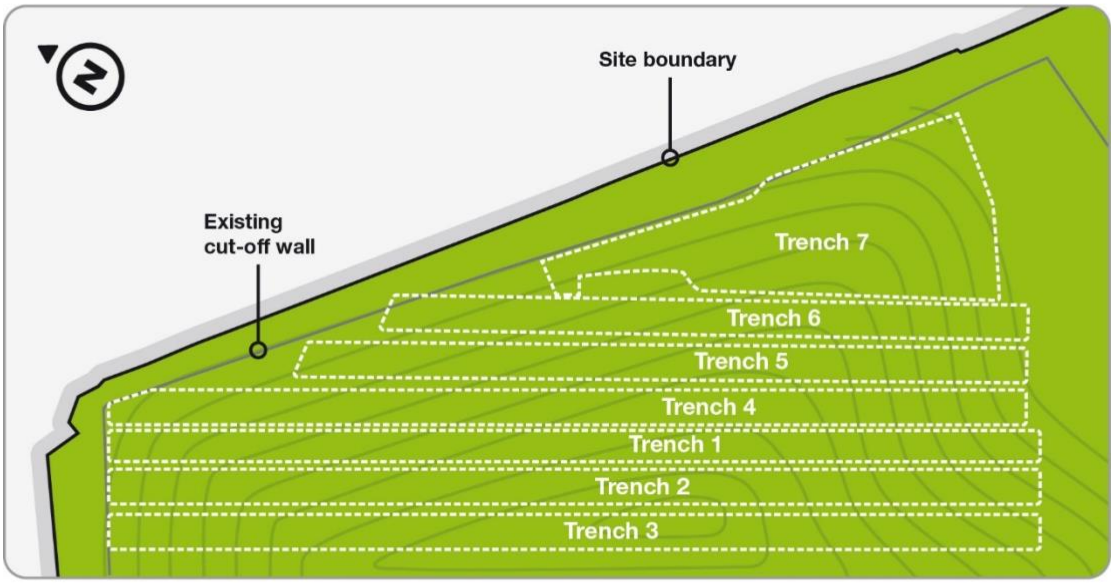

Figure 2.1: Trenches - schematic plan

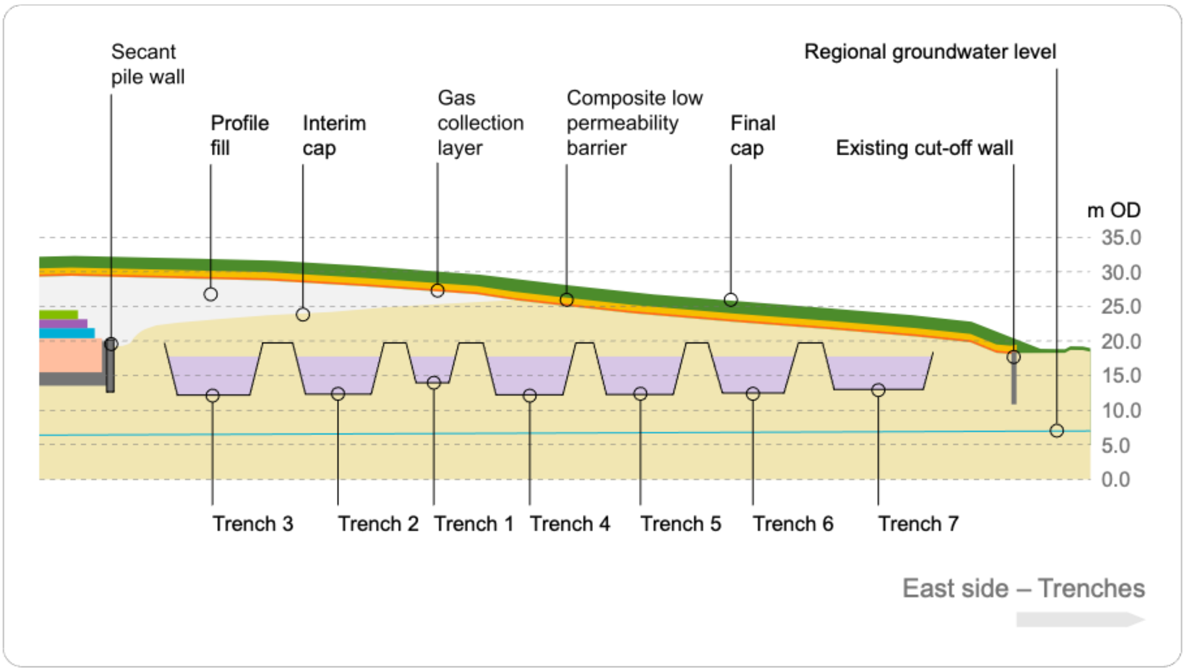

Figure 2.2: Trenches - schematic cross section (Note: Vertical scale exaggerated for clarity, see reference [5] for details)

Table 2.1: Trenches Design Summary

Category	Summary
Main Functions	Contain and control legacy loose tipped disposals. Hydrological management to reduce infiltration and to minimise lateral flows to other surface features, working with the cut-off wall.
Design Status	Already constructed (trenches and disposals). Southern Trenches Interim Membrane cap upgrade is currently being constructed.
Design and Optimisation History	Designed, built and operated from the late 1950s until 1995, including placement of the trench cut-off wall and the initial interim trench cap. Since 2012, several iterations of monitoring, assessment, optimisation and design leading to the replacement trench cap that is currently being implemented.
Implementation Schedule	Replacement trench cap is currently being implemented. Trench surcharge will be implemented consistent with final capping.
Priorities for Ongoing Optimisation and Design	No significant further optimisation of the design is expected.

2.2 Vaults

The vaults provide an improved, engineered system for the disposal of wastes, predominately contained in HHISO containers to date. Wastes were emplaced in grouted containers rather than tumble-tipped. These were stackable, providing an efficient use of space. The vaults comprise reinforced concrete bases that provide a running surface for placement and disposals of the wastes. Impermeable and low permeability systems under the bases and in the vault walls enable leachate to be collected within the vaults. This is currently pumped and discharged via the leachate management system. Once Vault 9a is implemented, operational leachate collection will move to a gravity-fed system. The operational leachate management system will be decommissioned as the site is closed. In the long-term, a passive leachate management system will discharge any infiltration entering the closed vaults by allowing water to overtop the walls and enter basal drainage blankets.

Space between the container stacks will be backfilled with inert and free-draining granular material before the final cap is emplaced. This will fill voids and thus provide stability, will provide preferential flow-paths around the waste containers, and will ensure the continued alignment of stacks after emplacement of the cap. The vaults will be progressively strip-capped, sealing the leading edge of the cap until the facility is finally closed.

Table 2.2 provides an overview of the functions and requirements of all existing and future vaults. Further information is available in reference [5].

Table 2.2: Existing and Future Vault Design Summary

Category	Summary
Main Functions	Contain and control existing and future wastes, using concrete vault with disposals predominately in grouted, mild-steel containers e.g. HHISOs, but also other wastes (e.g. direct grouted large items) in Vault 8. Provide a concrete running surface for plant, and for placement of disposals, on the vault bases. Ensure effective water and leachate management within the vaults via the clay, BES and geomembrane elements below the vault base (Vault 8 clay and BES only, other vaults BES and geomembranes), - working with the vault concrete base, and walls and drainage features. Support leachate management during the PoA (currently via active pumping to the MHT system, with a move to passive systems for the remainder of the PoA planned). Support long-term leachate management after closure, linking the vaults with the drainage blankets under future vaults.
Design Status	Vault 8 and Vault 9 are already constructed and operational. Future vaults will be similar and represent a mature design. The additional future vault features including passive drainage arrangements to the drainage blankets were optimised prior to the 2011 ESC and are also considered a mature design. The approach to Vault 8 closure has been approved for construction, including the surcharge approach. The approach to closure of the future vaults represents a mature design informed by the Vault 8 process. The approach to strengthened containers for LLW, and for ILW disposals including containers and shielded module structures, represent robust concepts for which there is confidence in implementation. They provide a robust basis for the ESC.
Design and Optimisation History	Vault 8 was designed and implemented in the late 1980s. The basic vault design has been retained, but further optimised and augmented since then. The approach to passive leachate

Category	Summary
	management post-closure was optimised for the 2011 ESC. Over the last few years, the closure approach for Vault 8 has been optimised and taken through detailed design, including requirements for surcharge. The approach to future LLW and any ILW to be disposed has also been subject to optimisation over recent years.
Implementation Schedule	Vault 8 will be closed in coming years. There is the potential for ILW disposals to commence in Vault 9 on similar timeframes. Vault 9a will also be built on a timeframe that allows early closure (via cap sealing) of the first strip of Vault 9 and Vault 9a as a priority. Vault 10 will be constructed on a timeframe sufficient to provide interim warehouse protection for future LLW disposals. There will be concurrent updates to the operational leachate management strategy including a move to a gravity system. Closure of the remainder of Vault 9, and construction and closure of the remaining future vaults, will then occur over the subsequent decades up to the 2130s, consistent with the rates of disposals.
Priorities for Ongoing Optimisation and Design	Detailed design of Vault 9a, and then Vault 10, will be required prior to construction. Further optimisation of the approach to strengthened containers in Vaults 9 and 9a, and stacking above current levels in general, together with slab assessments (Vault 9) and slab design and assessment (Vault 9a) will be taken forward. Any updates to the design for Vault 9a will also be reflected in the concept for future vaults.

2.3 Closure Engineering

2.3.1 Final Cap

The final cap design is described in reference [5]. It will be a 3 m thick multi-layered structure. Once strip-capping is complete, it will form a single dome covering both the trenches and the vaults. The main functions of the final cap are:

- Provision of layers to encourage evapotranspiration and drainage, above a composite barrier that will reduce infiltration of water into the wastes;
- With the profile fill, to form a barrier reducing the likelihood of, and impacts associated with, intrusion into the wastes;

- Working with the profile fill, to collect and route gas to vents, managing the bulk gases and reducing the radiation doses from trace gases such as radon; and
- Reduction of direct and indirect external irradiation doses.

Specifically in terms of the groundwater pathway, the cap will work with the cut-off wall, summarised in the following section, in an integrated way. Together with other components such as the passive drainage systems in the vaults and the sub-vault drainage blankets these will ensure that:

- Water contact with wastes will be minimised for as long as practicable; and
- As the cap begins to degrade, any leachate that does arise will be preferentially directed to deeper groundwater systems.

To ensure water contact is minimised for as long as practicable, the final cap will be designed to resist damage due to movement and settlement, erosion, seismic activity, or biota. It will perform passively without maintenance after the end of the PoA and mitigate the visual impact of the site.

Table 2.3: Final Cap Design Summary

Category	Summary
Main Functions	Isolate the wastes from humans and the environment; reduce infiltration into the wastes; manage bulk and trace gases.
Design Status	The design of the final cap over Vault 8 and the adjacent trenches has been approved for construction. The design of the remainder of the cap will follow the approach set out for the first strip.
Design and Optimisation History	Many iterations of design, optimisation and review. Current design has evolved from those first developed in the late 1980s.
Implementation Schedule	The first strip of the cap will be implemented by 2037. Further strips of the cap will be progressively implemented until after disposals cease, around 2130.
Priorities for Ongoing Optimisation and Design	No significant further optimisation of the cap design is expected. Further minor refinement of the detail of the cap, e.g. contours, connections between components, are anticipated. This will reflect experience and aspects such as the evolving understanding of inventory volumes and the detailed designs for future vaults.

	The approach to gas venting, including the approach to decisions on closure of the vent at the end of the PoA, and alternative approaches, will continue to be reviewed.

2.3.2 Cut-off Wall

The final cut-off wall will:

- work with the passive drainage arrangements to direct any leachate generated to deeper groundwater systems as the final cap begins to degrade; and
- minimise lateral flows into the trenches and sub-vault drainage blanket.

It will supplement the existing cut-off wall, which runs alongside the north and east sides of the trenches and limits any potential release of contaminated water from the trenches to the environment immediately surrounding the LLWR. The existing cut-off wall is 1 m wide and extends approximately 7 to 9 m deep. The extension will also be 1 m wide and will extend to below the sub-vault drainage blanket to key into the low permeability elements of the final cap. Both will be cement-bentonite slurry walls and the extension will be implemented progressively during strip capping. There is confidence that the cut-off wall will control groundwater movement over the long term. Its potential role in influencing the migration of gas is yet to be determined. Ongoing modelling and monitoring, once strip-capping commences, will inform decisions. Further information on the cut-off wall design is available in reference [5].

Table 2.4: Cut-off Wall Design Summary

Category	Summary
Main Functions	Preferentially direct any leachate that arises (e.g. during cap degradation) to deeper, rather than shallower, groundwater systems, working with the cap and the below-vault drainage. Minimise water flows into the facility, including the wastes and the drainage blankets to be installed below future vault bases. During the PoA, the existing cut-off wall will also continue to reduce flows and prevent contaminant releases from the east side of the trenches into domains including the railway drain.
Design Status	Already constructed (alongside the eastern edge of the trenches); approved for construction (for the first strip of the cap); mature design (for the remainder).

Category	Summary
Design and Optimisation History	Alread implemented along the trenches. The remainder has been subject to many iterations of design, optimisation and review, informed by monitoring of the existing installation. The current design for the remainder of the cut-off wall is very similar to the existing section which has been shown to be operating effectively.
Implementation Schedule	The cut-off wall along the eastern side of the trenches is already in place. The next part of the cut-off wall will be installed consistent with the first strip of the cap which will be implemented in the coming years. Further strips of the cap, and associated sections of the cut-off wall, will be progressively implemented until after disposals cease, around 2130.
Priorities for Ongoing Optimisation and Design	No significant further optimisation of the cut-off wall design is expected.

2.4 Geosphere

The geological sequence in the region of the LLWR consists of Quaternary age deposits (clay, sands and gravels) up to 60 m thick overlying older bedrock (Triassic Ormskirk Sandstone). Groundwater generally flows from the Lake District hills towards the coast. Investigations and monitoring have allowed the identification of an Upper and Regional Groundwater. The Upper Groundwater is present within the upper Quaternary deposits and overlies the Regional Groundwater. It is most evident in the north-west and central parts of the site, where it has a flow pattern that is distinct from that of the Regional Groundwater. The Regional Groundwater is observed in the Quaternary deposits and in the underlying Ormskirk Sandstone. The groundwater flow direction in the Regional Groundwater at the LLWR is generally to the south-west (towards the coast), where it discharges to the inter-tidal zone and off-shore. Towards the south-east boundary of the site, the direction of groundwater flow in the Upper Groundwater merges with that in the Regional Groundwater and the two cannot be differentiated in this area. A component of the Regional Groundwater passing under the south-eastern part of the site discharges to the River Irt and the Ravenglass Estuary.

2.5 Biosphere

The LLWR is located on the West Cumbrian coastal plain, about 0.5 km inland, to the west of the B5344 Seascale to Holmrook road, close to the village of Drigg and approximately

5 km south-east of the Sellafield nuclear site. Apart from the nearby nuclear site, the area is predominantly rural (see Figure 2.3). The site is enclosed by a boundary fence to prevent unauthorised access. Along the north-eastern boundary is the Whitehaven to Barrow-in-Furness railway line, a siding from which enters the site for the delivery of containerised waste and other items and materials (see Figure 2.4).

Figure 2.3: The LLWR site and its immediate environs

The topography surrounding the site varies from 20 m above Ordnance Datum (aOD) to the north-east and west of the site to less than 5 m aOD at the south-eastern site boundary. The surface of the interim cap that covers the trench area is around 25 m aOD. To the west of the site, the topography gently undulates towards a small cliff line marking the edge of the Drigg Beach. The site is mainly surrounded by grazing land, but some cereal crops are grown in fields to the east. The area along the coast adjacent to the site is designated as a Site of Special Scientific Interest (SSSI), known as the Drigg Coast SSSI. The area is also a candidate Special Area of Conservation (SAC) under the European Habitats Directive. The western boundary of the area of the site borders the SSSI.

Figure 2.4: Key features in the vicinity of the LLWR site

The Drigg Stream flows through the site roughly parallel with the western site boundary. Towards the centre of the site, the Drigg Stream is joined by the East-West Stream, which originates off site to the northeast, draining farmland and also taking water from the railway drain. The Drigg Stream leaves the site to the south and discharges into the River Irt, which is tidal at that point. The Irt forms the northern arm of an estuary complex, known as the Ravenglass Estuary which discharges to the sea opposite the village of Ravenglass.

Most of the LLWR site is between about half to one kilometre from the coast. At its north-western corner it is only about 400 m from the high water mark, so that the site is vulnerable to sea-level rise and coastal erosion. Based on qualitative and quantitative evidence, including modelling studies, we have concluded that the site will be eroded on a timescale of a few hundred to a few thousand years, with consequent disruption of the repository.

