Nuclear Waste Services

MAIN REPORT

2026 Environmental Safety Case for the LLWR

LLWR/ESC/R(26)10166, May 2026

Conditions of Publication

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 report is the main report 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.

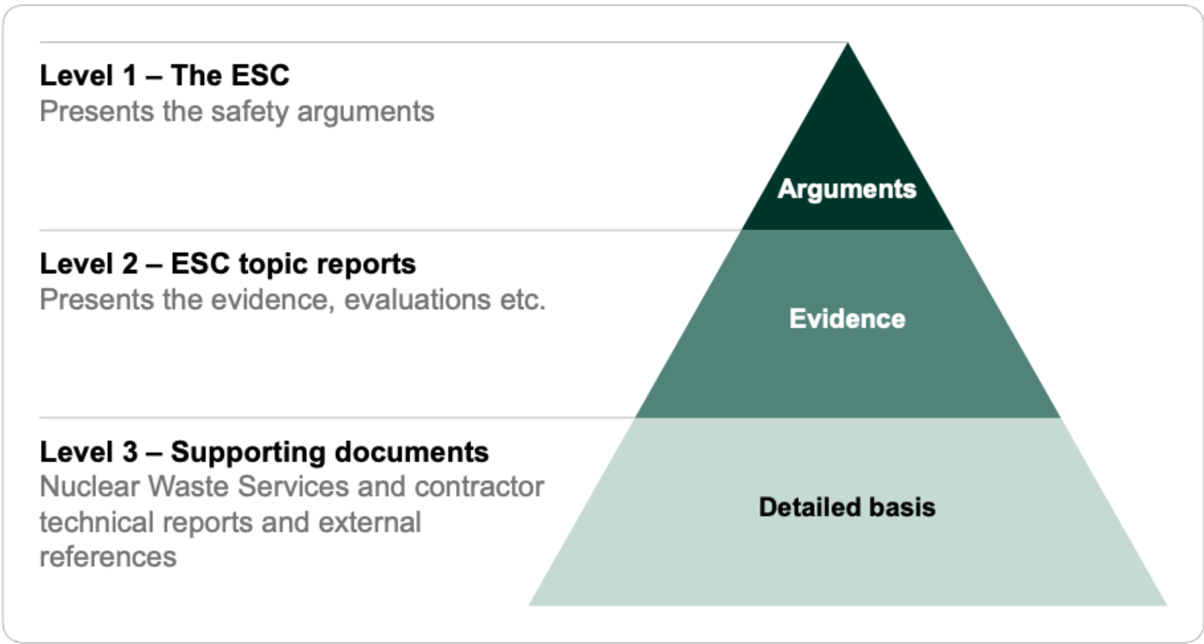
The 2026 ESC consists of documents at two levels:

- 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.

This is the Level 1 report. 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

[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.

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 (this report)	
Level 2	
Management and dialogue	
Management and Dialogue [1]	Describes our environmental management systems and interactions with regulators and stakeholders
System characterisation and understanding	
Site History and Description [2]	Provides a history and description of the site
Disposal Facility Inventory [3]	Describes the wastes already disposed and wastes that may be disposed at the facility

Engineering Design [4]	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 [5]	Describes our understanding of the chemical and physical evolution of the engineered disposal system
Hydrogeology [6]	Describes our understanding of the geology and hydrogeology of the site
Site Evolution [7]	Describes our understanding of how the site will evolve, with a focus on coastal erosion
Monitoring [8]	Presents our programme of environmental monitoring supporting the ESC
Optimisation and Site Development Plan	
Optimisation and Site Development Plan [9]	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 [10]	Presents our plans for managing the wastes produced by previous uses and operation of the site
Assessments	
Safety Functions [11]	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 Low Level Waste Repository (LLWR) has been the United Kingdom's principal facility for the disposal of solid Low Level Waste (LLW) since it opened in 1959. The facility is managed by Nuclear Waste Services Limited, a wholly-owned subsidiary division of the Nuclear Decommissioning Authority (NDA). We are regulated by the Environment Agency under the Environmental Permitting (England and Wales) Regulations 2016.

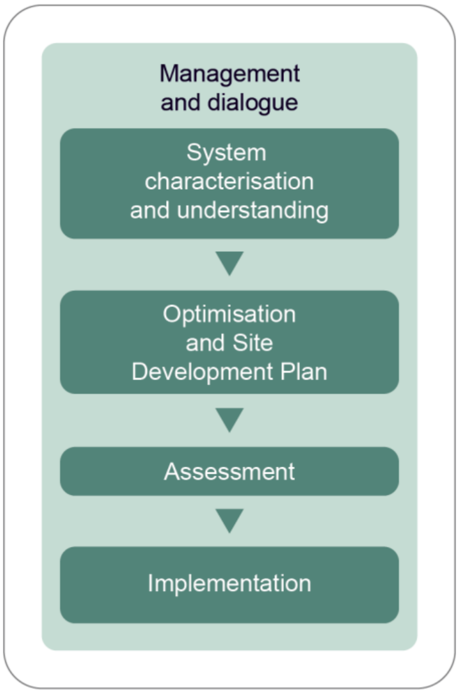
We are committed to operating the LLWR as a safe and efficient facility that provides a continuing option for the disposal of LLW in the United Kingdom. One of the means we use to operate the LLWR safely is to maintain and implement an Environmental Safety Case for the site. This report and supporting volumes comprise our 2026 Environmental Safety Case – the 2026 ESC.

The 2026 ESC will be submitted to the Environment Agency in fulfilment of two specific requirements (IC7 and IC8) of our current Permit, to submit an update to the ESC, based on a comprehensive review covering the full lifecycle of the facility, and prepare a waste management plan and site-wide environmental safety case. The ESC may be used to support applications to the Environment Agency for a revised Permit to dispose of radioactive waste, and to our Local Planning Authority for associated planning permissions, necessary to continue to develop and close the site.

The ESC has been developed according to our Environmental Safety Strategy, which lays out our approach to achieving the continuing environmental safety of the LLWR.

At a high level, our case is that:

- we work within a sound management framework and firm safety culture, while engaging in dialogue with stakeholders;
- we characterise and establish a sufficient understanding of the LLWR site and facility, and their evolution, relevant to its environmental safety;
- on which basis, we carry out comprehensive evaluation of options to arrive at an optimised Site Development Plan for the LLWR;
- we assess the environmental safety of the Site Development Plan, to show that impacts are consistent with regulatory guidance;
- we implement our Site Development Plan and ESC to ensure safe and optimal use of the LLWR.



Consistent with the Environment Agency's guidance, the ESC is presented in terms of a set of arguments in support of each of the above claims. For each argument, we identify the regulatory requirement or guidance that the argument addresses and, also, the supporting ESC report ('Level 2' report) in which the evidence in support of that argument is presented. We confirm all relevant regulatory requirements have been met. A more detailed analysis of the requirements and supporting guidance and where they are addressed in our documentation is given in our '*Addressing Regulatory Requirements and Guidance*' report.

The 2026 ESC presents the approach by which we have developed an optimised Site Development Plan for the LLWR to help meet our objective, and our demonstration of the environmental safety of the Plan. Under the Site Development Plan, the LLWR will continue to operate as the primary destination for disposal of LLW in the United Kingdom until approximately 2135.