3 Approach to Controls and Safety Functions

3.1 Regulatory Context

The GRA [19] gives guidance on the information and analysis to be presented during the permitting process for near-surface solid radioactive waste disposal. This guidance has been developed progressively and is based on international advice and good practice. The GRA requires the ESC to describe the safety functions of the disposal system, saying:

> *“The environmental safety case should include an explanation of, and substantiation for, the environmental safety functions provided by each part of the system. It should also identify which radionuclides each function is relevant to and the expected time period over which the function is effective. The environmental safety case for the period after closure of a disposal facility should not depend unduly on any single function.*
>
> *The developer/operator will need to explore the contribution that each environmental safety function makes to the environmental safety case (for example, by sensitivity analyses). The developer/operator will also need to explore the circumstances where more than one function is impaired.”*

It emphasises that safety functions can encompass all aspects of the disposal system - the disposal facility and its surrounding environment - that offer containment and/or isolation of the waste. The definition of safety functions provided in the GRA includes the example of the host rock providing both a physical (isolation) and chemical (containment) barrier to radionuclide migration. The GRA also recognises that other aspects, such as the management of the disposal system, can contribute to environmental safety. For example, the GRA indicates that active institutional control can be one of the claims of the ESC as it provides a period of time during which shorter-lived radionuclides decay. As the LLWR is an operating facility we also consider controls that manage any residual releases so as to minimise their effects.

The breadth of issues that can be covered means that safety functions need to describe the functions of multiple barriers (or components) of the disposal system. Diverse controls and safety functions build confidence that safety is not overly reliant on any one part of the disposal system.

The process of establishing optimised controls and their associated safety functions provides the opportunity to ensure that all the principles and requirements have been interpreted appropriately and are sufficiently fulfilled. Other parts of the ESC provide the detail to substantiate this, but the volume of information can mean that this is difficult to appreciate.

The purpose of this document is to communicate the controls and safety functions of the disposal system and its management in a succinct and direct way.

3.2 Approaches to Controls and Safety Functions

3.2.1 Approaches in Other Programmes

As the GRA does not describe specific expectations of how safety functions can be identified and presented we have reviewed international guidance and examples to establish the types of approaches recommended or adopted elsewhere (e.g. by SKB [20], ONDRAF/NIRAS [21] and in the UK Geological Disposal Facility (GDF) programme [22]).

IAEA has published safety requirements for the disposal of radioactive waste [23], which contains a requirement that the disposal facility shall be designed and operated to ensure that safety is provided by means of multiple safety functions. It emphasises that they may be diverse, and safety should be demonstrated not to be unduly dependent on any one safety function. IAEA also makes extensive reference to safety functions in its specific safety guide that covers the preparation of the safety cases and safety assessments [24]. IAEA's guidance is that the safety case should include a description of the safety functions assigned to each component of the disposal system and should provide an assessment of the ability of these components (including natural barriers) to fulfil their given role. IAEA suggests that they may be explained in a "safety strategy" but does not provide guidance on how they are derived.

Other radioactive waste management programmes do, however, provide an illustration of the approaches that can be taken to identify and present safety functions. In interpreting their relevance, it is important to take account of the particular context (regulatory system, disposal concept, stage in the waste management lifecycle, etc.) to which they relate. These influence not only the safety functions themselves but also the extent to which they are developed and how they integrate into the waste management process.

SKB, the Swedish nuclear fuel and waste management company, has operated the SFR facility for low and intermediate level radioactive waste disposal since 1988. The facility is in caverns below the Baltic Sea. SKB's most recent safety analysis [20] was developed according to a process which uses the concept of Features, Events and Processes (FEPs) to synthesise the understanding of the disposal system and provide the basis for its analysis. In SKB's process, safety functions feature as a method of linking FEPs to the main performance objective of the disposal system, the retention of radionuclides in the facility. They are also used as a tool to determine what information is needed from the safety assessment ("safety function indicators") in order to demonstrate the function. These are presented as a linkage:

- disposal system component – safety function indicator – safety function.

For example:

- waste packages – corrosion rate – retention of radionuclides.

The SKB approach is very structured and systematic. Such an approach offers rigour, but is dependent on the FEP approach being embedded in the safety analysis. It also constrains the definition of safety functions to those things that are adequately represented by FEPs, and thus could lead to a narrow view of safety functions.

An alternative approach is to identify the functions from the overarching safety objectives. An example of this method can be found in the safety case for the Belgian surface disposal facility at Dessel, for which construction has recently commenced. ONDRAF/NIRAS [21] also used a systematic approach in which safety functions are introduced in terms of disposal system design. A limited number of core safety functions were defined at a high level:

- R1: Limitation of contaminant releases from waste forms
- R2a: Limitation of water flow through the system by protective barriers
- R2b: Limitation of advection and of diffusion through the contaminant retention barriers
- R3: Delay and attenuation of contaminant migration by chemical barriers
- S: Support of another system, structure or component to fulfil its long-term safety function
- I1: Reduction of likelihood of inadvertent human intrusion and of its possible consequences

In this case the core safety functions were derived from the “strategic safety orientations” (such as containment and isolation, passive safety, defence in depth, isolation and containment) rather than FEPs. ONDRAF/NIRAS have used the concept of safety functions as a main driver for the disposal concept design. Like SKB, they are mapped onto disposal system “components”, although in this case the FEPs are not central to this mapping. This mapping recognises that some safety functions are delivered by several disposal system components, and that they may act on different timescales.

We used a similar approach in relation to the planned GDF for the UK’s higher-activity radioactive wastes [22]. From the fundamental objectives of containment and isolation, a set of safety functions were identified and linked to the various components of the disposal system (geology, wasteforms and engineering) using influence diagrams. The nature of the waste and disposal concept is, however, very different to the LLWR.

3.2.2 Approach in the 2011 ESC

The last ESC prepared for the LLWR in 2011 [25] did not seek to present a formal analysis of safety functions for each component of the disposal system. Rather, the Environmental Safety Strategy for 2011 ESC was centred on optimising safety controls, from which safety functions can be inferred. The strategy:

- defines the objectives, which are to maximise the capacity of the LLWR consistent with the characteristics of the site, support the implementation of the waste hierarchy, and optimise the environmental performance of the LLWR;
- defines the approach, centring on implementing control measures that will ensure environmental safety, consistent with a set of principles (which include those set out in the GRA);
- sets out the main categories of controls - controlling the source (of hazard), isolating the source, containing the source, and minimising the effects of any residual releases.

A process of optimisation was used to identify the preferred set of control measures that will achieve doses and risks that are ALARA. Controls over design and operation describe the safety functions required of the different components of pre- and post- closure engineering. Information gained from assessments of the performance of the components and their evolution with time was used to develop the understanding of the role of these components and therefore the controls that are, or could be, applied to deliver environmental safety.

After the 2011 ESC had been issued, we provided the Environment Agency with a clarification of our approach and how safety functions feature in it [26]. We presented a mapping of controls to safety functions, also explaining on what timescale they applied and the basis for understanding of their performance. It was noted that many of the components of LLWR work together and in some cases provide several different safety functions.

3.3 Identification and Presentation of Controls and Safety Functions in the 2026 ESC

3.3.1 Approach to Defining Controls and Safety Functions

Penfold [27] reviewed the treatment of controls and safety functions in the 2011 ESC and the approaches described in the preceding sections. It was concluded that:

- safety functions are a valuable part of an ESC, demonstrating the regulatory requirements have been met and showing multiple barriers to safety;
- there is no uniformly accepted way of developing or presenting safety functions; but
- there are broadly two ways in which safety functions can be defined:
  - starting with a description of the disposal concept in its component parts (perhaps with reference to FEPs) and using these to systematically develop safety functions, or
  - starting with high-level safety objectives and associated safety functions and asking how these are fulfilled by the disposal system.

The method of developing safety functions by systematically considering the components of the disposal system is illustrated by SKB's approach. This is well suited to a situation in which the disposal facility has been developed methodically from a single design concept. Although it is methodical, such an approach may not identify those safety functions in which a number of components of the disposal system work together. An example is the safety function related to limiting the generation of leachate from wastes during the period of operations. At the LLWR, waste containers, grout, CPUs, shielded modules, interim storage warehouses, trench interim cap, and the vault leading edge seal all play a role. An alternative approach that starts with safety objectives (similar to those that form the LLWR's Environmental Safety Strategy) and associated safety functions, and then asks how the components of the disposal system contribute to achieving them, has been demonstrated by ONDRAF/NIRAS. This is better able to capture and describe situations in which several components work together to achieve a safety function.

As highlighted in Section 2, the disposal concept of the LLWR has evolved over more than 65 years. Consequently, it is composed of a range of different engineered barriers, some of which have been introduced to supplement those originally present. Describing how a safety function is fulfilled by a combination of components is particularly important. The method of starting with the high-level safety objectives and safety functions is therefore better suited to a disposal facility like the LLWR. This type of approach was taken in the 2011 ESC, with the objectives and safety functions expressed as controls applied to achieve safety.

We have retained this approach for the 2026 ESC but sought to develop the detail in which we describe the safety functions. To do this, we have made use of the ongoing process of optimisation of the disposal system, reported in reference [10] and drawn on our initial work to develop a Disposal System Specification (DSS, [28]). We have used judgement based on our knowledge of the disposal system and its performance to identify the key controls and safety functions presented here. We have explicitly stated the safety function(s) that each control provides and characterised its effect, making use of information from assessments and other studies where relevant.

3.3.2 Definition of Controls and Safety Functions

Understanding what controls need to be applied to the disposal system draws on the knowledge base that has developed for the LLWR over decades. This comprises information gathered from site characterisation and monitoring, understanding from international programmes, projects and experience, and our own research and studies. The knowledge base is reflected throughout the documents supporting the ESC and provides the input to optimisation studies. The specific controls that are identified through optimisation can be active management measures or engineered features. Examples include controls on the waste inventory (via waste acceptance criteria), the design (design specification and implementation) and its operation (waste emplacement, discharge management, and facility closure).

The more historical features of the disposal facility also provide some important controls and some controls are the consequence of actions taken to apply other controls, therefore we also document these. For example, grout is added to waste containers to provide chemical conditioning and fill voids, but it also provides some extra shielding of the radiation emitted from the wastes therein. There are also controls provided by the environmental setting of the disposal facility, such as the retardation by the geology of contaminants released in groundwater and these can be identified through the understanding gained from safety assessments. These are all aspects that we refer to as controls because they contribute to ensuring that the impact of the LLWR on environmental safety is acceptably low.

The DSS provides means of verifying that the identified controls deliver the required safety objectives. By capturing the requirements arising from optimisation, the assessments, and the wider ESC, it provides another method of highlighting the safety functions that the disposal system provides.

3.3.3 Characterisation of Controls and Safety Functions

Evaluation of the performance of the optimised disposal system is achieved by means of assessment, both the engineering performance assessment and safety assessments for relevant pathways. This process provides information that can be used to characterise the safety functions by quantitatively or qualitatively describing how the disposal system components deliver the desired controls. An important development in our presentation of controls and safety functions has been to provide more information characterising the way in which they benefit the environmental safety of the LLWR.

4 Key Controls and Safety Functions

The 2011 ESC established the concept of controls which provide the safety functions that deliver the objectives of the Environmental Safety Strategy. Since then, taking account of feedback on the 2011 ESC, we have continued to develop the list of controls and safety functions. As discussed in Section 3, these have been identified via the ongoing process of optimisation, using our knowledge of the disposal system and the understanding gained from safety assessment.

The controls and associated safety functions identified through these activities are compiled in Table 4.1 to Table 4.4 that follow.

We firstly identify the special role of Waste Acceptance Criteria (WAC) in Table 4.1. WAC differ from other controls because they can limit the hazards posed by the wastes across all pathways. We use our understanding of the LLWR and its performance to define requirements that must be met by those consigning waste to the LLWR. The WAC provide the method by which we ensure that the waste accepted for disposal is consistent with the ESC and the requirements at the facility for transporting and handling it. In addition to limiting the presence of radionuclides and other hazardous substances, we define WAC that ensure that the waste that is received in a form that is compatible with the LLWR's design and the requirements on its performance. Furthermore, WAC provide the ability to actively manage the overall safety of the LLWR. For example, if we identify a waste characteristic that could be significantly deleterious to safety, we can act to ensure that it is not present in wastes consigned to the repository.

The subsequent tables organise the other controls into the four categories described in the ESS - other controls offered by the waste form, controls that contribute to the isolation of the waste, those that provide containment of the waste and controls related to the management of residual releases.

Note that in many cases, characteristics of the waste form referred to in Table 4.2 contribute to the isolation and containment of the waste and are therefore also relevant to the controls discussed in Table 4.3 and Table 4.4.

For each category, we describe

- The controls that are applied to the disposal system to deliver the ESS;
- The safety functions that are performed by the control, noting that in some cases there may be more than one;
- The components involved in delivering the controls and safety functions, which also may be more than one;
- The exposure pathway(s) to which the control applies and the timeframe that it is relevant to.

The commentary included in Table 4.1 to Table 4.4 to explains how the controls and safety functions contribute to delivering the ESS. The pathway(s) on which each control acts is summarised in Table 4.6.

A detailed mapping of the controls, safety functions, components and pathways is provided in Appendix A.

Table 4.1: Controls and safety functions provided by WAC

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
WAC1: Control of the radiological characteristics of the waste	Limitation of the radiological hazard	Site management	Relevant over all timescales and all pathways	Ensure that the total activity and activity concentration (including heterogeneities) will not lead to unacceptable radiation doses and risks
WAC2: Control of chemical and biological hazard of the waste	Limitation of non-radiological hazards	Site management	Relevant over all timescales and all pathways except external irradiation	Limit the hazard to health associated with non-radioactive substances
WAC3: Control of the physical composition of the wastes	Ensure the wasteform is compatible with the disposal system	Site management	Relevant over all timescales and all pathways	Aspects such as container strength and the presence of voids require control to ensure stability and integrity of the wastes.
WAC4: Control of the biogeochemical characteristics of the waste	Minimisation of any adverse biological or chemical effects	Site management	Relevant over all timescales and all pathways except external irradiation	Control of properties deleterious to safety performance, such as the presence of reactive metals, complexants, corrosive and putrescible materials.

Table 4.2: Controls and safety functions relating to the waste form*

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
W1: Control of the integrity of the waste	Provision of structural stability of wastes Provision of a foundation for the final cap Protect containers from loading by cap	Waste containers, grout, void fill	During and after the emplacement of the final engineered cap, and relevant to groundwater and gas pathways	The containment and isolation functions of the waste form may be compromised by the loading of the cap. Maintaining its integrity will contribute to maintaining these functions for as long as possible. Surcharging is additionally applied to ensure any residual voidage is expressed.
W2: Control of waste placement	Limitation of doses from exposed or disturbed wastes Provision of time for radon to decay during migration	Site management	Relevant during the operational period to external irradiation, and after institutional control to exposures arising from the release of radon and human intrusion	Placement of certain wastes in certain locations benefits safety performance, for example locating wastes with higher dose rates further from the site boundary reduces the off-site radiation dose during waste disposal operations.
W3: Control of radiation dose rates by shielding	Limitation of external dose	Waste container	Relevant to external irradiation prior to the emplacement of the final engineered cap	The container wall will attenuate radiation from the waste form.

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
W4: Control of dispersible materials	Immobilisation of wastes	Grout	Relevant to human intrusion and coastal erosion after institutional control	The grout fill reduces the potential for the release of contaminants in a form that can be dispersed and/or inhaled if wastes are disturbed.
W5: Control of waste contact with water	Reduction of the generation of contaminated leachate Consumption of free water through corrosion Reduction in migration of contaminated leachate	Waste container, grout	Relevant to liquid discharges during the operational period, and to groundwater and gas pathways after emplacement of the final cap	Limitation of the amount of water that can contact the wastes limits the release of contaminants in that water and/or gases evolved by reactions that consume water.
W6: Control of the chemical environment	Reduction of corrosion rate of some metals Reduction of mobility in of some elements by sorption and solubility limitation Reduction of biodegradation rate	Grout	Relevant over all timescales to gas release and groundwater releases	The high pH conditions due to the grout provide chemical conditions that limit or reduce the significance of various processes including corrosion, biodegradation, and the mobility in water of important radionuclides (through enhancing sorption and solubility limitation), allowing for radioactive decay.

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
	Reduction of rate of release of C-14			
W7: Control of contaminant concentrations in waste	Additional dilution of contaminants	Grout	Relevant to external doses during operations and to human intrusion and coastal erosion after institutional control	Deliberate dilution of radioactive waste is not permitted, but the addition of grout necessary for stabilisation, immobilisation and chemical conditioning of the waste will also reduce the bulk concentration of the waste form.

Note: * The characteristics of the waste material and its form contribute to controls provided by the other components of the disposal system. For example, controls on dose rate by shielding are provided by waste form (Control W3) and also vault walls, CPUs and shielded modules and caps (Control I6).

Table 4.3: Controls and safety functions that provide isolation

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
I1: Control of access to site during operations	Prevention of uncontrolled exposure to wastes during PoA	Site management	Relevant to external exposures, gas and human intrusion during operations	Access restrictions prevent unnecessary radiation exposure of members of the public.

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
I2: Control of access to site during institutional control	Prevention of damage to engineered barriers during PoA Prevention of intrusion to wastes during PoA	Site management, knowledge and records	Relevant after institutional control to groundwater and gas pathways and prevention of human intrusion	Control and surveillance of the closed site ensures that passive engineered barriers are not damaged and maintain function, and that inadvertent human intrusion does not occur. While they cannot be relied to prevent indefinitely the possibility of human intrusion, information and records would be intended to be retained beyond the period of institutional control, although they are not relied upon.
I3: Control of use of surrounding land during institutional control	Prevention of activities that could lead to exposure (e.g. wells)	Site management (ownership of land), knowledge and records	Relevant to the groundwater pathway during the PoA	Radionuclides from historical disposals are migrating in groundwater off-site, however contaminated groundwater is beneath land owned by NDA which can control its use and prevent exposure to groundwater.
I4: Control of depth of waste from surface	Reduction of likelihood that an intrusion will encounter waste	Final engineered cap, Profile fill	Relevant after institutional control to groundwater, gas and	Sufficient isolation (by depth) of the waste from the surface prevents disturbance of key engineered

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
	Protection of cap from damage by roots and burrowing animals Attenuation of radon gas that could be released to surface Prevention of external irradiation at ground surface		human intrusion pathways	barriers and/or the waste by some mechanisms and reduces the likelihood of others occurring.
I5: Control of physical access to wastes	Protection of waste should intrusion occur	CPUs, shielded modules, cap	Relevant after institutional control to human intrusion	Should inadvertent intrusion occur, robust physical barriers around wastes, and the bio-intrusion layer in the cap, may deter situations leading to exposure to the wastes.
I6: Control of radiation dose rates by shielding	Provision of shielding	Trench interim cap, Vault walls, CPUs, shielded modules, final engineered cap	Relevant to external exposures during operations and potentially during coastal erosion	Structures surrounding wastes will reduce external exposures by isolating the radioactive material.
I7: Control on the timing of erosion	Delay of the onset of coastal erosion	Hinterland	Relevant after institutional control to coastal erosion	Although the site was selected before the threat of coastal erosion was appreciated, it is nevertheless

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
				the case that the hinterland between the LLWR site and the coast provides a barrier that must be eroded before erosion of the disposal system may commence. The delay in erosion of waste allows decay of radionuclides present.
I8: Control of contaminants concentrations in disturbed waste	Additional dilution of contaminants	CPUs, shielded modules, final engineered cap	Relevant after institutional control to coastal erosion and human intrusion	Deliberate dilution of radioactive waste is not permitted, but various engineered structures are required within the LLWR to provide a variety of containment and isolation functions. These will also reduce the bulk concentration of contaminants if waste is disturbed.

Table 4.4: Controls and safety functions that provide containment

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
C1: Control of water entering the repository during operations	Reduction of the generation of contaminated leachate Direct surface water away from interim cap and vault leading edge seal	Waste containers, grout, CPUs, shielded modules, interim storage warehouses, trench interim cap, vault leading edge seal, cut-off wall, cap drains, final engineered cap	During operations and institutional control, relevant to liquid discharges and gaseous releases	Limitation of the entry of water into the trenches and vaults will limit the amount of leachate generated and gas/vapour evolved from saturated wastes, while diversion of the water away from waste will limit the concentrations of contaminants in the leachate that is generated
C2: Control of water entering the repository after operations	Reduction of water flow into the wastes Reduction in leaching of grout Reduces recharge around and below site Reduction in gas generation rate Provide gas headspace to mitigate pressurisation	Waste containers, grout, CPUs, shielded modules, cut-off wall, cap drains, final engineered cap	After operations, groundwater and gas pathways	Minimisation of the ingress of water into the LLWR will minimise the generation of leachate that could be released to groundwater, and reduce the source of water for reactions that generate gases.

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
C3: Control of integrity of waste form	Protection of waste containers from loading by cap Provision of structural stability of wastes	Vault base, CPUs, shielded modules, void fill	After institutional control, groundwater and gas pathways	The waste form provides a variety of containment and isolation functions, but may be compromised by the loading of the cap. Vault structures will contribute to maintaining these functions for as long as possible. In vaults and the trenches existing vault wastes will be surcharged before the final cap is emplaced to ensure that the structural performance of the engineering is assured.
C4: Control of contaminant migration in water through vaults after institutional control	Provision of flow paths around waste containers Reduction of mobility in groundwater of some elements by sorption	Vault base and walls, CPUs, shielded modules, void fill	After institutional control, groundwater pathway	Water that has entered the LLWR can be channelled away from the wastes to reduce the potential for the migration of contamination; water that has contacted waste will contact structures that can sorb some of the contaminants present and retard their migration, allowing decay.

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
C5: Control of lateral migration of leachate	Prevent release of contaminants to surrounding surface environment Reduces groundwater flow through waste Direct leachate to deeper groundwater (after institutional control)	Vault base and walls, cut-off wall, under-vault drainage blanket	During operations, liquid discharges, after institutional control, groundwater pathway	Vault structures, including the drainage blankets and the cut-off wall, prevent lateral release of leachate to the surface environment, and after the leachate collection system is decommissioned, will ensure that leachate that is generated is directed towards deeper groundwater.

Table 4.5: Controls and safety functions relating to the management of residual releases

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
M1: Control of leachate generated during operations	Limit release of leachate to groundwater during operations	Vault base and walls, leachate collection and discharge system	During operations and institutional control, relevant to liquid discharges	Leachate generated in the LLWR is contained so far as practicable by the engineering (noting that there is some unavoidable leakage from trenches) and collected for controlled discharge under permit.

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
M2: Control of gas release after operations	Enable gas dispersal and mitigate pressurisation Release gas so as to protect the cap and to minimise dose Limit the release of radioactive gas	Void fill, final engineered cap	After operations, gas pathway	Unsaturated porosity provides gas headspace to manage pressurisation and mitigate the potential for damage to engineered barriers, while the cap design can both manage and control the release of gas.
M3: Control of contaminant migration through geosphere	Reduction of mobility in groundwater of some elements by sorption	B2 hydrogeological unit, B3 hydrogeological unit	Relevant over all timescales to the groundwater pathway	Sorption of contaminants to the geological media will retard their migration, allowing decay and preventing some contaminants from reaching the environment on the timescale of interest.
M4: Control of contaminant concentrations in groundwater	Reduces contaminant concentrations by dilution and dispersion	B3 hydrogeological unit	Relevant over all timescales to the groundwater pathway	Uncontaminated groundwater will mix with leachate released from the LLWR and reduce the concentrations of contaminants.

Control	Safety Function	Component(s)	Timescale & Pathway	Commentary
M5: Control of contaminant concentrations in environment	Reduces contaminants concentration by dilution and dispersion	Stream, marine environment, atmosphere	Relevant over all timescales to the groundwater, gas, liquid discharge and coastal erosion pathways.	Contaminated groundwater will become diluted and dispersed when it is released to surface water. Contaminated gas will be diluted and dispersed in air. Eroded waste will be diluted and dispersed in the beach and marine sediments.

Table 4.6: Relationship between controls and pathways

Control	Ground-water	Gas	Liquid Discharge	External	Coastal Eros'n	Human Intrus'n
Waste Acceptance Criteria						
WAC1: Control of the radiological characteristics of the waste	X	X	X	X	X	X
WAC2: Control of the chemical and biological hazard of the waste	X	X	X		X	X
WAC3: Control of the physical composition of the waste	X	X	X	X	X	X
WAC4: Control of the biogeochemical characteristics of the waste	X	X	X		X	X
Controls on waste						
W1: Control of the integrity of the waste	X	X				
W2: Control of waste placement		X		X	X	X
W3: Control of radiation dose rates by shielding				X		
W4: Control of dispersible materials					X	X
W5: Control of waste contact with water	X	X	X			

Control	Ground-water	Gas	Liquid Discharge	External	Coastal Eros'n	Human Intrus'n
W6: Control of the chemical environment	X	X				
W7: Control of contaminant concentrations in waste				X	X	X
Controls on isolation						
I1: Control of access to site during operations		X		X		X
I2: Control of access to site during institutional control	X	X				X
I3: Control of use of surrounding land during institutional control	X					
I4: Control of depth of waste from surface	X	X				X
I5: Control of physical access to wastes						X
I6: Control of radiation dose rates by shielding				X		X
I7: Control on the timing of erosion					X	
I8: Control of contaminants					X	X

Control	Ground-water	Gas	Liquid Discharge	External	Coastal Eros'n	Human Intrus'n
concentrations in disturbed waste						
Controls on containment						
C1: Control of water entering the repository during operations	X	X	X			
C2: Control of water entering the repository after operations	X	X				
C3: Control of integrity of waste form	X	X				
C4: Control of contaminant migration in water through vaults after institutional control	X					
C5: Control of lateral migration of leachate	X		X			
Management of residual releases						
M1: Control of leachate generated during operations			X			
M2: Control of gas release after operations		X				
M3: Control of contaminant	X					

Control	Ground-water	Gas	Liquid Discharge	External	Coastal Eros'n	Human Intrus'n
migration through geosphere						
M4: Control of contaminant concentrations in groundwater	X					
M5: Control of contaminant concentrations in environment	X	X	X		X	

5 Characterisation of Key Controls and Safety Functions

This section describes the significance of the controls and safety functions to environmental safety. This is done mainly using performance measures derived from the assessments of the main pathways and other sources of information about the disposal system (e.g. the EPA [12]). The following subsections discuss each pathway in turn. Not all controls are characterised in detail in this section; the focus is on the controls that we think are most significant in explaining the performance of the system and also on those that are amenable to quantification.

The control of the waste characteristics (control WAC1, WAC2 and WAC3) applies to all pathways. WAC represent the primary method of controlling the hazards posed by the wastes consigned to the LLWR. They therefore apply to all pathways. WAC are defined on the basis of the ESC outcomes through the analysis of capacities and the required physical and chemical properties of the wastes. This definition of WAC is discussed in detail in reference [17].

5.1 Groundwater

5.1.1 Control of Waste Contact with Water

Control of water contacting the waste and its movement in the LLWR (controls W5, C1, C2, C4, C5) can be characterised collectively in terms of the quantity of water infiltrating the facility and the flux of contaminants from the near field into groundwater (Table 5.1). These aspects are represented in the groundwater pathway assessment [29].

In the assessment, some components are modelled explicitly and some are excluded from the model for simplicity. For example, the effect of the containers in providing a barrier to water contact with waste has not been represented. Other aspects, such as the function of the cap in limiting water ingress and the physical barriers to water movement within the disposal facility, are modelled.

Table 5.1: Characterisation of controls relating to waste contact with water

Controls and Safety Functions	W5: Control of waste contact with water C1: Control of water entering the repository during operations C2: Control of water entering the repository after operations C4: Control of contaminant migration in water through vaults after institutional control C5: Control of lateral migration of leachate

Description	Where containers are well-grouted, the primary contaminant transport mechanism will be diffusion out of the grout, slowing release to the leachate in the gaps between waste stacks relative to transport by advection through cracks in the grout to the gaps. The latter is likely to be the primary transport mechanism for containers where the quality of grouting is poor. When infiltration rates are low, the water can be fully consumed by corrosion reactions [6]. Under these conditions, the grout will generally not be able to resaturate, and there will be few opportunities for contaminant transport out of the grout in the liquid phase. When infiltration rates exceed the consumption by corrosion reactions, grout that can be contacted by the residual water will take up water until saturated. Thus, the grout provides a water sink that will consume infiltration. This will reduce contaminant transport until the grout is fully saturated. Additionally, water will not begin to flow through high-flow features until the grout is completely saturated and there is excess water which can drain through high-flow features (e.g. cracks in grout). Diffusion of contaminants will be slower through partially saturated grout than it would be through fully saturated grout. Sorption to the grout is included in the groundwater assessment model. The containers provide a key barrier to contaminant release as they limit infiltration contacting the grout and the waste and diffusion from it. Existing containers in Vault 8 and part of Vaults 9 and 9a will be damaged to some extent as part of surcharging which will take part prior to installation of the final cap. Future stronger containers are not expected to be damaged during cap installation and will be stored in temporary warehouses prior to disposal, protecting them from corrosion. As corrosion of the containers occurs, the corrosion processes consume infiltrating water, reducing the amount of water reaching the grout even when the containers are partially breached. Perforations due to deformation during surcharging (for some containers) and due to corrosion will allow infiltration into the grout. However, infiltration rates will remain low enough that the release of contaminants via diffusion or advection is greatly reduced (relative to if no containers were present). CPUs (where present) will divert water away from the containers to the gaps. Within the groundwater assessment model, containers are not modelled. The cautious assumption is made that all infiltrating water can make contact with the full pore space of the wastes, so no credit is given to the physical containment provided by the containers during the post-PoA. The consumption of water by corrosion reactions (i.e. corrosion of containers

or metallic wastes) is cautiously not included in the model. Grout is treated as fully saturated throughout the assessment.

Shielded modules are concrete walled and roofed disposal modules intended to be used for wastes which require additional shielding. These structures may help limit water inflow to containers inside the structure. The shielded modules are not specifically modelled or accounted for in the groundwater assessment.

Cut-off walls limit the lateral flow of water into (and out of) the repository and help prevent the under-vault drainage blankets from becoming saturated. This reduces lateral flows through the repository and also reduces the potential for migration of contaminants into the near surface surrounding the LLWR. The cut-off walls are included in the underlying compartment flow model (CFM), which is used to calculate flows and water levels within the LLWR in the groundwater assessment model [30].

The vault walls prevent lateral flows from surrounding geology into the vaults. In Vault 8, the walls are not considered to constitute a significant barrier to flow and there is some inflow from groundwater which will be addressed by the future cut-off wall. The vault walls are modelled within the CFM.

The BES (Bentonite Enhanced Sand) layer in the vault bases acts to prevent leachate entering the groundwater during the operational period and any water ingress into the repository from below while the vault bases are dry. A long-term passive drainage system prevents the vaults from saturating once the cap begins to degrade. The vault bases are modelled within the CFM.

The current interim cap over the trenches marginally reduces infiltration. The planned improvement of the interim cap will further reduce infiltration.

The final cap limits the inflows of rainfall into the repository, reducing the potential for transport of radionuclides. The low infiltration rate limits the loss of alkalis from the grout, so helps to maintain high pH conditions for an extended period of time (see Subsection 5.1.3). The geomembrane is expected to remain functional and provide a significant barrier to water ingress for 1000 years or more [12, 29].

In the groundwater assessment model [29], the cap is not modelled explicitly but the properties of the cap are used to derive infiltration rates into the trenches and vaults [31]. While the geomembrane is intact, infiltration rates through the cap are around 0.001-0.1 mm y^{-1}, compared to about 10-300 mm y^{-1} after the geomembrane has degraded (a factor of 10,000 reduction) [12].

Significance	We use the migration of I-129 as an indicator of the effectiveness of key barriers. This is because it is a long-lived, low sorbing and thus mobile radionuclide which is immediately available for release from the waste and can be rapidly transported in groundwater; therefore, it is a cautious indicator of contaminant migration. Figure 5.1 shows the total mass of I-129 within certain cells of the GoldSim model in the groundwater assessment deterministic reference case. Here 'Vault saturated/unsaturated' is the saturated or unsaturated part of the waste disposed within the vault (Vault 8 used as an example) and 'Top of B2' is the top cell of the B2 hydrogeological unit. Figure 5.1 demonstrates that over 99% of I-129 is retained within Vault 8 over the assessment timescale due to the very low infiltration through the vaults prior to cap degradation. Prior to capping, leachate is contained by the vault base slab, beneath which is a drainage layer underlain by clay with low permeability. Vault 9 and future vaults additionally incorporate a basal geomembrane with BES. For U-238 (more strongly sorbing, and solubility limited), the amount of contaminant release from the vaults is negligible; the low infiltration rates result in the majority of U-238 remaining in the unsaturated zone within the vaults (Figure 5.2)[3]. Figure 5.3 shows an equivalent result for release of I-129 from the trenches (Trench 7). Significant leaching occurs during the PoA, before the final cap is in place. A variant case in the groundwater assessment [29] considers the impact of poorer than expected cap performance, with earlier geomembrane failure (at 2700 AD instead of 3500 AD) and higher infiltration rates (increased by a factor of 10,000 from the reference case, to ~500 mm y^{-1}). In this case there is some overtopping of the trenches and vaults. The peak risks are higher than the reference case, but remain below the risk guidance level. There are higher contributions from solubility limited uranium isotopes (U-234, U-238). The final engineered cap is the most significant barrier to water contact with the waste. Uncertainties in the performance of the cap are considered in the probabilistic reference case from the groundwater assessment, by

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[3] The safety function analysis presented here uses Phase 2 results from the groundwater assessment [29]. When reviewing these results, we identified that the solubility limits for uranium in the trenches significantly overestimate the solubility of uranium in the trench environment. Therefore, solubility limitation for uranium may have a more significant safety function than is indicated here.

sampling from the PDFs for infiltration rate and the time of onset of cap degradation [29].