We have identified, considered and treated uncertainty within the ESC sufficiently to meet its objectives. We have described our intended future work programme to further reduce key uncertainties.

The 2026 ESC takes into account the issues and recommendations identified by the Environment Agency during its review of the 2011 ESC. The ESC describes how this has been done. Improvements to the ESC since 2011 include the following:

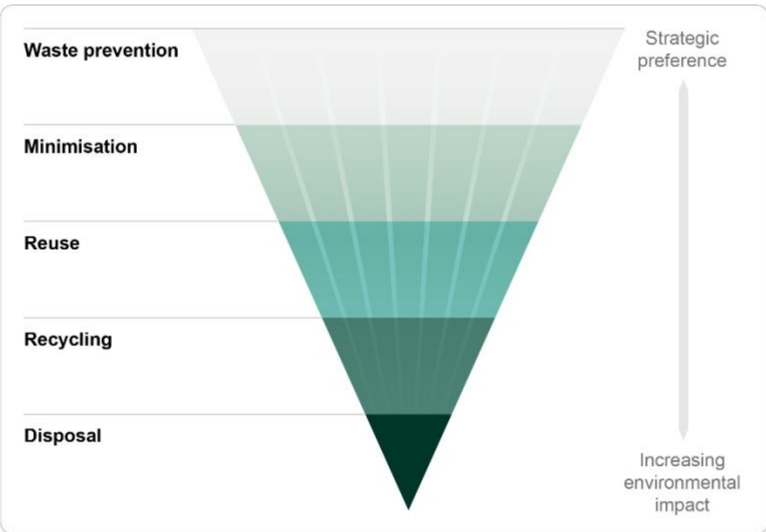
- Development of processes to implement the ESC.
- Application of better understanding of:
    - both the already disposed waste inventory and wastes that may be disposed of at the LLWR;
    - performance of the waste container stacks under load;
    - performance of the final cap;
    - timescales and nature of coastal evolution;
    - geology and hydrogeology.
- Development and application of a new model of the repository near field using the PFLOTRAN tool.
- Development of a Site-wide Environmental Safety Case and Waste Management Plan.

The development and documentation of the ESC have been subject to independent peer review by a group of experts with relevant experience from both the United Kingdom and abroad.

The 2026 ESC demonstrates the safety of the LLWR now and during the rest of its lifetime. This includes the period of continuing disposal operations, at time the final closure engineering is installed, during the period of active institutional control, and after, including during and after coastal erosion of the facility.

Once the 2026 ESC is submitted to the Environment Agency, we will begin its implementation, in dialogue with the Environment Agency. We anticipate that revisions to our Waste Acceptance Criteria, waste emplacement strategies and capacity management developed in the ESC will be introduced.

The ESC will continue to be maintained under a formal change control process, taking account of new information as it arises, for example, from our technical development programme to reduce uncertainties, and our environmental monitoring programme. Maintenance of the ESC will ensure that a suitable tool continues to be available to support future regulatory and management decisions concerning the facility, and that the Site Development Plan continues to provide optimised environmental performance.



One of our principal objectives, in accordance with government policy and NDA strategy, is to promote and ensure the best use of the LLWR. This means developing plans for the safe and optimised use of the LLWR for disposal of radioactive waste and implementing those plans, subject to necessary regulatory permissions and planning approvals. The development of the ESC has been framed by this objective. It requires optimising the environmental performance of the disposal facility and site both during operations and in the long term. This objective is partly achieved by our supporting the implementation of the waste hierarchy in the management of radioactive waste in the United Kingdom, which reduces the volume of waste that needs to be disposed of. Proposals may be made to seek the necessary permissions to further optimise the use of the facility to dispose of a wider range of radioactive wastes than LLW, based on the safety analyses reported in the 2026 ESC. No decision has been made yet to seek these permissions and the decision would only be made by the NDA after appropriate consultation with stakeholders.

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1 Introduction

1.1 Background and Objectives of the ESC

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 of in trenches and is now being disposed of 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 (UK). This will be achieved consistent with good practice for the near-surface disposal of radioactive waste, in accordance with environmental and health and safety 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 and NDA strategy. This may involve the disposal of a broader range of wastes than just LLW.

One of the means we use to operate the LLWR safely is to maintain and implement an Environmental Safety Case for the site. This report is the main report presenting the 2026 Environmental Safety Case for the LLWR – the 2026 ESC.

Disposal of radioactive waste and radioactive discharges from the site are regulated by the Environment Agency under the Environmental Permitting (England and Wales) Regulations 2016.

Our current Permit [19], which is a variation on an Authorisation issued under previous legislation on 1st May 2006, is based on the Environment Agency's review and consideration of our 2011 Environmental Safety Case – the 2011 ESC [20]. The Permit states a requirement (IC7), with a completion date of the 1st May 2026, that Nuclear Waste Services:

> '*Submit an update to the environmental safety case for the site based upon a comprehensive review, covering the full life-cycle of the facility. The review shall demonstrate that all the requirements of the latest version of the environment agencies' guidance on requirements for authorisation for near-surface disposal facilities on land for solid radioactive waste have been met. The review shall address the findings of the Environment Agency's review of the 2011 ESC.*'

The Permit also states a new requirement (IC8), also with a completion date of the 1st May 2026, that Nuclear Waste Services:

'Prepare a suitable waste management plan and a site-wide environmental safety case to meet the requirements of condition 1.1.4 of this permit, and have these available for inspection by the Environment Agency.'

We also consider it good practice to undertake periodic reviews of our safety cases and it is a requirement of our management system.

We have prepared a combined case addressing both these requirements, referred to as the 2026 ESC. The 2026 ESC sets out the arguments and evidence that it is safe for the LLWR to be operated and closed as a LLW disposal facility. It provides a sound basis for our management of the site and regulation of the site by the Environment Agency.

Outcomes of the Environment Agency's review of the 2011 ESC [21] included twenty-nine Forward Issues [22] and a much larger number of Recommendations [23, 24, 25, 26, 27]. The 2026 ESC addresses the Forward Issues. The Recommendations have been taken into account in the development of the 2026 ESC.

The 2026 ESC will support any future application for a revised Permit to dispose of radioactive waste at the site. It will also support applications for any necessary planning permissions to continue to develop and close the site.

In May 2024, the UK government and devolved administrations published a new policy framework for managing radioactive substances and nuclear decommissioning [28]. Under the new policy, those responsible for creating and managing radioactive waste should take a 'risk-informed' approach to decision-making, throughout the full waste management lifecycle, including disposal. The best practicable use of resources should be made, by disposing of radioactive waste to facilities designed to provide the isolation and containment appropriate to the risk posed by that waste. The implication that some less-hazardous Intermediate Level Waste (ILW)[2] might be disposed of in near-surface disposal facilities is explained in the policy framework document. It is stated in the policy that the UK government and devolved administrations wish to ensure that the best use of disposal capacity is made across the UK and expect the NDA to ensure the optimal use of the LLWR. It is also stated that the NDA should explore with relevant stakeholders, including regulators, local authorities and the local community the potential for optimising the existing near-surface facility, the LLWR, to take less-hazardous ILW.[3]

We interpret risk-informed decision making on the disposal of radioactive waste to mean deriving the safety controls[4] on the disposal of wastes to a facility from the relevant safety cases, which have been developed using risk-based methodologies. The safety controls would include Waste Acceptance Criteria (WAC), waste package emplacement strategies,

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[2] We use the term 'less-hazardous ILW' to describe ILW that can be safely disposed of at the LLWR, in line with regulatory protection criteria – specifically risk and dose guidance levels.