A variant case also considers higher conductivity of the vault base and walls. The overall impact on the assessed risks is minimal, since the risk is dominated by disposals in the trenches.

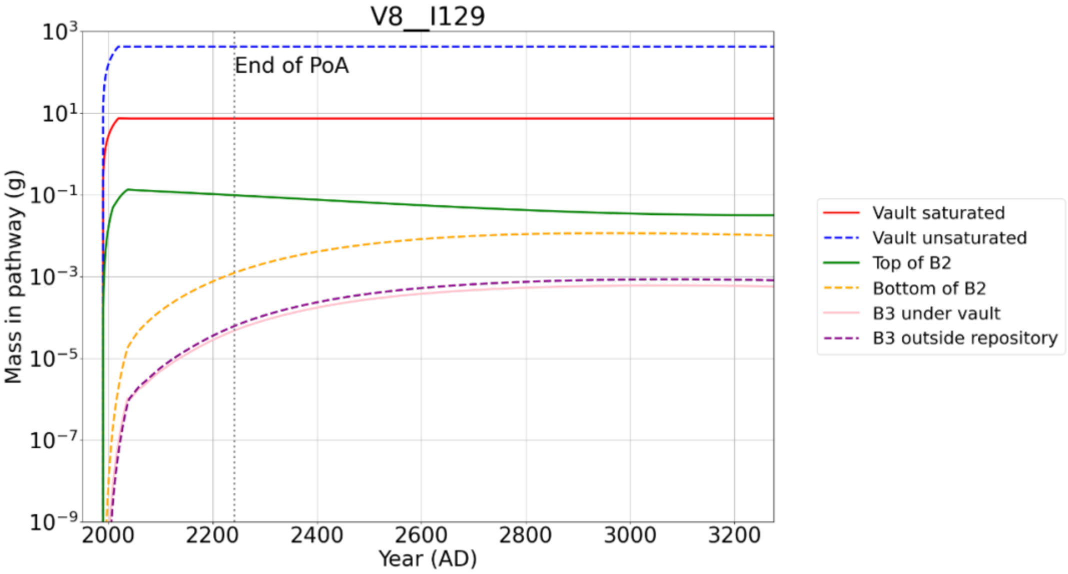

Figure 5.1: Evolution of I-129 from disposals in Vault 8, groundwater assessment deterministic reference evolution case

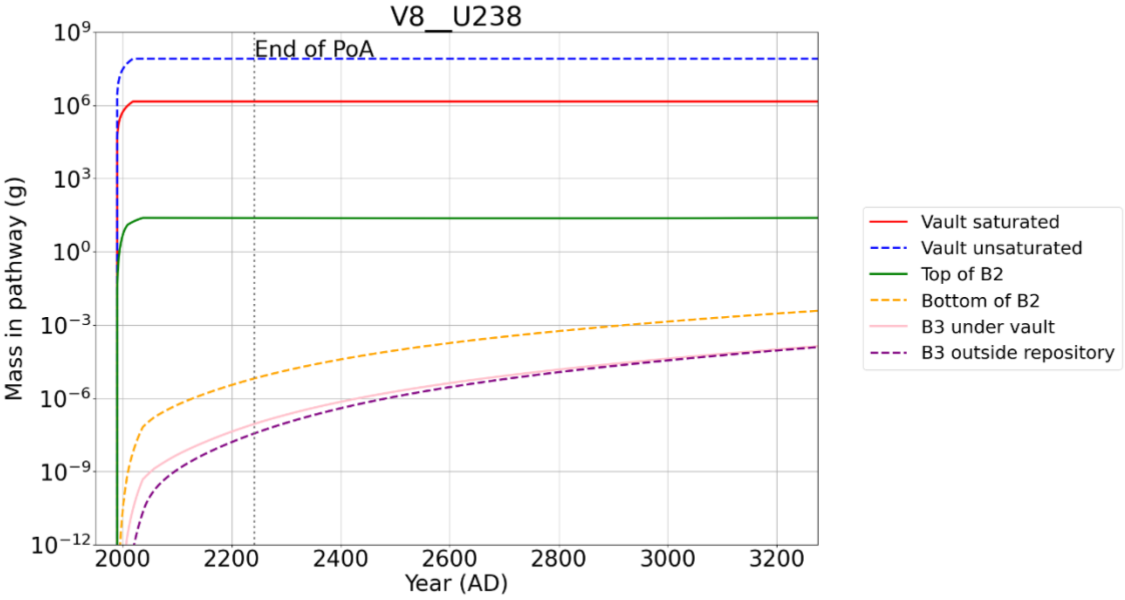

Figure 5.2: Evolution of U-238 from disposals in Vault 8, groundwater assessment deterministic reference evolution case

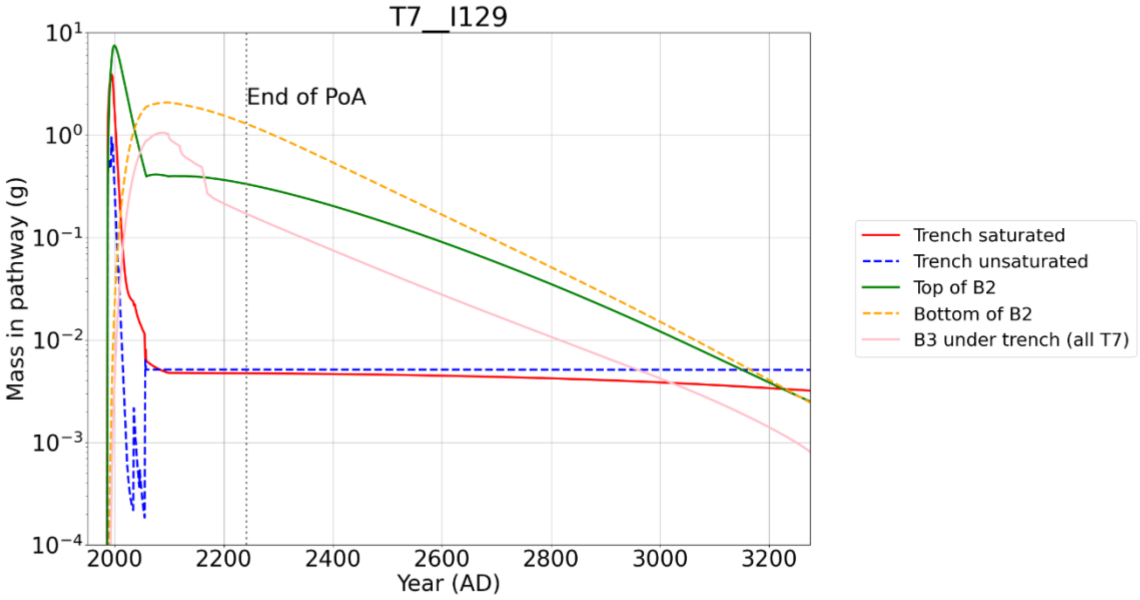

Figure 5.3: Evolution of I-129 from disposals in Trench 7, groundwater assessment deterministic reference evolution case

5.1.2 Control of the Integrity of the Waste Form

Controls on the integrity of the waste form (W1, C3) act to protect the engineered barriers and support the function of other engineered barriers. Components which support the structural integrity include the grout, containers, void fill, CPUs, shielded modules and vault bases. These controls are characterised in Table 5.2.

Table 5.2: Characterisation of controls relating to integrity of the waste form

Controls and Safety Functions	W1: Control of the integrity of the waste C3: Control of integrity of waste form
Description	The final cap provides a significant safety function in limiting infiltration to the repository and providing reducing conditions (see Subsection 5.1.1), therefore preserving its integrity is important. However, the final cap and profile fill will be thick and so will place a considerable load on the wastes. The wastes, assisted by the engineered components of the vaults, protect the integrity of the cap and maintain the containment and isolation functions of the containers and waste form despite loading of the cap. Voids in the vault waste containers are limited according to WAC, and those present are filled with grout. This helps to maintain the integrity of the waste form and minimise settlement of wastes, since differential settlement could generate strains that could damage the cap. Similarly, gaps between container stacks and any residual void space in the vaults are planned to be infilled with inert, free-draining material [12]. Wastes disposed in the trenches and in existing container designs in Vaults 8 and part of Vault 9 and 9a will be surcharged prior to installation of the final cap. This surcharging process is intended to help drive out potential settlements and provide a stable base prior to cap construction. Lateral restraints will control the effects of surcharging on wastes, but some containers will however be damaged during surcharging. Other vault wastes will be disposed in the future in stronger containers which will withstand the loads imposed during and after cap installation. These containers need not be surcharged and are not expected to be damaged during cap installation. CPUs are designed to protect the lid of the top of stack container, so it is not damaged by loads from the profile fill and cap during installation and once installed [12]. The CPU directs the loads into the structural corner elements of the containers, and down the structural elements of the underlying containers into the vault base. This ensures that the containers can remain intact for a long period and

	continue to provide an isolation function to limit water contact with waste (see Subsection 5.1.1). Shielded modules which could be used for disposal of some ILW comprise a concrete structure that would also protect waste containers from vertical loads from the final cap and profile material. The profile fill underlying the cap gives the cap the correct shape and slopes and protects the geomembrane and BES in the cap from potential strains that could otherwise arise from settlement of the waste. This is a key factor in protecting the cap and keeping infiltration into the repository low.
Significance	As discussed in Subsection 5.1.1, a variant case in the groundwater assessment considered the impact of poorer than expected cap performance, such as could occur if there were any unexpected settlement of waste. Such a situation was represented by assuming earlier geomembrane failure, at 2700 AD. This leads to an increase in peak risks, resulting from increased infiltration into the vaults and trenches (by a factor of 10,000) which leads to overtopping. The controls which act to maintain the integrity of the cap (particularly the low permeability geomembrane) therefore support good cap performance for longer.

5.1.3 Control of the Chemical Environment of the Wastes

The chemical environment of the wastes affects radionuclide transport (sorption and solubility limits) and evolution of materials in the repository (e.g. corrosion rates). The chemical environment is largely controlled by the presence of grout in the vaults (W6), which provides high pH conditions. This control is characterised in Table 5.3.

Table 5.3: Characterisation of controls relating to the chemical environment of the wastes

Controls and Safety Functions	W6: Control of the chemical environment
Description	Within vault containers, grout will provide high pH conditions (expected to be around pH 12.5) [6]. The high pH conditions promote low solubility limits and enhanced sorption of some contaminants to the waste form and grout. The degree of conditioning provided by the cap will be relatively minor compared with the degree of conditioning that the grout will provide. The

cap also limits oxygen ingress, so reducing conditions are established which are controlled by metal corrosion and water reduction.

The presence of complexants such as isosaccharinic acid (ISA) and ethylenediaminetetraacetic acid (EDTA) can cause increase in effective solubility limits and decrease in effective sorption coefficients for some elements. The high pH conditions in the grout porewater in vault containers are expected to inhibit microbial populations which could degrade ISA. The pH is lower in the gaps between stacks in the vaults, but the groundwater assessment cautiously assumes that ISA present in the vaults will not be degraded by microbial activity and will complex with some contaminant species.

Corrosion of metallic wastes and containers is also inhibited by the high pH conditions. This reduces the rate of release of radionuclides present in the corroding metal, and protects the waste form for longer.

Reducing conditions that develop within the grouted wastes encourage generally lower-solubility oxidation states for the redox-sensitive elements.

The chemical conditions promote the precipitation of C-14 into the solid phase.

Not all containers are perfectly grouted, and the proportion of grout within individual containers varies quite widely. Once infiltration penetrates the containers, the pH conditions will evolve differently, depending on the amount of grout, and sorption conditions will vary. Even if grout does not entirely surround particular waste forms (for example, those at the bottom of a container), the chemical barrier will still contribute to retardation as the porewater in the container will be influenced by the grout.

The low infiltration rate, which is primarily controlled by the cap (see Subsection 5.1.1), limits the loss of alkalis from the grout, so helps to maintain high pH conditions for an extended period of time. The infiltrating rainwater will be chemically conditioned following contact with the BES and other cap materials. This will increase the quantities of sulphate in the infiltrating water. In the profile fill, the reduction of sulphate by microbial conditions in the presence of hydrogen to produce dissolved sulphide will occur [6]. This is important as it encourages the formation of low-solubility compounds of lead and mercury.

In the trenches, the only controls are the existing waste characteristics and the interim and final cap. pH conditions are not high enough to inhibit microbial populations, so microbes will degrade any ISA present.

Significance	A variant case in the groundwater assessment investigates the effectiveness of the chemical barrier by allowing unlimited solubility and no sorption in the repository. In this case, contaminants can be transported more freely out of the near field and through the geosphere. Risks from the well pathway are larger than those in the reference case, with the largest risks arising from U-234 and U-238 because uranium is no longer solubility limited in this variant. Risks from the marine and estuary pathways are also larger than in the reference case. The chemical barrier in the geosphere is more important for reduction of risk relative to that of the near field (see Subsection 5.1.4). Another variant case considers uncertainty in the complexant loading associated with EDTA and ISA, by increasing the sorption reduction factors (SRFs) and solubility enhancement factors (SEFs) by an order of magnitude in the vaults, and increasing the EDTA loading in the vaults and trenches by an order of magnitude. Only nickel, europium and holmium complex to EDTA in the trenches; peak risks for isotopes of nickel are increased by an order of magnitude in this case, but these do not contribute significantly to overall risks. Similarly, many radionuclides complex to ISA in the vaults to varying extents, but the main contributions to risk from these radionuclides arise from their presence in the trenches (where ISA is not thought to be present), so there is little impact on the total risk. The groundwater assessment model assumes that radionuclides are instantaneously released from the waste materials, with no credit taken for slower congruent release with corrosion for radionuclides which are present in the matrix of metal waste (e.g. C-14 in steel). Congruent release with corrosion is modelled for non-radiological pollutants in some metals. If the pH in vault containers were reduced from pH 12.5 to pH 10-11, corrosion rates for steel would be expected to increase by a factor of six (see references [32] and [33]). This would increase the rate of release of radionuclides from steels; however, the assumption of instantaneous release made in the groundwater assessment is bounding.

5.1.4 Controls on Contaminants in Groundwater

The geosphere provides controls on contaminants in groundwater, both the rate of migration (due to sorption, control M3) and concentrations (dilution and dispersion in uncontaminated groundwater, control M4). These controls delay the transport of radionuclides and reduce the concentrations of contaminants released into the surface environment. These controls are characterised in Table 5.4.

The key hydrogeological units for the groundwater pathway are B2 (a unit made up of laterally extensive interbedded clay and sand layers which underlies the trenches and vaults) and B3 (a thick granular unit comprising of sands and gravels which acts as the regional aquifer, together with the underlying sandstone).

Table 5.4: Characterisation of controls relating to the concentration of contaminants in groundwater

Controls and Safety Function	M3: Control of contaminant migration through geosphere M4: Control of contaminant concentrations in groundwater
Description	Sorbing contaminants are retarded within the B2 and B3 lithofacies units. Concentrations in the geosphere are sufficiently low that solubility limitation is not relevant. Therefore, we do not consider any safety function related to solubility. The B2 layer contributes by delaying the transport of contaminants to the biosphere. The B2 unit is modelled with bulk properties representing both clay and sand layers (i.e. averaged hydraulic conductivities and sorption coefficients). The B2 layer also provides some dilution and dispersion of contaminants in uncontaminated water. The B3 layer acts to dilute contaminants with uncontaminated water and to disperse contaminants. The unit is principally comprised of sands and gravels. The sorption capacity of B3 also provides retardation. Sorption coefficients in the groundwater assessment are taken to be the same as those in the B2 unit.
Significance	Analysis of the reference case results from the groundwater assessment demonstrates that, even for a weakly-sorbing radionuclide such as I-129, the transport time through the B2 layer is long (around 100 years), due to the low flows (seen in Figure 5.1 by the lag in the peak in the mass in the "Bottom of B2" relative to "Top of B2"). The mass in B3 is around two orders of magnitude less than that in the top layer of B2 at the end of the assessment timeframe. For U-238, sorption to the Quaternary sediments in B2 retards contaminant transport to the lower layers below. The amounts in the lower layers of B2 and B3 are reduced by around two orders of magnitude compared to the amount at the top of B2 (Figure 5.2). Variant cases considering the impact of higher or lower groundwater flow rates within the B3 lithofacies unit show that the peak risk from the well pathway is inversely proportional to the change in groundwater flow rate, illustrating the safety function provided by additional dilution in the B3 unit.

5.1.5 Control of Contaminant Concentrations in the Environment

Four biosphere pathways are considered in the groundwater assessment: abstraction of groundwater from a well, groundwater releases to the marine environment, groundwater releases to an estuary environment, and releases to a stream. For the marine, estuary and stream, the surface water or marine environment provides additional dilution and dispersion of contaminants (M5). This is characterised in Table 5.2. No additional dilution and dispersion is applicable for the well abstraction, as water is drawn directly from the geosphere; controls specific to this exposure pathway are discussed further in Subsection 5.1.6.

Table 5.5: Characterisation of controls relating to contaminant concentrations in the environment

Controls and Safety Function	M5: Control of contaminant concentrations in environment
Description	Once radionuclides have entered the B3 aquifer, it is expected that the contaminant plume will continue to travel in the sub-surface and discharge into the intertidal zone. As a result, radionuclides will contaminate both the beach and intertidal zone, and also local coastal waters and sediments. They will be diluted and dispersed within the marine environment. Radionuclides will also be transported to more distant oceanic waters and their underlying sediments, involving a further degree of dilution. In addition to radionuclide discharges to the marine environment, a further possibility is that radionuclides could discharge into the East-West and Drigg Streams. This could occur if overtopping from the trenches or vaults takes place and flows overland. This is unlikely to occur, because the LLWR structure and engineering and drainage system are designed to minimise the likelihood of overtopping occurring. In the event that overtopping did occur, the stream would provide a significant degree of dilution and dispersion of contaminants. The Drigg Stream discharges to the Ravenglass Estuary via the River Irt. In addition, exchanges occur between waters of the estuary and local coastal waters. Contaminants in the estuary will therefore be subject to dilution and dispersion by marine and surface waters.
Significance	The results of the groundwater assessment illustrate that peak radionuclide concentrations in the local coastal waters are more than 100,000 times lower than concentrations in the main groundwater plume in the B3 lithofacies unit. This is primarily due to the additional dilution.

5.1.6 Control of Land Use

The groundwater assessment assumes the development of a well for groundwater abstraction in the area between the LLWR and the coastline. The location and likelihood of a well being present which intercepts the main contaminated groundwater plume are controlled by restrictions on use of the site and the surrounding land (I3). These controls are characterised in Table 5.6.

Table 5.6: Characterisation of controls relating to land use

Controls and Safety Function	I3: Control of use of surrounding land during institutional control
Description	The region between the LLWR facility and the coastline constitutes part of a larger area that is designated as a site of special scientific interest (SSSI). The designated SSSI is currently under a 999-year lease agreement to the NDA. We intend to maintain this lease during the PoA. This will ensure that we have control over future development on the SSSI, including the installation of groundwater abstraction wells. It is possible it will be maintained beyond this, although this cannot be relied upon indefinitely. Within the groundwater assessment model, the lease is not accounted for and it is cautiously assumed that wells can be dug throughout the post-PoA period (at any time). It is not credible that a well could be sunk in the near term (several decades or more) to abstract contaminated groundwater. However, there is greater uncertainty in the longer term, so in the PoA assessment [13], a 'what if' case calculates impacts in the unlikely situation that a well is sunk in the area and used for drinking water.
Significance	The significance of the control is to reduce doses and risks from use of contaminated groundwater abstracted from a well to zero over the period that the well installation is prevented. The results of the assessments can be used to indicate the significance of hypothetical doses from a well if the control were not in place. The results of the groundwater assessment confirm that risks remain below the risk guidance level even if it is assumed that wells can be dug in the region between the LLWR facility and the coastline during this period. In the deterministic reference case, peak risks from a well are 2.3 10^{-9} y^{-1} during the post-PoA. Similarly, doses during the PoA remain below the groundwater protection criterion of 0.01 mSv y^{-1} for ingestion of groundwater extracted via a well

	in this region (for the period beyond 2028). However, peak doses from the marine pathway are 10,000 times lower, indicating that abstraction of groundwater from a well would be the most significant exposure route for groundwater if permitted.

5.2 Gas Release

5.2.1 Control on Gas Generation

Control of water contacting the waste (controls W1, W5, C1, C2) and the chemical environment of the waste (control W6) act to limit the rate of generation and release of gas from the waste form.

Radon is generated by the radioactive decay of Ra-226, therefore the rate at which the gas is generated is controlled only by the disposed inventory of Ra-226. However, its release from the waste form is a gradual process represented by an emanation factor (essentially the fraction of the radon that is generated that is released). This accounts for the decay of some radon gas during its diffusion and any advection through the waste form. Within the vaults, the grout and waste containers act via these mechanisms to reduce the released fluxes. These controls are characterised in Table 5.7.

The subsequent rate of release to outdoor air is driven by the rate at which bulk gases are evolved, as these gas flows are necessary to transport trace gases such as radon to the environment. The generation of bulk gas from the corrosion of metals is a key component. Limiting metal corrosion (through alkaline conditions and reducing water ingress) therefore provides an additional safety function (covered in more detail in Subsection 5.2.2).

In relation to C-14, limiting the contact of waste with water will limit the rate at which some C-14 bearing gases can be generated. Furthermore, in the vaults the pH is maintained at a high level. A significant proportion of the C-14 inventory can therefore remain in solution in containers or in carbonate, so that there is no C-14 bearing gas release from some waste types. Limiting waste contact with water also reduces the potential for the release of tritium in the form of water vapour. This process can occur during the PoA when some of the wastes in the trenches are saturated, the interim cap is vented, and vault wastes are uncovered.

Table 5.7: Characterisation of controls relating to gas generation

Controls and Safety Functions	W1: Control of the integrity of the waste W5: Control of waste contact with water W6: Control of the chemical environment C1: Control of water entering the repository during operations

	C2: Control of water entering the repository after operations
Description	The waste form provides a barrier to the emanation of radon which must migrate through the waste material. The transport pathway is increased by the grouted waste form and waste containers in the vaults - gas must migrate to a grout port or corrosion perforation, increasing the proportion of radon gas that decays before release. High pH conditions in the vaults, due to limited water infiltration, minimise metal corrosion rates, bulk gas generation and the generation of C-14 bearing gas by microbial activity. Minimising bulk gas generation minimises the advective transport velocity of radon, increasing the proportion that will decay before release (Rn-222 has a half-life of only 3.8 days). C-14 present as matrix contamination in waste is released slowly (e.g. congruent with metal corrosion) or, for graphite, remains trapped in the graphite lattice. C-14 present in organic material or as surface contamination is released more rapidly, to solution in the form of small organics or inorganic molecules. C-14 released to solution in inorganic form reacts with cement minerals and is 'locked up' in carbonate minerals. The pH is too high for microbial metabolism of C-14 in small organics. Containers limit water contact with the grout and waste, maintaining high pH conditions and limiting release of C-14 in solution. Water contact with the wastes is minimised by components including CPUs and shielded modules for some future disposals, the cap (particularly the geomembrane) which reduces infiltration, vault and trench drains. In addition to minimising bulk gas generation rates, minimising water contact with the wastes also minimises the biodegradation rates (thus generation of C-14 gas by this mechanism) and the rate at which tritium can be released in water vapour (discussed further in Subsection 5.2.2).
Significance	Radon monitoring data from trench probes and trench inventory data were used to estimate an emanation fraction for the trenches, and to derive an emanation fraction for the vaults (expected to be lower due to additional barriers provided by grouted containers). The emanation fractions used in the gas assessment [34] are 15% and 7% respectively, i.e. 15% of radon generated is released from the waste in the trenches and 7% of radon generated is released from the waste containers in the vaults. The gas assessment does not take credit for additional barriers provided by Ra-226 sealed sources which would further reduce releases. Sensitivity

cases show that risks from radon would be negligible without advection by bulk gas [34].

Only 5% of C-14 is released from graphite waste in the vaults (Figure 5.4). Less than 1% of the C-14 inventory in steels in vaults is released before disruption of the site by coastal erosion due to the slow rate of corrosion in the alkaline vault conditions (Figure 5.5).

65.5% of the C-14 released from graphite to solution and 20% of the C-14 released from organic waste is released in inorganic form and reacts with cement minerals to form carbonate (shown in Figure 5.4 for graphite).

In the gas assessment reference case, the pH in the vault containers at closure is expected to be around pH 12.5 [6] as alkali metal hydroxides are not flushed from the grout due to limited water contact with the grout inside the containers. This pH leads to slow metal corrosion rates and is too high for microbial activity. A set of unlikely 'what if' calculation cases show that C-14 gas fluxes and doses significantly increase if the container pH is low enough for significant microbial metabolism of small organics in solution [34]; therefore, controls which maintain high pH conditions in the containers and limit waste contact with water provide a significant safety function in reducing release of C-14 bearing gas.

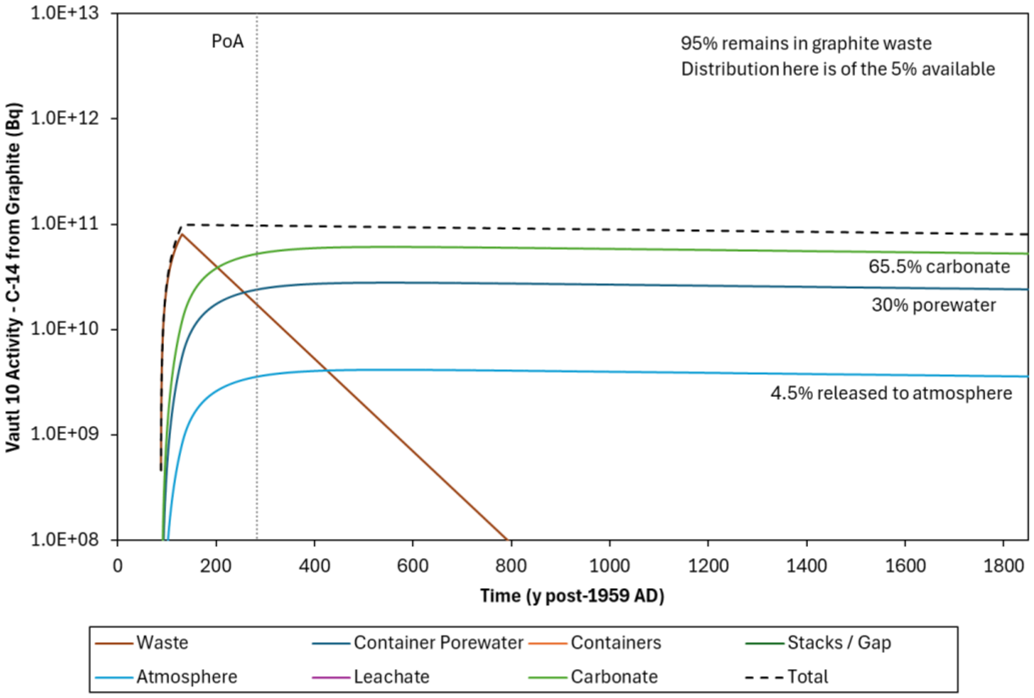

Figure 5.4: Activity distribution of C-14 in Vault 10 from graphite waste

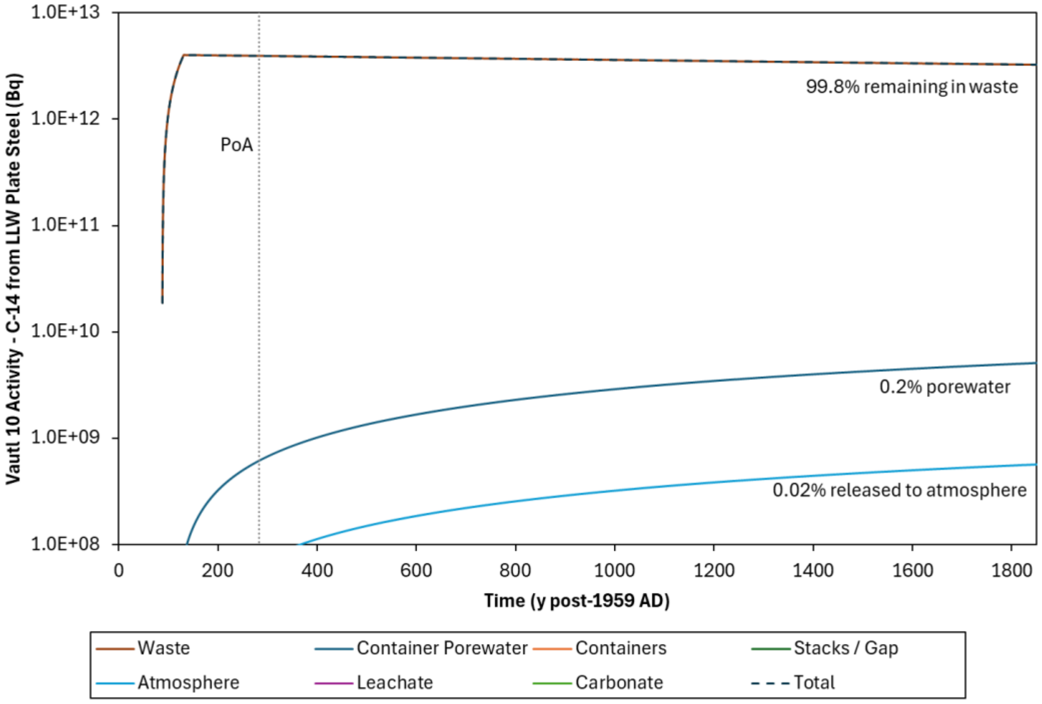

Figure 5.5: Activity distribution of C-14 in Vault 10 from plate steel

5.2.2 Control on Gas Transport and Release

Control of waste placement (W2) and depth of waste from the surface (I4) can act to increase the pathlength and the time that is taken for gas to be released from the repository. This provides an important safety function for radon gas because it has a short half-life of 3.8 days and will significantly decay before being released to the environment. A limit on the activity of Ra-226, the parent of radon, in waste containers at the top and bottom of stacks is proposed to be implemented [17] but has not been accounted for in our assessments.

Controls on generation of bulk gas are relevant to transport of radon, as radon itself is generated in extremely small volumes and therefore requires to be advected with bulk gases. These controls are similar to those described in section 5.2.1; controls on waste contact with water (W5, C1, C2) and the chemical environment of the waste (W6), which affect rates of bulk gas generation by corrosion and microbial activity. Lower generation rates of bulk gas will lead to lower gas velocities, which result in more decay of radon along the transport path before being released. Bulk gas pressures in the repository and hence advective velocities are reduced by low water saturation (controls W6, C1, C2).

Inside waste containers in the vaults, pH conditions are expected to be too high for microbial metabolism of C-14 bearing small organic molecules in solution (see Subsection 5.2.2). Outside containers, in the gap between stacks, the small organic molecules can be microbially metabolised, and the C-14 will be released as methane gas. Transport of C-14 bearing molecules in solution out of the containers is controlled by infiltration of water to the vaults (C2) and the waste contact with water (W6). C-14 bearing gas released from small organic molecules in this way can provide a significant contribution to releases after the period of institutional control.

Release of tritium in water vapour is controlled by evaporation of water from the trenches and vault wastes. This release is therefore controlled by water contact with the waste (controls W6, C1).

Gas release after closure and final capping is controlled through components such as the void fill and final engineered cap (M2). Decisions about the vent design for the final cap will be taken to optimise factors including bulk gas pressures in the repository and release of radioactive gases.

These controls are characterised in Table 5.8.

Table 5.8: Characterisation of controls relating to gas transport and release

Controls and Safety Functions	W2: Control of waste placement W5: Control of waste contact with water W6: Control of the chemical environment I4: Control of depth of waste from surface C1: Control of water entering the repository during operations

	C2: Control of water entering the repository after operations M2: Control of gas release after operations
Description	During operations there will be no barriers to gas transport and release from wastes in vaults beyond those of the waste form (grout and waste containers), but gases are rapidly dispersed in air. Nevertheless, as noted in Subsection 5.2.1, controlling water contact helps to minimise the rate of generation of some gases. For the trenches, the waste mass exerts some control on transport, but the trenches are vented through probe holes allowing gas to be released and disperse. Once capping commences, components such as the profile fill, gas collection layer and vent will act to manage the transport and release of gas from wastes so as to avoid any pressurisation. This may damage or degrade engineered structures. A decision has not yet been made about whether a gas vent (or vents) in the final cap will be left open after the end of the period of institutional control. This may be required to manage bulk gas pressures in the repository [12] The decision will be informed through monitoring of gas generation rates once the first strip of cap is installed. If the gas vent is left open, the majority of gas will be released through the vent to atmosphere (noting that radon generated furthest from the vent will have decayed before reaching it). If the vent is closed at the end of the PoA, releases to atmosphere are expected to be through defects distributed across the cap. Learning from the gas assessment and monitoring data will be used to inform optimisation of the gas management strategy and vent design. Within the closed repository, radon is transported from the wastes where it is generated, through the waste stacks, profile fill and other cap layers, by diffusion and by advection with bulk gas. Profile fill material with a minimum thickness of 2 m will be placed over the waste. The travel time through the profile fill layer is an important barrier to the radon released from the containers, as radon may decay significantly during this transport. If there is a large permeability contrast between the profile fill and the gas collection layer, this maximises the travel time through the profile fill. With a higher permeability contrast, flow is across the profile fill, with slow flow rates, rather than radially within the fill towards defects in the geomembrane, resulting in higher velocities. Over the trenches, it is planned to use site-won material with cohesive qualities for the main layer of profile material; this material should be significantly less permeable than the gas collection layer. Over the vaults, granular profile fill will be used, and faster radial flow may be possible.