[3] Not all ILW is suitable for near-surface disposal, and a Geological Disposal Facility would still be required.

[4] In this context, we use the term 'safety controls' to mean the various administrative and other measures we use to ensure the safe disposal of wastes.

and setting total maximum capacities for radionuclides and other materials. The relevant regulatory limits and guidance on acceptable levels of impact would be applied in the analysis in the safety cases to derive controls that optimised the capacity of the repository to accept waste. The safety cases would also be used in design studies, to optimise the capacity of the repository to accept waste. The safety controls would not be the only factors taken into account in making risk-informed decisions about whether to dispose of wastes at the LLWR but meeting them would be a prerequisite for disposal.

During the development of the 2026 ESC, we have assessed the ability of the facility to accept ILW for disposal. Any necessary engineering changes have been considered in design optimisation studies. We have also considered the safety controls that would be required.

ILW disposal at the LLWR would require revisions to the facility's Nuclear Safety Case and consequent changes to the procedures and processes used to manage the LLWR. Revised planning permission may also be required. These aspects are not addressed by the ESC.

The objective of this work has been to understand the types and quantities of ILW that could be safely disposed at the LLWR and the changes that would be required, and hence inform NDA's and others' consideration of the option, in line with government policy.

1.2 Scope and Documentation of the ESC

The regulatory guidance for the disposal of radioactive waste in a near-surface facility is set out in the environment agencies' '*Near-surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation*' (the GRA) [29]. The scope and content of the ESC should, therefore, be consistent with the GRA, and satisfy the qualitative and quantitative requirements therein.

This report describes how we have satisfied all the relevant requirements of the GRA. It specifically addresses GRA Requirement 3, which requires that an environmental safety case should be submitted in support of an application to dispose of solid radioactive waste (see the box below). Paragraph 6.2.2 provides the environment agencies' definition of an environmental safety case in terms of a set of claims substantiated by a collection of arguments and evidence, which we adopt as the basis for the presentation of the ESC in this report.

Box 1.1: GRA Requirement R3: Environmental safety case

GRA Requirement R3: Environmental safety case (from reference [29][5])

6.2.1 An application under RSA 93 relating to a proposed disposal of solid radioactive waste should be supported by an environmental safety case.

6.2.2 An environmental safety case is a set of claims concerning the environmental safety of disposals of solid radioactive waste, substantiated by a structured collection of arguments and evidence. It should demonstrate that the health of members of the public and the integrity of the environment are adequately protected. It will be provided by the developer/operator of the disposal facility and should be designed to demonstrate consistency with the principles set out in Chapter 4 of this guidance and that the management, radiological and technical requirements set out in this chapter (Chapter 6) are met. …

6.2.3 We shall expect the developer/operator of a near-surface disposal facility to show in the environmental safety case that the facility meets each requirement set out in this chapter. … we shall expect the developer/operator to adopt an approach to each requirement that is proportionate to the level of hazard the eventual inventory of waste in the facility will present. In this paragraph, 'hazard' includes both the radiological hazard the waste presents and any non-radiological hazard it may also present.

We are also required to prepare a suitable waste management plan (WMP) and a site-wide environmental safety case (SWESC) and have done this as part of the development of the 2026 ESC. The relevant guidance is set out in the environment agencies' '*Management of Radioactive Waste from Decommissioning of Nuclear Sites: Guidance on Requirements for Release from Radioactive Substances Regulation*' (the GRR) [30]. The scope and content of the ESC must, therefore, be consistent with the GRR, and satisfy the qualitative and quantitative requirements therein.

This report describes how we have satisfied the requirements of the GRR. As set out below, we specifically address GRR Requirement 7, which requires that a site-wide environmental safety case is maintained. Paragraph A4.4 provides the agencies' definition of a site-wide environmental safety case also in terms of a set of claims substantiated by a collection of arguments and evidence.

[5] We have been advised that the Environment Agency is planning to issue a revised version of the GRA. The 2026 ESC has been prepared against the 2009 version.

Box 1.2: Requirement R7: Site-wide environmental safety case

GRR Requirement R7: Site-wide environmental safety case (from reference [30])

A4.2 Operators should maintain a site-wide environmental safety case (SWESC) to demonstrate that people and the environment will be adequately protected from ionising radiation and any associated non-radiological hazards, both before and after their site is released from radioactive substances regulation.

A4.3 The SWESC is a set of claims concerning the environmental safety of the nuclear site, substantiated by a structured collection of arguments and evidence (see glossary). It should address the present condition and all envisaged future conditions of the site, both during the lifetime of the permit and during the indefinite period after the permit has been surrendered. The SWESC should consider all radioactive substances remaining on and adjacent to the site including any ground or groundwater affected by contamination. It should demonstrate that people and the environment will be protected from the radiological hazard and any non-radiological hazards associated with both radioactive waste and contamination. The SWESC should consider evolution of the site without operator control in the period after the permit has been surrendered. …

A4.4 Operators should maintain, and provide to the relevant environment agency when required, a SWESC that demonstrates conformity with the principles and requirements set out in this guidance. The SWESC should be technically sound, comprehensive and robust, but also proportionate to the magnitude of the radiological and any associated non-radiological hazards.

Our WMP is reported in one of the Level 2 reports comprising the ESC [10].

The 2026 ESC is a SWESC as defined in the GRR, with a subset of it being an ESC as defined by the GRA and meeting the requirements set out in the GRA (see Figure A1 in reference [30]). We have chosen to retain the name 'ESC' for the 2026 ESC because the great majority of the content of the safety case is aimed at meeting the requirements of the GRA. This is because of the nature of the site and facility, which is a disposal facility with some temporary waste storage. The wastes in the disposal facility form the main environmental hazard. Retaining the name 'ESC' is also helpful because the organisation is familiar with the term and the importance of the safety case.

One of our principal objectives, in accordance with government policy and NDA strategy (see Subsection 2.1), is to promote and ensure the best use of the LLWR. This means developing plans for the safe and optimised use of the LLWR for disposal of radioactive waste and implementing those plans, subject to necessary regulatory permissions and planning approvals. The ESC is presented within the framing and context of this objective.

The ESC sets out our Site Development Plan.[6] The Site Development Plan sets out our proposals and assumptions on operations, remedial activities, vault design, capacity and future waste disposal practice, disposal facility closure design, site decommissioning and restoration, and management up to the end of regulatory control. The Site Development Plan has been developed using our Environmental Safety Strategy, which lays out our approach to achieving the continuing environmental safety of the LLWR disposal facility and site. The Environmental Safety Strategy is the process and means by which we achieve our strategic plans in a demonstrably environmentally safe way. Our Environmental Safety Strategy leads to an optimised Site Development Plan. The Site Development Plan forms the basis of our assessments of repository performance, an important part of our demonstration of environmental safety. The Site Development Plan will be amended as necessary in the light of UK radioactive waste management needs, operating experience, results of monitoring, future iterations of the ESC, regulatory and planning guidance and decisions, and stakeholder views.

The ESC is structured around the presentation of our safety arguments and the evidence that supports them. We show how the arguments and evidence correspond to regulatory requirements and hence demonstrate that the requirements are satisfied.

The overall document plan for the ESC has been set out in the Preface. This '*Main Report*', the 'Level 1' report, of the ESC, sets out our arguments that it is environmentally safe for the LLWR to continue to operate as a facility for the disposal of radioactive waste, meeting the requirements of the GRA and GRR.

This report is a high-level articulation of our safety arguments. The report refers down to the 'Level 2' reports, which give more complete presentations of our arguments and also present the supporting evidence that underpins our arguments. A listing of the Level 2 reports is given in the table in the Preface. The categorisation of the Level 2 reports is explained in Subsection 4.1. In Table 1.1: below, we indicate which reports address the requirements of both the GRA and GRR or one of these sets of requirements.

References to supporting work in this Level 1 report are mainly to the Level 2 reports, where full referencing to Level 3 documents can be found.

[6] We are developing a Strategic Site Strategy, in collaboration with the NDA. The Strategic Site Strategy will help to ensure that the site meets the government's policy objectives and the NDA's strategic objectives. The optioneering undertaken as part of developing the 2026 ESC is playing an important role in the development of the optimised Strategic Site Strategy. The ESC will be used to demonstrate the safety of the Strategic Site Strategy and hence will need review once the Strategy is developed.

Table 1.1: Reports addressing GRA and GRR requirements

Main Report (this report)	Addresses the whole site but with a focus on the disposal facility and meeting the GRA requirements.
Management and Dialogue [1] Site History and Description [2]	Cover the whole site, meeting the requirements of both the GRA and GRR.
Disposal Facility Inventory [3] Engineering Design [4] Near Field [5] Safety Functions [11] Engineering Performance Assessment [12] Assessment of Long-term Radiological Impacts [14] Implementation [17]	Address GRA requirements for the disposal facility.
Hydrogeology [6] Site Evolution [7] Monitoring [8]	Focus on meeting the requirements of the GRA but cover the whole site and hence provide understanding underpinning the meeting of the GRR requirements.
Optimisation and Site Development Plan [9]	Addresses the whole site and meeting the requirements of both the GRA and GRR.
Waste Management Plan [10]	Addresses the requirement in the GRR for a WMP.
Environmental Safety During the Period of Authorisation [13] Hydrogeological Risk Assessment [15] Assessment of Radiological Impacts on Non-human Biota [16]	Focus on the disposal facility but use monitoring data for the whole site. The first and third reports assess the impact of some of the contamination on the wider site.
Addressing Regulatory Requirements and Feedback [18]	Addresses requirements and related feedback for both the GRA and GRR.

1.3 Structure

In this report:

- Section 1, this section, has set out the high-level background to the submission of our 2026 ESC, our overall objectives and the objective and scope of this report.
- Section 2 summarises the context for this ESC and provides a high-level introduction to the site. The national strategic context is described first. Further details are then provided on the objectives, scope, nature and history of the ESC. The history and current conditions, and the environmental context, of the LLWR are then described. The future evolution of the site environment is also addressed.
- Section 3 describes our Environmental Safety Strategy, by which we develop an optimised Site Development Plan that forms the basis for our assessments and demonstration of environmental safety.
- Section 4 describes our safety case arguments under five headings. These are: management and dialogue; system characterisation and understanding; optimisation and Site Development Plan; assessment; and implementation.
- Section 5 outlines progress that has been made in developing the ESC since the previous environmental safety case for the LLWR was presented.
- Section 6 presents, at a high level, a future programme of work to further reduce uncertainties related to the environmental safety of the LLWR disposal facility and site.
- Section 7 confirms that each of the relevant requirements of the GRA and GRR is addressed by one or more of the safety case arguments presented in Section 4 and thus provides a map by which our approach to complying with each of the requirements may be examined.
- Section 8 provides a set of concluding statements that we consider encapsulates the key features of our 2026 ESC.

A list of abbreviations used in this report and a general glossary for the ESC are provided in Appendices A and B respectively.

2 The Low Level Waste Repository

This section summarises the context of the 2026 ESC. This includes the:

- national policy and strategic waste management context;
- role of the ESC;
- 2011 ESC;
- history and current conditions of the site;
- environmental context of the site.

The future evolution of the site is also briefly described.

2.1 National Context and Role of the LLWR

The LLWR has been the only national facility for the disposal of LLW since it opened in 1959. Other LLW facilities exist but they are limited to accepting lower-activity LLW or LLW from specific sites. Hence, the LLWR is an important national asset. The LLWR is owned by the NDA, which is a non-departmental public body created under the Energy Act 2004. The NDA is a strategic authority that owns the 19 civil nuclear sites, and associated nuclear liabilities and assets, previously under the control of United Kingdom Atomic Energy Authority and British Nuclear Fuels. The NDA's future plans account for the need to fund disposal of radioactive waste at the LLWR from its programme.

It was noted in the Introduction (Section 1) to this report that, in May 2024, the UK government and devolved administrations published a new policy framework for managing radioactive substances and nuclear decommissioning [28]. Several aspects of the new policy framework are important for the national context and role of the LLWR, including:

- the need for radioactive waste to be managed safely and compliantly throughout its lifecycle, including during disposal;
- the need for early planning and preparation for the management of radioactive waste, to ensure optimised and integrated approaches. Management should then be an ongoing, iterative process throughout the waste lifecycle;
- the new policy framework replaces the 2007 '*Policy for the Long Term Management of Solid Low Level Radioactive Waste in the United Kingdom*' [31]. The 2007 policy introduced the application of the waste hierarchy (see Figure 2.1) into LLW management in the UK. The new 2024 policy framework requires the application of the waste hierarchy generally to the management of radioactive waste;
- the NDA should make its treatment, storage and disposal facilities, including the LLWR, available to other waste producers (on commercially agreed terms);

- under the new policy, those responsible for creating and managing radioactive waste should take a risk-informed approach to decision-making, throughout the full waste management lifecycle, including disposal;
- the best practicable use of resources should be made, by disposing of radioactive waste to facilities designed to provide the isolation and containment appropriate to the risk posed by that waste;
- the UK government and devolved administrations wish to ensure that the best use of disposal capacity is made across the UK and expect the NDA to ensure the optimal use of the LLWR. The NDA should explore with relevant stakeholders, including regulators, local authorities and the local community the potential for optimising the existing near-surface facility, the LLWR, to take less-hazardous ILW.

We have developed optimised plans for the disposal of wastes stored or generated at the LLWR, in accordance with the new policy. These plans are described in our '*Waste Management Plan*' [10]. These plans will continue to evolve over the operational life of the facility.