	Low water saturation in the repository will act to decrease bulk gas pressures, reduce bulk gas and radon pore velocities, and hence increase the amount of radon decay before release. Components which reduce saturations in the repository include the cap which limits infiltration (particularly the geomembrane) and the cut-off wall which prevents lateral inflow of groundwater.
	Water contact with waste also controls the release rate of tritium in water vapour. Evaporation of water in the trenches and porewater in the vault containers is a source of tritium in water vapour. Following final capping, infiltration into the repository is expected to be very low and water will be consumed by corrosion of containers, so release of tritium in water vapour will largely cease. Cautiously, no credit is given for the impact of containers and CPUs in restricting water contact with waste in the PoA assessment, or for the waste form itself (e.g. sealed glass vials in the trenches). Shielded modules are assumed to prevent any significant infiltration from contacting waste contained within them.
	For C-14 bearing gas, there is not expected to be any significant hold-up of gas in the vault (relative to the longer half-life of C-14).
	When the cap geomembrane is intact, infiltration into the vaults is expected to be very low [12] and most infiltrating water will be consumed by corrosion processes of containers. There is therefore no flow path for C-14 in solution to be transported out of the containers. Once the cap begins to degrade, infiltration into the vaults will increase (although still reduced by other layers of the cap such as the BES). For the existing container designs in Vaults 8 and 9, water may flow through stacks of damaged containers and through cracks in the grout, transporting C-14 in solution from the waste. Future stronger containers are expected to be mostly intact, and CPUs at the top of waste stacks would direct water down the sides of the stacks. C-14 in solution could diffuse out of these containers where they are locally perforated. Shielded modules may provide additional containment of C-14 in solution, but no credit is given to this in the gas assessment.
	Once C-14 bearing small organic molecules in solution have been transported out of the high pH environment of the containers, they can be rapidly microbially metabolised and the C-14 will be released as methane gas.
Significance	During the PoA, the assessment assumes that gases are released to air and dispersed without accounting for any transport other than through the wasteform. Even with these cautious assumptions during this period the

highest annual doses are a few µSv to nearby residents and dog-walkers, who may be most exposed. Radon is the dominant gaseous radionuclide.

After the PoA, tritium will have decayed to insignificant amounts therefore the main gaseous radionuclides to consider are radon and C-14.

Variant cases in the gas assessment [34] considered the impact of different thicknesses of profile fill above the vaults and trenches. The profile thickness is a minimum of 2 m. Every additional 2 m of profile fill reduces doses from radon by a factor of around seven above the trenches and around five above the vaults, due to the additional transport time. Other components (e.g. BES, overlying cap layers) also provide a barrier to radon transport. The gas assessment considered a case where the BES (and cap geomembrane) has degraded; peak doses in this case were increased by about a factor of ten due to the reduction in diffusive resistance.

Doses from radon are highly sensitive to the flow behaviour in the profile fill. If the profile fill has a similar permeability to the gas collection layer, such that there is radial flow in the profile fill towards defects in the cap geomembrane, doses are increased by a factor of two to three for the vaults and by more than an order of magnitude for the trenches. This is because the thickness of profile material is typically much greater over the trenches. The planned use of less permeable material in the profile fill over the trenches therefore provides an important safety function in preventing risks from radon from exceeding the risk guidance level.

Transport time and attenuation of radon while migrating between container stacks is cautiously neglected in the gas assessment. A side calculation suggests that this would further reduce doses by an extra factor of two to three, depending on the properties of the material between the stacks (air or granular fill). There is an estimated factor of 10 difference in doses between radon arising from wastes at the top and bottom of stacks, due to the additional travel time and decay. Therefore, controls are proposed to limit the activity of radon in waste containers at the top of stacks [17].

A bounding sensitivity case in the gas assessment [34] considered the impact of no bulk gas, so transport of radon is by diffusion only. In this case, risks from radon are decreased to negligible levels. Therefore controls relating to generation of bulk gas are important.

For radon, optimisation of the vent design could consider the location of the vent relative to disposals of waste containing Ra-226. The capture radius of the vent is about 60 m, with radon generated outside this radius decaying before it is released from the repository. For C-14, the cap geomembrane provides an important safety function in limiting infiltration into the vaults. It is likely that the cap geomembrane will remain intact until the repository is disrupted by coastal erosion [12]. The gas assessment alternatively considers a case where the cap geomembrane degrades earlier; in this case, peak doses from C-14 bearing gas are a factor of 20 higher (but remain below the regulatory risk guidance level). This is because of the additional release of C-14 from small organic molecules in solution which can be transported out of containers once water ingress to the vaults increases.

In the gas assessment, no credit is given for any containment provided by the existing container designs after geomembrane failure, and the infiltration is cautiously assumed to immediately increase following failure of each strip of the cap geomembrane. By contrast, future stronger containers are expected to be largely intact, with C-14 in solution diffusing from localised perforations, and the number of stronger containers from which C-14 in solution can diffuse gradually increases as the geomembrane degrades (over a period of 100 years). Given these assessment assumptions, peak doses from future stronger containers are around a factor of 100 lower than those from the existing containers (for a given inventory of C-14) due to the longer time over which C-14 is released in solution from containers [34].

The gas assessment considered impacts from C-14 and radon gas with a cap vent left open or closed after the end of the PoA. If it is assumed that a receptor (house or smallholding) is present above the vent, then calculated doses to that receptor could be a factor of four higher than the reference case for C-14. However, risks are low because the probability that a house or smallholding would be present on the vent is low.

5.2.3 Control of Contaminant Concentrations in the Environment

Control of access to the site during the period of operations (control I1) and institutional control (I2) prevent the construction of dwellings on top of the cap and use of the cap for agriculture, which are the activities that could lead to the highest exposures from radioactive gases. Off-site exposures to radioactive gas during the PoA are subject to atmospheric dispersion (control M5, dilution and dispersion with uncontaminated air). These controls reduce the concentration of contaminants in the environment to which receptors are exposed and are characterised in Table 5.9.

Table 5.9: Characterisation of controls relating to contaminant concentrations in the environment

Controls and Safety Functions	I1: Control of access to site during operations I2: Control of access to site during institutional control C10: Control of contaminant concentrations in the environment
Description	During the PoA, active management control of the site precludes habitation and agriculture on the cap, which significantly limits the radiation doses that might arise from Rn or C-14 bearing gases. Tritium has a short half-life, so will decay significantly during this period, with very low (negligible) concentrations remaining in the repository by the end of the PoA. Off-site exposures to radioactive gases during the PoA are subject to atmospheric dispersion, which reduces the concentrations to which receptors could be exposed. The most significant potential exposures of people after the end of the PoA relate to occupancy of the cap. People residing on the cap may be exposed to radon gas, if it collects in buildings, and to C-14 in crops as a result of plant uptake of C-14.
Significance	In the gas assessment, peak concentrations of Rn-222 are three to four orders of magnitude lower outdoors than indoors, due to the additional dispersion and dilution with clean air [34]. Concentrations of tritium and C-14 in plants are a factor of about 50 lower at an off-site farm [35] compared to a smallholding on the cap [36], due to the atmospheric dispersion. Therefore, contaminant concentrations during the PoA are very significantly reduced by these controls. Tritium has a half-life of 12.3 years. Final disposals to the repository (in 2135) will have been subject to 8.7 half-lives of decay by the end of the PoA (2242), reducing the amount remaining by a factor of more than 400. The first disposals to the repository (in 1959) will have been subject to 23 half-lives of decay by the end of the PoA, reducing the inventory by a factor of 8 million. Variant cases in the gas assessment consider no period of institutional control, so on-site receptors can be present from the time of final capping (2142) [34]. For C-14, the peak gas fluxes occur within this period, driven by relatively rapid releases of gas from graphite and pucks[4]. Therefore,

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[4] Some soft wastes (e.g. clothes, paper towels) in drums are processed into super-compacted pucks in the existing and committed waste inventory. In the gas assessment, it is assumed that microbial activity can occur in

	the peak dose is increased by a factor of three if on-site receptors are assumed to be present from 2142, compared to the reference case, which assumes a 100 y period of institutional control. For radon, there is only a very small increase in the peak doses since the fluxes of bulk gas and radon from the repository are almost constant over the time period.

5.3 Liquid Discharges

The key controls related to managed liquid discharges during the period of operations are those related to generation and migration of leachate (Subsection 5.3.1), and management of leachate and contaminant concentrations in the environment (Subsection 5.3.2).

The release of contaminants in liquid after the leachate management system is decommissioned is covered in Subsection 5.1.

5.3.1 Controls on Waste Contact with Water

Radioactive leachate is primarily generated by precipitation contacting waste. Leachate generation is therefore controlled by waste contact with water (controls W5, C1). Waste contact with water also affects the migration of leachate, discussed subsequently in Subsection 5.3.2. The controls on waste contact with water are characterised in Table 5.10.

Table 5.10: Characterisation of controls relating to waste contact with water

Controls and Safety Functions	W5: Control of waste contact with water C1: Control of water entering the repository during operations
Description	Limitation of the entry of water into the trenches and vaults will control the amount of leachate generated, while limitation of the water that can contact the waste will control the concentrations of contaminants in the leachate that is generated. In the vaults, the grouted waste forms and containers limit meteoric water contact with wastes. Sorption of radionuclides onto the grout reduces the potential for dissolution of radionuclides in leachate. These act to reduce the concentration of radionuclides in leachate. Infiltrating water is consumed by anaerobic corrosion of steel containers, also reducing the volume of leachate.

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niches on the surface of cellulosic waste in pucks; therefore, there can be microbial metabolism of some C-14 associated with pucks, resulting in release of C-14 bearing gas [34].

	Containers are planned to be stored temporarily in warehouses, before being placed in the final vault positions, to minimise water contact with waste. This protects them from rainfall and reduces the period in which containers are exposed before being covered by the next strip of the final cap. In the PoA assessment, this is represented by assuming that a maximum of 10 years' wastes are uncovered, with the remainder being protected by a warehouse. For future disposals to the vaults, CPUs and shielded modules may further reduce meteoric water contact with wastes and thus generation of leachate. In the PoA assessment, waste in shielded modules is assumed not to contribute to the radionuclide concentration of leachate, but cautiously no credit is taken for additional containment provided by CPUs and future stronger containers compared to existing wastes. The final cap and profile fill significantly reduce infiltration into the repository [12], which minimises leachate generation and potential for liquid discharges to surface water or marine environment. In the PoA assessment [35], liquid discharges are assumed to cease from each vault once it is capped (with the leading edge seal also acting to restrict infiltration into each capped section). The interim trench cap is being replaced over the southern area of the trenches which will also reduce infiltration into the trenches prior to placement of the final cap [35]; cautiously, no credit is taken for this improvement in the PoA assessment. The cut-off wall prevents any leakage directly to surface soils and waters and direct any leachate leakage towards deeper groundwater.
Significance	The reduction in leachate generation as a result of temporarily storing containers in warehouses is assessed through a 'No Warehousing' variant case in the PoA assessment [35]. No warehousing increases the annual dose from the leachate pathway to the marine environment by a factor of 1.6 (it remains very small, less than 3 μSv). While the effect of storing wastes in warehouses is therefore fairly minimal in terms of direct impact on dose, it is important for other reasons such as reducing the rate of corrosion of waste containers. The significance of other components in reducing leachate (e.g. trench interim cap, containers, grout, CPUs) is not quantitatively assessed. Once the final cap is emplaced, these play a secondary role. The PoA assessment demonstrates that, even cautiously excluding the benefit of CPUs and future stronger containers, potential doses from leachate discharges to the marine environment or discharges to surface water in an extreme storm event remain below the dose guidance level.

	Infiltration rates through the final cap are described in the EPA [12]. While the cap geomembrane is effective, infiltration rates are well below 1 mm y-^{1}. This water is expected to be consumed by corrosion reactions and not result in generation of leachate. This is a very significant barrier to liquid discharges from the repository.

5.3.2 Controls on Migration and Discharge of Leachate

The leachate management system provides a safety function during the PoA by collecting leachate for controlled discharge (C5, M1, M5). Currently, leachate is collected from the trenches and pumped from Vaults 8 and 9 and monitored before being discharged to sea via a marine pipeline [12]. Once Vault 9a is constructed, the operational leachate collection will move to a gravity-fed system. For other future vaults, an internal passive (gravity) drainage system is planned to manage leachate during operations. It is assumed that the leachate management system will remain in operation for a period after cap emplacement to manage any residual leachate. Once the site is closed, the operational leachate management system will be replaced by a long-term passive system (to discharge into the under-vault drainage blankets).

These controls are characterised in Table 5.11.

Table 5.11: Characterisation of controls relating to migration and discharge of leachate

Controls and Safety Functions	C5: Control of lateral migration of leachate M1: Control of leachate generated during operations C5: Control of contaminant concentrations in the environment
Description	The trenches are graded to the south to facilitate the collection of leachate in drains at the southern end of each trench [12]. In the vaults, the vault walls contain rainwater and leachate within the vault, preventing overspill into soils and surface water. This leachate is then captured in a drainage layer below the base slab of the vaults and directed into the leachate management system. The vault bases are designed to capture leachate effectively during the operational phase and to the end of the period of active institutional control [12], although leachate generation is expected to drop to negligible levels during this period (see Subsection 5.3.1). Through the leachate management system, liquid discharges are made to the marine environment via a pipeline several hundred metres out to sea. The discharges are rapidly dispersed in the water, reducing concentrations of radionuclides very substantially. In exceptional

	circumstances, such as an extreme storm that generates excessive leachate in the vaults, leachate may be discharged to the Drigg Stream, which is a permitted discharge route. This route has not been used in the recent past, and there are contingency arrangements for managing excess leachate other than by this route, but it nevertheless remains a possible discharge route. The stream discharges to the Irt Estuary, which then enters the sea where radionuclides are dispersed. The leachate management system is expected to be decommissioned before the end of the period of active institutional control. In the long-term, under-vault drainage blankets have the potential to capture any leachate which overtops the 1 m high vault walls and direct it to deeper groundwater systems rather than surface soils and water. Long-term degradation of the vault bases will aid passive drainage by providing a direct route to the drainage blankets.
Significance	The length of the marine discharge pipeline was selected to ensure adequate dispersion of effluent, which is discharged at suitable times to ensure effective mixing with seawater. The local marine environment is highly dispersive due to relatively strong coastal currents. The entire volume of seawater in the modelled local marine compartment in which the pipeline discharges is flushed with water from the Irish Sea every four days. The PoA assessment [35] calculates potential impacts to members of the public from contamination of seawater, sediment, and marine biota. Radionuclide concentrations in the marine environment and resulting doses remain low throughout the period of operation, confirming the effectiveness of this discharge pipeline. The PoA assessment also undertook a cautious scoping calculation to assess the impact of discharges to the Drigg Stream during an extreme storm. Doses in this case remain below the dose guidance level.

5.4 External Irradiation

5.4.1 Controls on Radiation Dose Rate

The key controls that mitigate radiation doses are those that relate to shielding of the waste (W2, W3, I6), the distance and any direct line of sight between potential receptors and the waste (W2, I1), the duration of exposure (I1), and the concentration of radionuclides in the waste (W7). These controls are characterised in Table 5.12.

Following installation of the final cap, the cap and profile material is expected to provide a such a significant degree of shielding such that external dose from the repository will be negligible unless the shielding layers are disrupted by coastal erosion (see Subsection 5.5) or human intrusion (see Subsection 5.6). Therefore, external irradiation is mainly relevant during the PoA, before completion of the final cap.

Table 5.12: Characterisation of controls relating to radiation dose rate

Controls and Safety Functions	W2: Control of waste placement W3: Control of radiation dose rates by shielding W7: Control of contaminant concentrations in waste I1: Control of access to site during operations I6: Control of radiation dose rates by shielding
Description	During the period of operations prior to final capping of the repository, access to the site by members of the public will be controlled, limiting the external dose that they can receive. Radiation dose rate drops off with distance, so off-site receptors with longer occupancy times would receive a lower dose rate owing to their distance from the wastes. Routine monitoring of external dose rates is being undertaken during the PoA to ensure that controls are sufficient to keep these below acceptable levels [37]. For the trenches, the interim cap provides essentially complete shielding of the wastes. For waste disposed in the vaults, shielding is provided by components including the waste containers, grout, CPUs, vault walls, and ultimately the final cap. Higher dose ILW, if accepted, would be disposed in shielded modules with thick concrete walls that provide an additional degree of shielding. In the PoA assessment model [35], external doses are calculated based on the radionuclide concentration, distance from the source, and area of the source. For direct radiation, the relevant source area is any area with direct line-of-sight to potential receptors (assumed to be the side of any vault wastes above a stack height of four containers). The vault walls will provide effective shielding for any containers below this stack height. Exposures can still occur without any direct line-of-sight between the receptor and the source, by the scattering by air of upwards-directed radiation back to ground ('skyshine'). The relevant source area for scattered radiation is the plan area of the vaults or trenches.
Significance	In the PoA assessment model [35], shielding by waste containers is modelled explicitly. Shielding by a few millimetres of steel attenuates the radiation dose rate by about 15%. No account is taken for shielding by grout or concrete components. However, comparison between modelled

and measured dose rates at present day indicates that doses are overestimated by a factor of about three; this may be due to shielding by these (or other) materials and/or due to over-estimation of the radionuclide inventory or other modelling pessimisms.