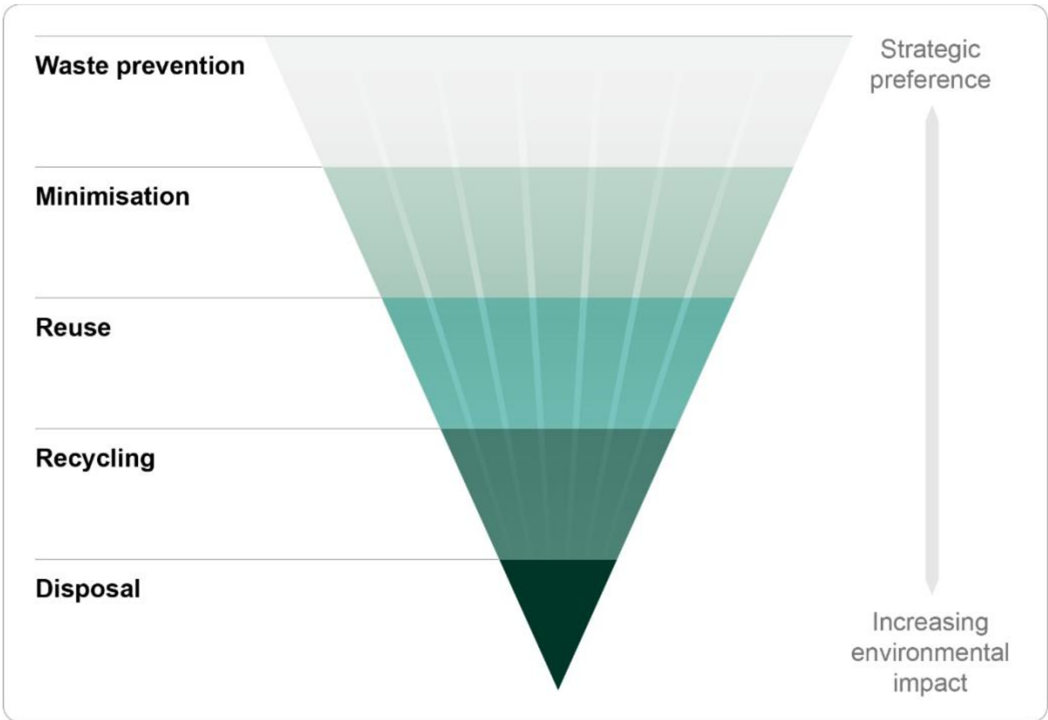

Figure 2.1: Waste hierarchy

Prior to the publication of the 2007 policy for the management of LLW, estimates of future LLW arisings indicated that the LLWR would be filled within a few decades. One specific objective of the 2007 policy was to reduce the use of the vaults at LLWR for the disposal of LLW that does not require the levels of environmental protection provided by the facility, thus avoiding the need to provide a new facility. This was achieved through the introduction by the nuclear industry of the waste hierarchy into the management of LLW (see Figure 2.1). The LLWR provided services to facilitate the diversion of LLW to metal treatment, incineration and disposal of Very Low Level Waste (VLLW) into landfill facilities, greatly reducing the volume of waste now requiring disposal at the LLWR.

Our interpretation of risk-informed decision-making in the context of the LLWR has been set out in the Introduction to this report (Section 1). We have assessed the ability of the facility to accept ILW for disposal. Any necessary engineering changes have been considered in design optimisation studies. Some consideration has been given to the operational safety controls that would be required. The objective of this work has been to understand the types and quantities of ILW that could be safely disposed at the LLWR and the changes that would be required and hence inform NDA's and others' consideration of the option, in line with the new government policy.

The strategic role of the LLWR is to provide for disposal of radioactive waste, requiring vault disposal and treated to minimise its volume, in a safe and optimal way while supporting the implementation of the waste hierarchy in the UK.

2.2 Role and Regulatory Context of the Environmental Safety Case

This subsection sets out in more detail the objectives, scope and nature of the ESC.

The main objective of the ESC is to provide a clear demonstration of the environmental safety of the management of radioactive wastes at the LLWR, where the wastes include those generated and stored at the site and past and planned future disposals of waste. It is designed to satisfy the requirements of the Environment Agency as set out in its guidance (the GRA [29] and GRR [30]) and as elaborated through liaison with Environment Agency staff (see Section 2 in the '*Management and Dialogue*' report [1]).

For the disposal of wastes, the GRA sets the fundamental protection objective:

> *'to ensure that all disposals of solid radioactive waste to facilities on land are made in a way that safeguards the interests of people and the environment now and in the future, commands public confidence and is cost-effective.'*

The GRR sets the fundamental protection objective:

> *'Our fundamental protection objective is to ensure that a nuclear site is brought to a condition at which it can be released from RSR, through a process which protects the health and interests of people and the integrity of the environment, both during the period of regulation and afterwards, and which inspires public confidence and takes account of costs.'*

The guidance and requirements relate to the protection of members of the public and the environment. Radiological protection of members of the public and of non-human biota, and protection of members of the public and the environment from non-radiological hazards presented by the wastes, are required. There is particular emphasis on the optimisation of radiological protection, which is discussed in Subsection 3.2.

The ESC is not concerned with demonstrating protection of workers or with conventional safety, or security, which are regulated by the Office for Nuclear Regulation (ONR). These aspects are, however, an input to decisions on site management options.

The ESC is also not concerned with conventional environmental impacts, for example, traffic, noise, and visual amenity. These are dealt with in submissions under local planning procedures. Some of these aspects may, however, be relevant to the choice of site management options, for example, confidence that planning permission can be gained for proposed site developments is an important factor.

As well as being required as a condition for a Permit, the ESC is a key management and communication tool:

- to develop the LLWR as an environmentally safe facility;
- to communicate the arguments and evidence concerning the environmental safety of the facility.

The ESC presents the knowledge and understanding on which our plans for waste management and assessments of environmental safety are based. It also provides a basis for our future consideration of options for the management the facility, including on waste acceptance for disposal. The ESC is implemented as a 'live' safety case and continues to evolve under a formal change control process. The 2026 ESC is the result of a major review and necessary changes will be implemented, with the agreement of the Environment Agency where appropriate.

Both the GRA (paragraph 6.2.2 in reference [29]) and GRR (paragraph A4.3 in reference [30]) define an environmental safety case as a set of claims concerning environmental safety, substantiated by a structured set of arguments and evidence, in the GRA for disposals of solid radioactive waste and in the GRR for a nuclear site.

The scope of a combined SWESC and ESC is wide ranging, encompassing information on:

- the environmental management of the facility;
- regulatory and stakeholder engagement;
- characterisation of all relevant aspects of the facility and its locality;
- optimisation;
- development plans;
- engineering designs;
- waste management plans;
- assessments of environmental impacts;
- implementation, including waste acceptance.

We have taken the above regulatory definitions of an ESC as a guide for the presentation of our safety arguments and evidence. The structuring of our safety arguments is described in Subsection 4.1 and the arguments presented in the rest of Section 4. How the ESC meets the requirements of the GRA and GRR is set out in Section 7.

Both the GRA and the GRR require that an environmental safety strategy is described (paragraph 7.2.2 in the GRA [29] and paragraph 2.3.3 in the GRR [30]). Our Environmental Safety Strategy is the subject of Section 3 of this report.

The development of an ESC is an iterative process ongoing throughout the life of a facility. It involves progressive development and focused improvement of data, understanding, design options and assessments. The development must integrate information from a wide range of technical studies, as well as non-technical inputs and decisions. The ESC will also reflect the stage of evolution for the facility, for example, design, construction, operation and closure. Currently, the LLWR is an operational site but with a mix of disposal facilities, including trenches and vaults. The trenches are no longer used for disposal but have not yet been finally capped. One vault is full and the other is in use and there are plans to build further vaults as required. The development of the 2026 ESC has been iterative, building on the earlier safety cases [32, 33, 20]. How the ESC has developed and been improved since 2011 is described in Section 5.

The further development of the ESC will continue to be managed under formal change control, as a live safety case, as changes occur and decisions are made. The ESC will develop incrementally in this way. There will also be further 'full' iterations of the ESC over the life of the LLWR, at such times as required by the Environment Agency and possibly by future management decisions on the role of the LLWR. The future programme to implement and develop the ESC is described in Section 6.

2.3 2011 ESC

Prior to the development of the 2011 ESC, an environmental safety case for the LLWR was submitted to the Environment Agency in 2002. This consisted of two cases, an Operational Environmental Safety Case [32] and a Post-closure Safety Case [33]. The Environment Agency, after reviewing these cases, concluded that they did not meet its requirements [34]. The revised Authorisation issued by the Environment Agency in 2006 restricted the use of future vaults to storage of LLW, leaving only a small amount of remaining disposal space in Vault 8.

The 2011 ESC was developed in the above context. It was a new safety case but drew on research and development work undertaken for the 2002 safety cases. It was intended to address the inadequacies of the earlier cases. The Environment Agency reviewed the 2011 ESC [21] and concluded that it provided sufficient basis to allow continuing disposal of LLW and final capping of the facility, albeit with further improvement and information requirements. A revised Permit to that effect was issued in 2015 [19].

The 2011 ESC was implemented at the site and within the organisation to ensure site operations, including the receipt of waste for disposal, are undertaken in accordance with the ESC. The ESC is managed as a live safety case, which continues to evolve. It is used to help make decisions on the site. For example, we use the understanding developed in the ESC to consider whether new wastes can be accepted for disposal. It is also used in making detailed design decisions.

The 2026 ESC is an update to the 2011 ESC, based on a comprehensive review, as required by our Permit. It is a full restatement of the ESC but should be understood to be an evolution of the 2011 ESC. The 2026 ESC addresses the new requirements to provide a SWESC and WMP. It considers the potential of the LLWR to safely accept some ILW for disposal, following the new government policy framework.

2.4 History and Description of LLWR as it Exists Today

The site of the LLWR was first developed in 1940 as a Royal Ordnance Factory for the production of TNT. Ownership later passed to United Kingdom Atomic Energy Authority, which in 1957 was granted planning consent for the disposal of waste in the northern 40 hectares of the site. The first Certificate of Authorisation for disposal of LLW was granted in 1958 under the terms of the Atomic Energy Act 1954, and disposal operations commenced in 1959. Ownership and responsibility for the site was transferred to British Nuclear Fuels Limited when the company was formed in 1971, and the site became a part of the NDA's estate when that body was established in 2005. Between 2008 and 2021, the management of the site was contracted to UK Nuclear Waste Management Limited. The site is now operated by Nuclear Waste Services Limited, a wholly-owned subsidiary division of the NDA.

The LLWR receives wastes from a range of consignors, including nuclear power stations, defence establishments, general industry, hospitals, universities and from the clean-up of historically contaminated sites and redundant fuel cycle, isotope manufacturing and research facilities.

For the first thirty-six years of operation, disposals were by tipping of drummed, bagged and loose wastes into successive trenches within the 'consented area' (see above) – see Figure 2.2. The first trench followed the course of a railway cutting through northern part of the site associated with the Royal Ordnance Factory. Subsequently, five wider and deeper trenches were excavated parallel to, and on either side of, Trench 1 such that their bases should lie within low-permeability clay at a depth of 5 to 8 m below ground level. In the case of the later trenches at least, if natural clay was locally absent, bentonite clay was rotovated into the bases to reduce the permeability of the trench bases. A final trench, Trench 7, of irregular shape was excavated to fully use the site area towards its north-eastern boundary. All trenches have a north to south fall, to facilitate the collection of leachate at the southern end of each trench, where it is diverted to an interceptor drain.

Figure 2.2: Photograph of trench disposal operations in the 1980s

From the early years, the disposed waste was covered by soil at the end of each working day. Periodically, a hardcore layer was placed to facilitate tipping operations. Trench 7 was closed in 1995.

From 1987 onwards, disposal operations were upgraded. Remedial work was also carried out on the trenches; this included installation of a low-permeability cut-off wall (to limit lateral movements of groundwater and radionuclides) to the north and east of the trenches, interim capping of the filled trenches and upgrading of the leachate drainage system, to allow for discharge directly to sea (rather than surface water) through the Marine Pipeline via the Marine Holding Tanks. An engineered, concrete disposal vault was constructed, Vault 8, which allowed the orderly emplacement of containerised waste within an engineered concrete structure according to modern disposal standards – see Figure 2.3. The emphasis of the Vault 8 design was largely on operational aspects of waste emplacement and storage. The vault has surface water drains to collect rainwater from the surface of the base slab, while an under-slab drainage blanket and perimeter drains relieve the possible build-up of hydrostatic pressure beneath the floor slab and also collect any leakage through the slab. Vault 8 commenced operation in 1988, the first seven years of its operation overlapping with the operation of Trench 7, to use up the available capacity in the trench.

Figure 2.3: Vault 8 disposals

Wastes were disposed of in Vault 8, and now in a second vault, Vault 9, in steel ISO (International Organization for Standardization) containers of different heights. Prior to disposal, the wastes are grouted on site at the Drigg Grouting Facility, operational since 1994 – see Figure 2.4. Waste containers consigned to the repository before this date were grouted once the Drigg Grouting Facility was operational. Sometimes wastes have been disposed of in different waste containers or directly disposed to the vaults and grouted in situ. Sometimes, containers have been accepted that are too heavy to be fully grouted and then emplaced. The grouting of such containers was completed after emplacement.

The introduction in 1995 of waste monitoring and high-force compaction at the Waste Monitoring and Compaction Plant on the Sellafield site significantly improved the waste loading of the ISO containers. Some containers received before 1995 were sent to the Waste Monitoring and Compaction Plant for the waste to be compacted.

Vault 8 was mostly filled to its original planned capacity by 2009. A small area at the northern end of the central bay of Vault 8 was left unfilled to allow vehicular access to the vault via a ramp and to allow disposal of any overweight or uncontainerised waste. The central bay of Vault 8 was also used to store ISO containers stacked up to an additional height of two half-height ISO containers above the disposed containers stacked up to a height of four half-height ISO containers. These higher-stacked containers were placed in Vault 8 before Vault 9 became available. It has now been decided to leave these higher-stacked containers in place in Vault 8 for disposal. The movement of 171 containers from Vault 9 to the unfilled area of Vault 8 was completed in January 2025. The movement to Vault 8 of building rubble from one of the waste stores on site, which has been stored in Vault 9, is underway. The rubble is being used for infill of Vault 8, including the access ramp. Recent disposals to Vault 8 include additional LLW WAGR Boxes from Sellafield in 2019. LLW Treated Radwaste Store drums from Winfrith were disposed of in a gap on the eastern side of Vault 8 between 2022 and 2024.

Figure 2.4: Drigg Grouting Facility

Construction of Vault 9 started in 2008 and was completed in December 2010. At the time, it was only permitted and only had planning permission for LLW storage. The vault had a 'bathtub' design, with a base and walls containing layers of bentonite-enhanced sand. The bathtub design aspect was not completed during construction. Design optioneering during the development of the 2011 ESC preferred a design with lower sealed walls and the bentonite-enhanced sand was not placed to the full height of the vault walls.