Figure 5.6 shows attenuation of the two radionuclides most significant for external dose (Co-60 and Cs-137) with concrete thickness. Less than 20 cm of concrete is required to attenuate fluxes by an order of magnitude.

A variant case considered shielding by CPUs at the top of stacks for future disposals of LLW and ILW (assumed to be 60 - 70 cm thick concrete). This would reduce doses from scattered radiation by over a factor of 1000 but with no impact on direct radiation [35].

Estimation of the shielding provided by shielded modules (60 to 75 cm of concrete) indicates that doses from ILW in shielded modules would be reduced by at least four orders of magnitude [35]. Doses after emplacement of the final cap would be negligible.

In the assessment model, it is assumed that radionuclides are distributed homogenously throughout the vault. However, controls could be used to emplace more hazardous wastes towards the bottom of stacks (particularly those with high concentrations of Co-60 or Cs-137) [35]. There would be no direct line-of-sight to these containers, and they would be shielded by any wastes disposed in the stacks above.

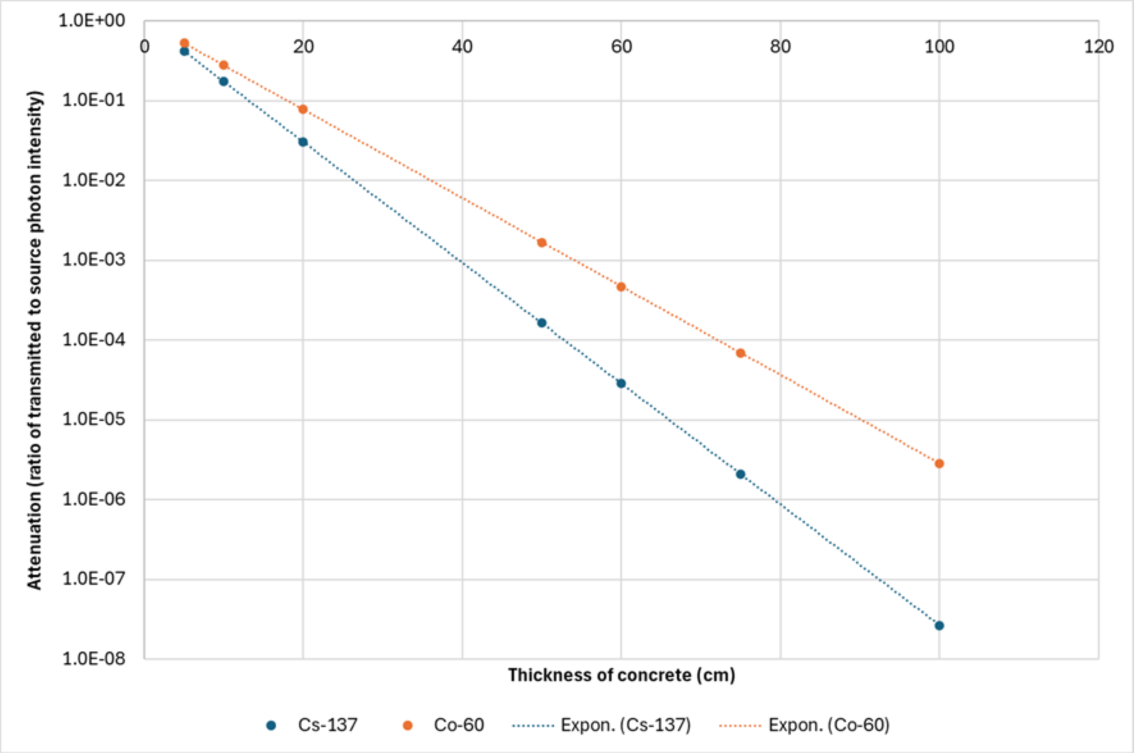

Figure 5.6: **Attenuation of Cs-137 and Co-60 by different thicknesses of concrete**

5.5 Coastal Erosion

5.5.1 Controls on Concentration in the Eroded Waste

Most of the components and safety functions considered in Section 4 are not relevant to the coastal erosion pathway, or do not have a strong influence on the potential impacts from coastal erosion, because such an event will disturb and disrupt the barriers. A control on the timing of erosion (I7) is provided by the hinterland (Quaternary sediments) between the coastal cliffs and repository, which acts as a barrier that must be eroded before erosion of the repository can commence. This provides a safety function by delaying the onset of coastal erosion of the repository, during which time there is radioactive decay of the disposed waste, reducing concentrations in the eroded waste.

If intact, the containers and grouted waste forms may also provide containment and shielding of the waste once it is exposed, and the grout also reduces the bulk concentrations of contaminants (controls W7, I6, I8), reducing the dose rate. However, the main safety function for the coastal erosion pathway is control (limitation) of the vault inventory (control WAC1). Emplacement strategies can provide another safety function for some radionuclides (control W2).

Wastes disturbed by erosion will initially be deposited on the beach before being broken up and dispersed in the marine environment (control M5). The offshore environment acts to disperse both solid material and that in solution.

These controls are characterised in Table 5.13.

Table 5.13: Characterisation of controls relating to concentration in the eroded waste

Controls and Safety Functions	I7: Control on the timing of erosion I8: Control of contaminant concentrations in disturbed waste W2: Control of waste placement W7: Control of contaminant concentrations in waste M5: Control of contaminant concentrations in environment
Description	At present day, there is a minimum of 350 m of hinterland (Quaternary sediments) between the coastal cliffs and the repository. The timescale for this to be fully eroded and the repository to be first exposed is estimated to be several hundred to a few thousand years after present. There is no reliance in the coastal erosion assessment on the maintenance of existing defences or construction of new defences. These could further delay the disruption of the repository. The ESC cannot rely on such active maintenance over the long-term; this is inconsistent with the GRA. Once the repository has begun to be disrupted by coastal erosion, users of the beach and local coastal environment may be exposed to radiation from the wastes. The key exposure pathways are external irradiation from exposed and eroded waste, and ingestion of marine foodstuffs. Scavengers may also interact with exposed items of waste on the beach [38]. Concentrations of radionuclides in the exposed wastes and eroded material are affected by the bulk properties of the waste form and engineered structures in the repository, including the grout and clean materials such as the cap. The residence time and distribution of eroded material on the beach is determined by the same processes that result in coastal erosion. Eroded material is ultimately dispersed in the vast quantities of offshore marine sediment. Placement of the wastes in the coast-inland direction (perpendicular to the direction of erosion) controls when wastes will be exposed in the cliffs and coastal environment. Controlling the concentration of radiological hazard exposed at any one time along the coast will provide a control on the concentration in the exposed and eroded waste.
Significance	Figure 5.7 shows the effect of decay and ingrowth on the radionuclide activity in the repository from the date of final disposals to the first disruption of the repository by coastal erosion. The total activity reduces

by 94% between the end of disposals and the earliest start of disruption of the repository.

The key radionuclides contributing to dose in the coastal erosion assessment [39] are C-14, Pu-239, Th-228, Ra-228 and Nb-94. These have long half-lives relative to the time taken for erosion of the hinterland (or in the case of Ra-228 and Th-228, they are effectively in secular equilibrium with Th-232 which has a very long half-life), so their activity does not decrease significantly over this period. However, without the delay provided by the hinterland, other shorter-lived radionuclides may provide more significant contributions to dose.

Figure 5.8 shows the evolution of radiological hazard for the wastes in the vaults from the end of disposals. This shows the relative change in hazard from the end of disposals to the vaults (2135) due to decay and ingrowth only (ignoring any other losses from e.g. erosion). The hazard decreases by 99.7% between the end of the PoA and the earliest start of disruption of the site by coastal erosion, because radionuclides such as Co-60 and Cs-137 have largely decayed within this time.

The coastal erosion assessment [39] considered the impact of heterogeneity of waste disposals, with particular focus on the placement of ILW in shielded modules. Concentration of the radiological hazard in sub-areas such as shielded modules could lead to higher doses when those sub-areas are eroded. Variant cases in the assessment demonstrated that spreading the shielded modules in the east-west direction (i.e. spreading them out through time of erosion) could reduce peak concentrations in the eroded waste and therefore peak doses by 40%, compared to a more concentrated layout.

Finally, we have dedicated considerable study to the marine environment and coastal dynamics [40, 41]. In the context of the UK coastline, dispersion is relatively rapid. These processes act to reduce the effective concentration of radionuclides on the beach (noting that intact articles and items would remain present for a period), and very substantially reduce them in the marine environment. Figure 5.9 shows dilution factors for radionuclides as they are transported away from the cliffs, based on concentrations of Th-232 in environmental media (a radionuclide with a very long half-life). There is a dilution factor of about 70 between the concentrations in the cliffs and the concentrations in the local offshore marine environment.

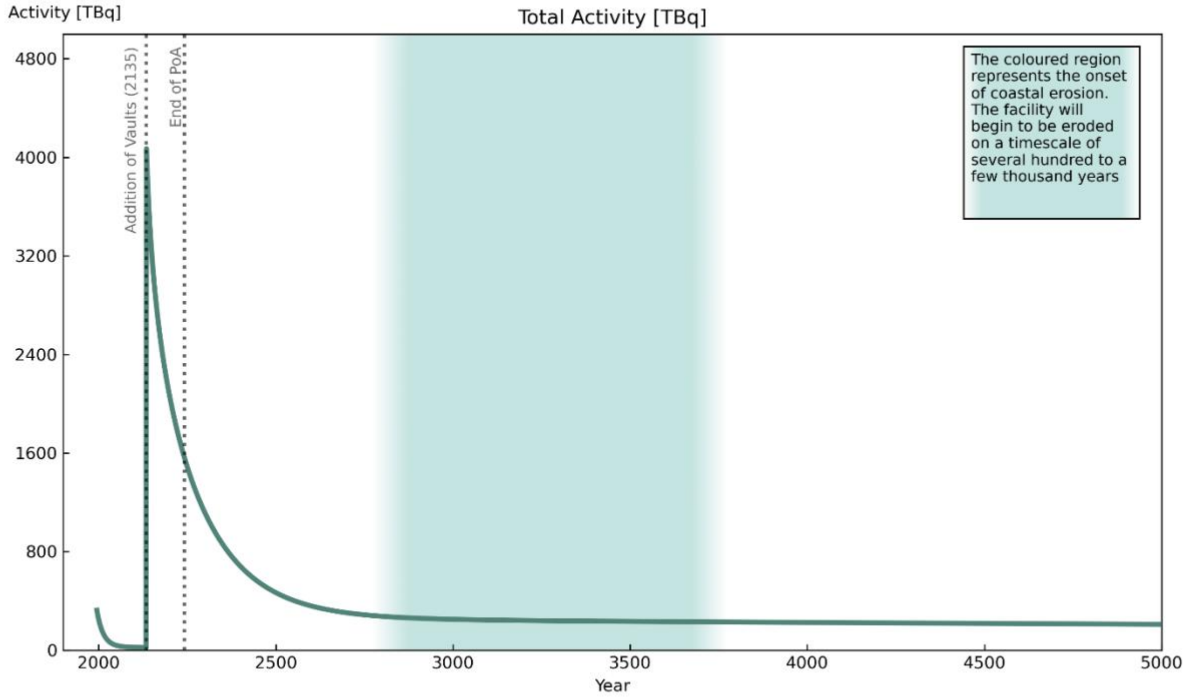

Figure 5.7: **Decay and ingrowth of radionuclide activity in the repository (excluding any other losses)**

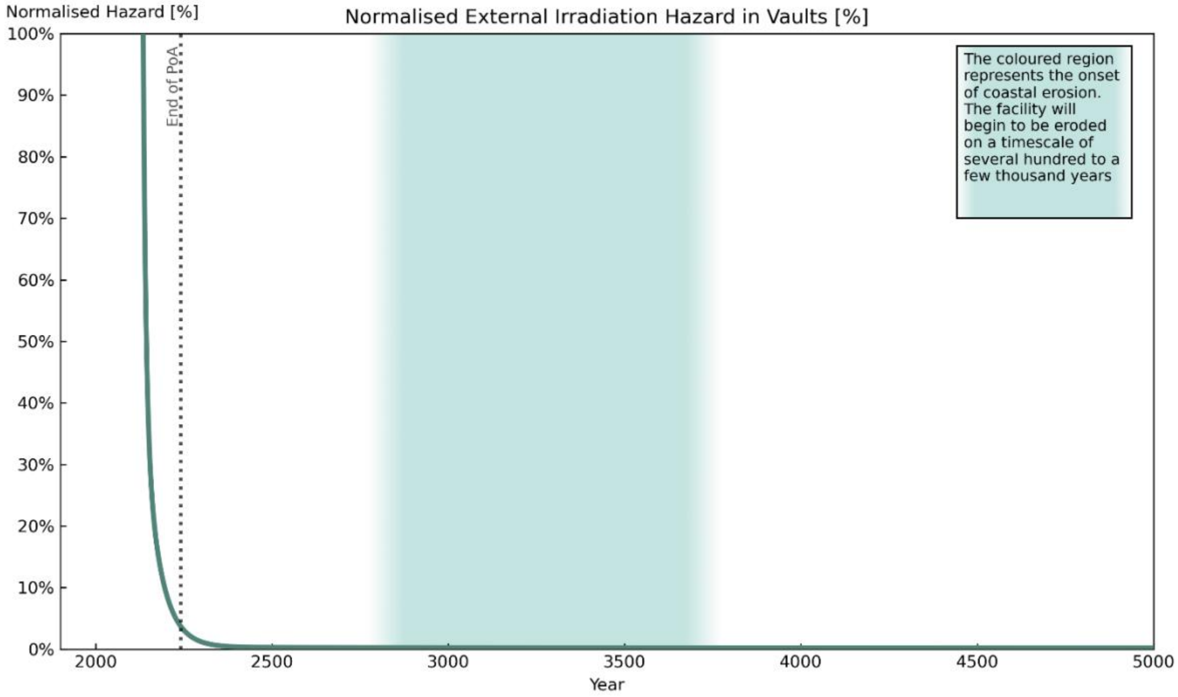

Figure 5.8: **Evolution of radiological hazard (from direct radiation) in the vaults**

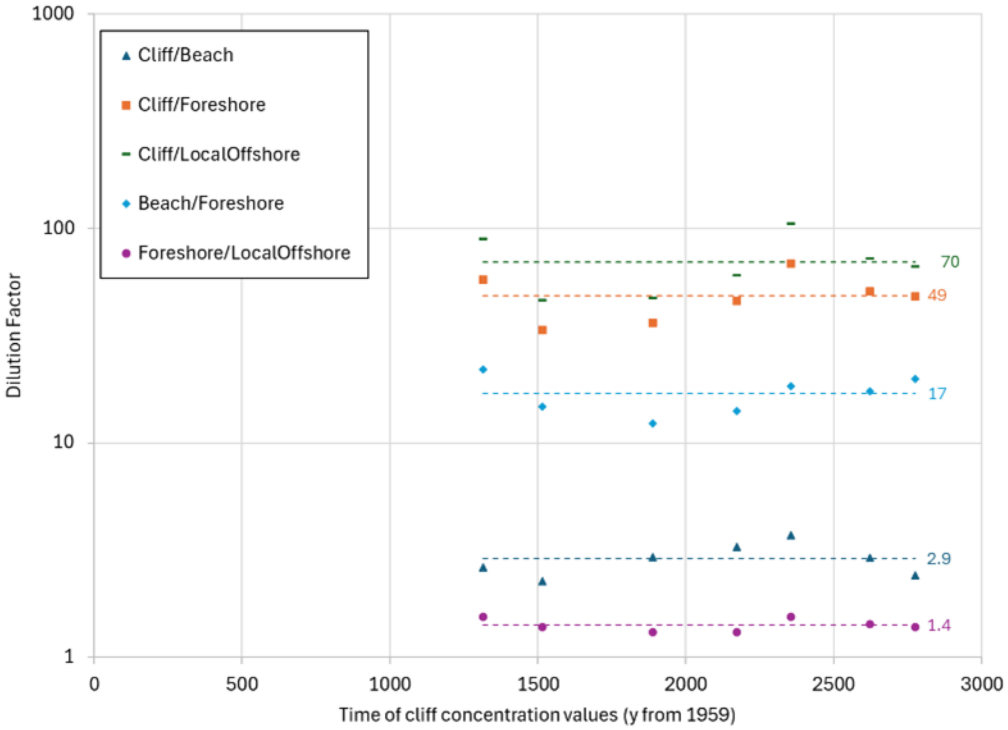

Figure 5.9: Dilution and dispersion of Th-232 away from the eroding repository, coastal erosion assessment model

5.6 Human intrusion

For the human intrusion pathway, the radiation doses that may arise are a function of the method of intrusion and the radionuclide concentrations in the wastes that are exposed due to it. The key controls that mitigate impacts are those that prevent human intrusion or which reduce its likelihood, those that limit the forms of intrusion that may encounter waste, and those which control contaminant concentrations of the exposed waste.