Following the 2015 Permit revision and subsequent planning permission in 2016, Vault 9 could be used for disposal. The vault contains approximately 2,000 disposal containers. Most wastes are now received within half-height or third-height ISO containers. The containers are first stored in Vault 9 and then grouted in campaigns. The ISO waste containers in Vault 9 have not been placed in their final disposal positions. The intention is to move the containers to the northern end of the vault and extend the final cap over them at the appropriate time. Some LLW WAGR Boxes have been emplaced in their intended final disposal positions at the northern end of the vault. Vault 9 has also been used to store demolition wastes, pending disposal in Vault 8. The volume of wastes received in recent years has greatly diminished due to the introduction of the waste hierarchy into the management of LLW and the consequent diversion of wastes down other waste management routes. To date, no uncontainerised waste or overweight containers have been disposed of in Vault 9.

In the period 2015 to 2018, the security fence around the site was upgraded. It now does not enclose all the land at the southern end of the site. The NDA has also taken out a 999-year lease on the land between the site and coast, providing control over the use of the land.

Ten magazines were built as part of the Royal Ordnance Factory to store the manufactured TNT before shipment off site. These were subsequently used to store radioactive waste including ILW. Five of the magazines were emptied in the early 1980s and were subsequently demolished in 1995. The remaining magazines have now been emptied and partially demolished. The covering soil has been removed. The intention is to demolish the remaining concrete and brick constructions and use the material, along with the soil, in the construction of the final cap over the repository.

Preliminary civil engineering works for the initiation of final capping of the disposal facility were undertaken between 2019 and 2023. Stockpile areas, a haul road and run-off management infrastructure were constructed. Replacement of the membrane over the southern area of the disposal trenches, which will not be covered by the final cap for some decades, began in 2024 to reduce infiltration into the trenches.

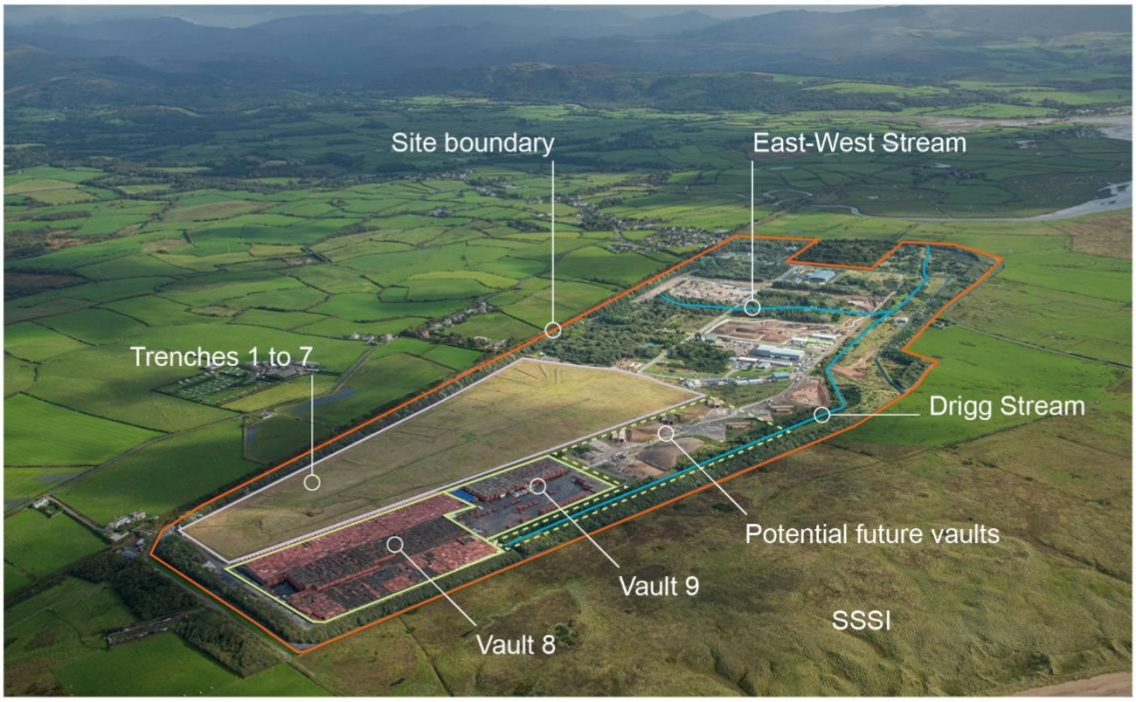

Figure 2.5: The LLWR site

The layout of the site is shown in Figure 2.5. Further information on the site is given in the '*Site History and Description*' report [2]. This includes information on how the regulation of the site has evolved.

2.5 Environmental Context of the LLWR

The LLWR is located on the West Cumbrian coastal plain, close to the village of Drigg and approximately five kilometres south-east of Sellafield. A map of the locality is shown in Figure 2.6: and the immediate environs in Figure 2.7. Apart from nearby Sellafield, the area is predominantly rural. 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 Special Area of Conservation designated under the European Habitats Directive. The inshore area along the coast is also a Marine Conservation Zone. Along the north-eastern boundary is the Carlisle to Barrow-in-Furness railway line, sidings from which enter the site for the delivery of waste containers and other items and materials. The main north-south road through West Cumbria, the A595, runs about two kilometres to the east of the site. The Ravenglass Estuary lies to the south. The Cumbrian mountains rise further to the east. The LLWR lies outside the Lake District National Park, which is bounded by the A595 and the Ravenglass Estuary.

The LLWR site is about two kilometres long and half a kilometre wide and lies on a north-west to south-east axis. A boundary fence, designed to prevent unauthorised access, encloses most of the site. The northern half of the site is used for waste disposal. The south-western boundary of the northern area of the site borders the SSSI. The height of the site varies from 20 m above Ordnance Datum (OD) to the north-east and west of the site to less than 5 m above OD at the south-eastern site boundary. To the west of the site, the topography gently undulates towards a small cliff line marking the edge of the Drigg Beach. The surface of the interim cap that covers the trench area is around 25 m above OD. The Drigg Stream rises immediately to the south of Vault 8 and 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 the site to the north-east, 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 the Ravenglass Estuary, comprising also the rivers Mite and Esk, which discharges to the sea opposite the village of Ravenglass.

Further information on the environmental context of the LLWR can be found in the '*Site History and Description*' report [2].

The geological structure in the region of the LLWR consists of Quaternary age deposits (up to 2.6 million years old) overlying older bedrock. Quaternary deposits at the LLWR site are a result of complex glacial processes, which were responsible for the deposition of a sequence of deposits of clay, sands and gravels up to 70 m thick.

The Quaternary deposits overlie Triassic Ormskirk Sandstone (around 240 million years old) in the vicinity of the LLWR site.