5.6.1 Controls on Likelihood of Encountering with Waste

During the PoA, control of access to the site (I1, I2) prevents any inadvertent intrusion events occurring. Passive controls after the end of the PoA reduce the likelihood of intrusion and limit the range of activities that could result in exposing the wastes. We have designed the facility with barriers that reduce the possibility of intrusion because they are difficult to penetrate (the biointrusion layer in the cap). There is in addition to providing sufficient depth of cap and profile fill over the wastes that certain sorts of intrusion will not occur (controls I4, I5, W2).

These controls are characterised in Table 5.14.

Table 5.14: Characterisation of controls relating to likelihood of contact with waste

Controls and Safety Functions	I1: Control of access to site during operations I2: Control of access to site during institutional control I4: Control of depth of waste from surface I5: Control of physical barriers to wastes W2: Control of waste placement
Description	During the period of active institutional control following cessation of disposals and installation of the closure engineering, access will be controlled to ensure no intrusion by members of the public is possible. During this period, radioactive decay will occur which will offer some benefits in reducing the hazard posed by shorter-lived radionuclides. After the end of the PoA, members of the public would need to penetrate the cap and profile fill deliberately, and without knowledge of the radiological hazard, in order to be exposed to waste. (If the presence of radioactive material is known, it can be assumed that those involved would take suitable precautions.) Preservation of knowledge of the site and suitable deposition of records will be required before the PoA can end (cessation of regulatory control). It is very likely that knowledge of the facility will persist beyond the PoA, although the length of time for which this knowledge will persist is uncertain. Therefore, no credit is taken for this in the human intrusion assessment [38], and it is cautiously assumed that intrusion can take place immediately after the end of the PoA. The cap design includes a biointrusion layer which may impede or deter intrusion, although no credit is taken for this in the assessment calculations [38]. The depth of the profile fill underlying the cap varies across the repository, but its thickness means that shallow intrusions may not intrude into the waste over large parts of the repository. Together, the cap and profile fill is a minimum of 4 m thick, and typically 5 m. The cap and profile fill will together provide almost complete shielding. This will prevent external exposure when the cap is intact, and reduce external doses during and after an intrusion event. The thickness of the cap and profile fill will ensure that external dose would only arise from waste that was exposed during the intrusion event (e.g. spoil left on the surface following excavation of a trial pit or borehole). The capping and profiling materials would become mixed with waste during some intrusion events (e.g. sinking boreholes). The level of mixing

	would depend upon the location and nature of the intrusion event, but this mixing will dilute the activity in materials excavated or retrieved from the waste. We consider this effect in our assessment calculations [38]. Aside from the engineered cap, other engineered elements such as CPUs or the shielded modules may impede or deter intrusion. These structures do not displace any thickness of profile fill in the design and they therefore provide an additional thickness of clean material (around 60 to 70 cm in the case of the CPUs).
Significance	Figure 5.7 and Figure 5.8 show the evolution of activity and hazard of radionuclides in the repository from the time of final disposals. Between the time of final disposals and the end of the period of active institutional control (assumed to be 100 y), the total activity in the repository decreases by a factor of two due to radioactive decay. The external irradiation hazard from the vaults decreases by 96% due to the decay of short-lived radionuclides most significant for external dose (such as Co-60 and Cs-137). This affects the doses that could be received at the earliest time for human intrusion, events like geotechnical investigations or house development, for which external irradiation is the main pathway. The human intrusion assessment [38] considered a variant case where the period of institutional control is extended to 300 years. The maximum doses for the relevant events are further reduced by about a factor of two to five. For the borehole core analyst, doses are dominated by inhalation of thoron (Rn-220) and are not affected by the increased period of institutional control. The shape of the cap also provides a safety function for human intrusion. At the crest of the cap, where the flatter ground makes inadvertent intrusion more likely than on the flanks, the minimum thickness is 5 m [12]. Many human intrusion events considered would therefore not penetrate the wastes (e.g. domestic housing development would be unlikely to have foundations deeper than this). Emplacement strategies could potentially be used to place restrictions on consignments at the top of waste stacks, to further reduce the likelihood of penetrating waste with higher levels of hazard.

5.6.2 Controls on Exposure to Contaminants in Waste

In the event of inadvertent human intrusion which penetrates the waste, the resulting impacts are controlled by the contaminant concentrations in the exposed waste (W7, I8), immobilisation of those contaminants (W4) and shielding by clean material (I6).

These controls are characterised in Table 5.15.

Table 5.15: Characterisation of controls relating to exposure to contaminants in waste

Controls and Safety Functions	W4: Control of dispersible materials W7: Control of contaminant concentrations in waste I6: Control of radiation dose rates by shielding I8: Control of contaminant concentrations in disturbed waste
Description	The cap and profile fill together will provide significant shielding which reduces external doses from the waste before, during and after an intrusion event. External dose only arises from waste that was exposed during the intrusion event (e.g. spoil left on the surface following excavation of a trial pit or borehole). The capping and profiling materials would become mixed with waste during some intrusion events (e.g. sinking boreholes). The level of mixing would depend upon the location and nature of the intrusion event, but this mixing would provide some dilution of activity. This is taken into account in the human intrusion assessment [38]. Aside from the engineered cap, other engineered elements such as CPUs or the shielded modules will contribute to shielding and, if extracted with waste, will contribute to dilution of radioactivity. The grouted waste form will also provide some safety function in terms of diluting the extracted wastes and may also immobilise radionuclides, reducing the potential for the release of contaminants in a form that can be dispersed and/or inhaled and/or inadvertently ingested.
Significance	Doses from external irradiation are proportional to the activity concentration in the exposed waste. For the vaults, 45% of the container volume is filled with waste with the remainder filled with grout encapsulant [42, 42]. This therefore provides a factor of two dilution in the contaminant concentrations. The depth of the cap and profile fill over the waste varies but is always greater than 5 m. On average, the thickness of the cap and profile fill is similar to the depth of the waste in the vaults and about twice the depth of

the waste in the trenches. Therefore, if the cap and waste materials were extracted together, the cap and profile material would provide an additional factor of three dilution of contaminant concentrations for the trenches and factor of two dilution for the vaults.

Figure 5.6 demonstrates that the shielding provided by the cap and profile fill would attenuate external doses to negligible levels.

The human intrusion assessment considers a scavenging event where a person picks up a contaminated discrete item and may inadvertently ingest contaminated material from its surface while handling it. It is assumed that 1% of the surface contamination is removeable. This reflects the significance of the immobilisation of the radionuclides in grout [38], as well as the fact that much of the activity present on the item which could be removable by contact would already have been lost (e.g. by windborne attrition after the item is exposed) before it is handled.

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Appendix A: Mapping of Controls, Safety Functions, Components and Pathways

Table A.6.1: Controls and safety functions relating to the waste form

Control	Safety function	Component(s)	Pathway*	Defined in^
W1: Control of the waste characteristics	Limitation of the hazard	Site management (Waste Acceptance Criteria)	Groundwater Releases, Gaseous Releases, Liquid Discharges, External Irradiation, Coastal Erosion, Human Intrusion	Safety Assessment
W2: Control of the integrity of the waste	Provision of structural stability of wastes [#SSR-103]	Cut-off wall	Groundwater Releases, Gaseous Releases	RMS
	Provision of a foundation for the final cap [#SSR-63]	Waste containers, Grout, Void fill	Groundwater Releases, Gaseous Releases	RMS
	Protect containers from loading by cap [#SSR-7, #SSR-21, #SSR-144]	Grout, Profile fill	Groundwater Releases, Gaseous Releases	Safety Assessment, RMS
W3: Control of waste placement	Limitation of doses from exposed or disturbed wastes	Site management (emplacement strategy)	External Irradiation, Coastal Erosion, Human Intrusion	Safety Assessment
	Provision of time for radon to decay during migration		Gaseous Releases	Safety Assessment

Control	Safety function	Component(s)	Pathway*	Defined in^
W4: Control of radiation dose rates by shielding	Limitation of external dose	Waste container	External Irradiation	Safety Assessment
W5: Control of dispersible materials	Immobilisation of wastes [#SSR-1]	Grout	Coastal Erosion, Human Intrusion	Safety Assessment
W6: Control of water in the waste	Reduction of the generation of contaminated leachate [#SSR-9, #SSR-10]	Waste container, Grout	Groundwater Releases, Liquid Discharges	RMS
	Consumption of free water through corrosion	Waste container	Groundwater Releases, Gaseous Releases, Liquid Discharges	Safety Assessment
	Reduction of contaminant migration and release rate [#SSR64]	Grout	Groundwater Releases	RMS, Safety Assessment
W7: Control of the chemical environment	Reduction of corrosion rate of some metals	Grout	Groundwater Releases, Gaseous Releases	[26]
	Reduction of mobility in groundwater of some elements by sorption [#SSR 22, #SSR64]	Grout	Groundwater Releases	RMS, [26]

Control	Safety function	Component(s)	Pathway*	Defined in^
	Reduction of biodegradation rate	Grout	Groundwater Releases. Gaseous Releases	[26]
	Reduction of rate of release of C-14	Grout	Groundwater Releases, Gaseous Releases	[26]
W8: Control of contaminants concentrations in waste	Additional dilution of contaminants	Grout	External Irradiation, Coastal Erosion, Human Intrusion	Safety Assessment

Note:

SSR-xxx is the Unique Reference Number of the safety function in the RMS.

*This is the pathway that the safety function primarily acts on. In some cases the safety function can have a secondary effect on other pathways (e.g. reducing contaminants mobility primarily relates to the groundwater pathway, but reduced mobility would also yield a greater residual inventory subject to coastal erosion or human intrusion).

^The part of the ESC that the safety function is defined in. Safety functions all, by definition, ultimately contribute to the ESS.

Table A.6.2: Controls and safety functions that provide isolation

Control	Safety function	Component(s)	Pathway*	Defined in^
I1: Control of access to site during operations	Prevention of uncontrolled exposure to wastes during PoA	Site management (access restrictions)	External Irradiation, Gaseous Releases	Safety Assessment
I2: Control of access to site during institutional control	Prevention of damage to the cap or other engineered barriers during PoA	Site management (control of closed site)	Groundwater Releases, Gaseous Releases	[26]
	Prevention of intrusion to wastes during PoA		Human Intrusion	[26]
I3: Control of use of surrounding land during institutional control	Prevention of activities that could lead to exposure (e.g. wells)	Site management (ownership of land), Knowledge and records	Groundwater Releases	Safety Assessment
I4: Control of depth of waste from surface	Reduction of likelihood that an intrusion will encounter waste	Final engineered cap	Human Intrusion	[26]
	Protection of cap from damage by roots and burrowing animals [#SSR-158, #SSR-159]		Groundwater Releases, Gaseous Releases	RMS

Control	Safety function	Component(s)	Pathway*	Defined in^
	Attenuation of radon gas that may be released to the surface		Gaseous Releases	Safety Assessment
I5: Control of physical barriers to wastes	Protection of waste should intrusion occur [#SSR-160]	CPUs, Shielded Modules	Human Intrusion	Safety Assessment
I6: Control of radiation dose rates by shielding	Provision of shielding [#SSR-97, #SSR-154]	Trench interim cap, CPUs, Shielded Modules, Final engineered cap	External irradiation, potentially Coastal Erosion	RMS, Safety Assessment
I7: Control on the timing of erosion	Delay of the onset of coastal erosion	Hinterland	Coastal Erosion	Safety Assessment
I8: Control of contaminants concentrations in disturbed waste	Additional dilution of contaminants	Final engineered cap, CPUs, Shielded Modules	Coastal Erosion, Human Intrusion	Safey Assessment

Note:

SSR-xxx is the Unique Reference Number of the safety function in the RMS.

*This is the pathway that the safety function primarily acts on. In some cases the safety function can have a secondary effect on other pathways (e.g. reducing contaminant mobility primarily relates to the groundwater pathway, but reduced mobility would also yield a greater residual inventory subject to coastal erosion or human intrusion).

^The part of the ESC that the safety function is defined in. Safety functions all, by definition, ultimately contribute to the ESS.

Table A.6.3: Controls and safety functions that provide containment

Control	Safety function	Component	Pathway*	Defined in^
C1: Control of water entering the repository during operations	Reduction of the generation of contaminated leachate [#SSR-59, #SSR-89, #SSR-97, #SSR-145, #SSR-155]	Waste containers, Grout, CPUs, Shielded modules, Interim storage warehouses, Trench interim cap, Vault leading edge seal, Final engineered cap, Trench drains, Vault drains	Groundwater Releases, Gaseous Releases, Liquid Discharges	RMS
	Direct surface water away from interim cap and vault leading edge seal [#SSR 121, #SSR-122]	Cap surface drains	Liquid Discharges	RMS
C2: Control of water entering the repository after operations	Reduction of water flow into the wastes [#SSR-119. #SSR-161]	Waste containers, Grout, CPUs, Shielded modules, Final engineered cap, Trench drains, Vault drains	Groundwater Releases, Gaseous Releases	RMS
	Reduction in leaching of grout		Groundwater Releases, Gaseous Releases	Safey Assessment

Control	Safety function	Component	Pathway*	Defined in^
	Reduces recharge around and below site [#SSR-120]		Groundwater Releases	RMS
	Reduction in gas generation rate [#SSR-91]		Gaseous Releases	Safey Assessment
	Provide gas headspace to mitigate pressurisation		Gaseous Releases	Safey Assessment
C3: Control of integrity of waste form	Protection of wastes from loading by cap [#SSR-28, #SSR-30. #SSR-90]	Vault leading edge seal, CPUs, Shielded Modules, Void fill	Groundwater, Gaseous Releases	RMS
	Provision of structural stability of wastes [#SSR-36, #SSR-103]	Vault base	Groundwater Releases, Gaseous Releases	RMS
C4: Control of contaminant migration in	Provision of flow paths around waste containers [#SSR-29]	Void fill	Groundwater Releases	Safey Assessment

Control	Safety function	Component	Pathway*	Defined in^
water through vaults after institutional control	Reduction of mobility in groundwater of some elements by sorption	CPUs, Shielded Modules, Vault base and walls	Groundwater Releases	Safey Assessment
C5: Control of lateral migration of leachate	Prevent release of contaminants to surrounding surface environment [#SSR-50. #SSR-110]	Vault base and walls, Cut-off wall, under-vault drainage blanket	Groundwater Releases, Leachate Discharges	[26]
	Reduces groundwater flow through waste (after institutional control) [#SSR-49, #SSR-109]		Groundwater Releases	[26]
	Direct leachate to deeper groundwater (after institutional control) [#SSR-39, #SSR-55]		Groundwater Releases	RMS, Safey Assessment

Note:

SSR-xxx is the Unique Reference Number of the safety function in the RMS.

*This is the pathway that the safety function primarily acts on. In some cases the safety function can have a secondary effect on other pathways (e.g. reducing contaminant mobility primarily relates to the groundwater pathway, but reduced mobility would also yield a greater residual inventory subject to coastal erosion or human intrusion).

^The part of the ESC that the safety function is defined in. Safety functions all, by definition, ultimately contribute to the ESS.

Table A.6.4: Controls and safety functions relating to the management of residual releases

Control	Safety function	Component	Pathway*	Defined in^
M1: Control of leachate generated during operations	Limit release of leachate to groundwater during operations [#SSR-37, #SSR-134]	Vault base and walls, Leachate collection and discharge system	Liquid Discharges	[26]
M2: Control of gas release after operations	Enable gas dispersal and mitigate pressurisation [#SSR-30, #SSR-157]	Void fill, Final engineered cap	Gaseous Releases	RMS
	Release gas so as to protect the cap and to minimise dose [#SSR-156]		Gaseous Releases	RMS
	Limit the release of radioactive gas		Gaseous Releases	[26]
M3: Control of contaminant migration through geosphere	Reduction of mobility in groundwater of some elements by sorption	B2 hydrogeological unit, B3 hydrogeological unit	Groundwater Releases	[26]
M4: Control of contaminants	Reduces contaminants concentration by, dilution and dispersion	B3 hydrogeological unit	Groundwater Releases	[26]

concentrations in groundwater				
M5: Control of contaminants concentrations in environment	Reduces contaminants concentration by dilution and dispersion	Stream, Marine environment	Groundwater Releases, Gaseous Releases, Liquid Discharges, Coastal Erosion	Safey Assessment
	Reduces contaminants concentration by dilution and dispersion			Safey Assessment

Note:

SSR-xxx is the Unique Reference Number of the safety function in the RMS.

*This is the pathway that the safety function primarily acts on. In some cases the safety function can have a secondary effect on other pathways (e.g. reducing contaminant mobility primarily relates to the groundwater pathway, but reduced mobility would also yield a greater residual inventory subject to coastal erosion or human intrusion).

^The part of the ESC that the safety function is defined in. Safety functions all, by definition, ultimately contribute to the ESS.

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