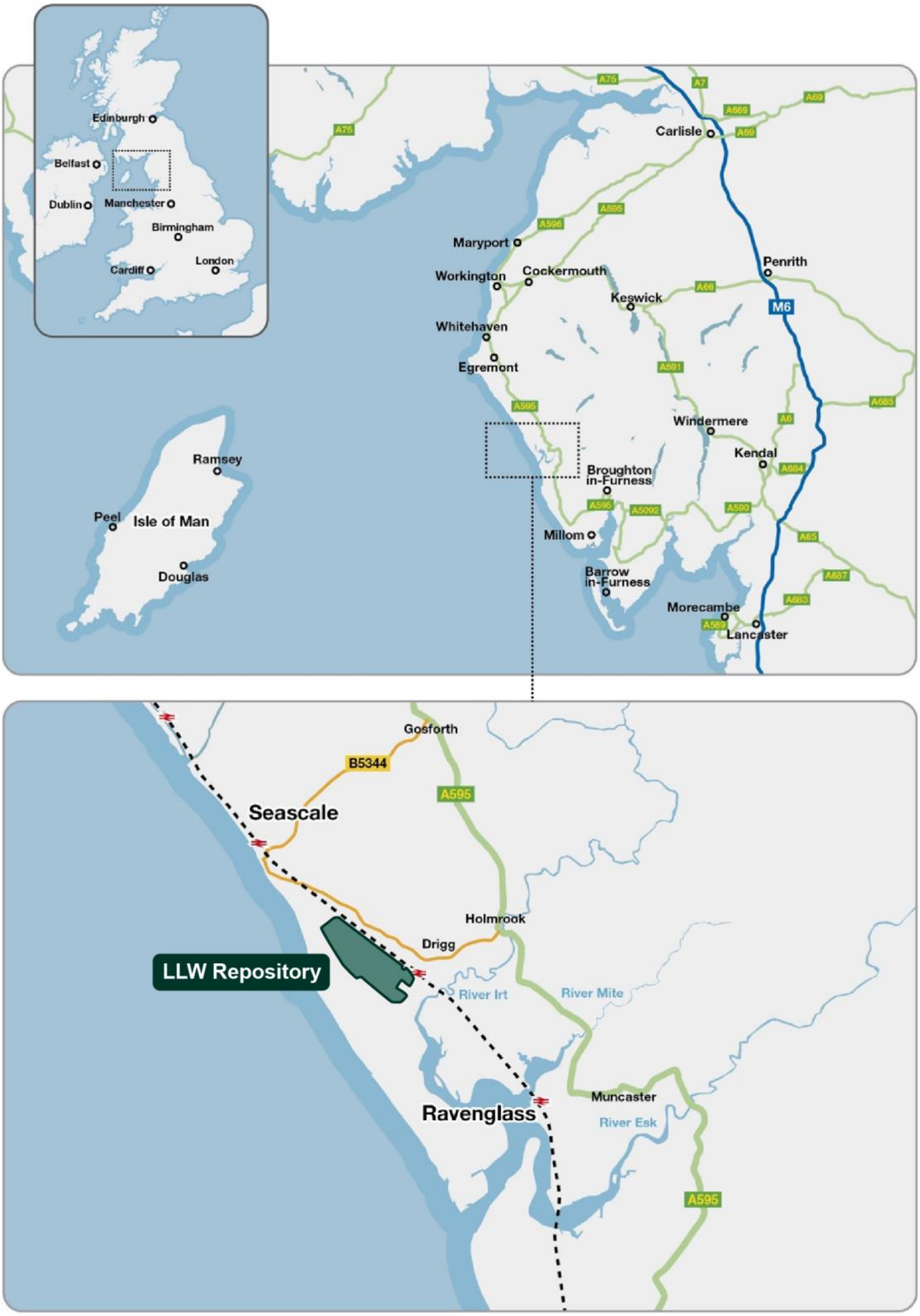

Figure 2.6: Map of LLWR location

Figure 2.7: The LLWR site and its immediate environs

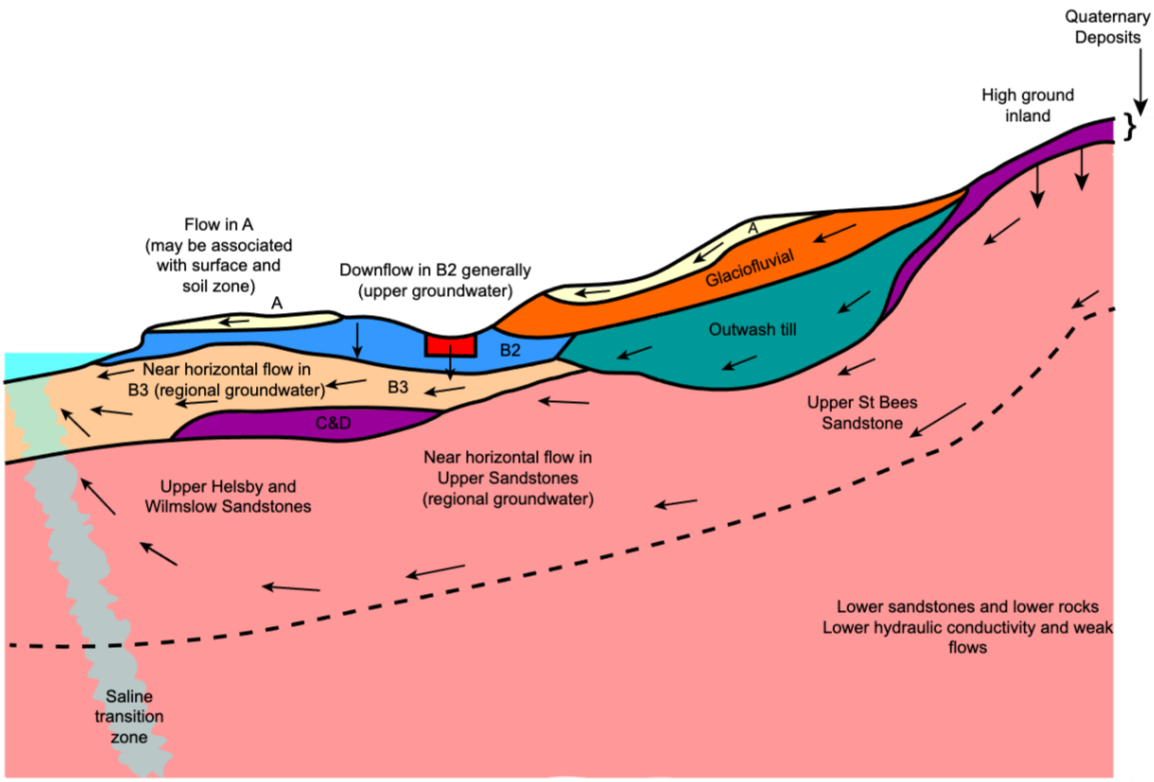

Figure 2.8: Hydrogeological conceptual model (schematic east-west section)

The Regional Groundwater occurs within the deeper Quaternary deposits and the underlying bedrock. The Upper Groundwater occurs in the shallower Quaternary sediments. In the Regional Groundwater, there is not a significant vertical gradient in the measured heads. Instead, there is a weak horizontal gradient that is generally perpendicular to the coastline. Flow is roughly from north-east to south-west, driven by the weak horizontal gradient. In areas where the upper part of the bedrock is sandstone, flow in the upper part of the bedrock makes a significant contribution to the regional groundwater flow. The flow is generally downwards in the Upper Groundwater because of a vertical head gradient, although, in places, the flow has a significant horizontal component. In discharge areas, which onshore are generally near streams, the flow has an upwards component. The flow in the Regional Groundwater is roughly horizontal, ultimately discharging into the sea. Figure 2.8 shows a schematic representation of the hydrogeological conceptual model.

Further information on the geology and hydrogeology in the vicinity of the site is given in the '*Hydrogeology'* report [6].

At its north-western corner, the LLWR disposal area is only about 350 m from the present-day coastline and the site is vulnerable to sea-level rise and coastal erosion. It is not believed that this vulnerability was a consideration when the site was first selected for waste disposal. Now, consideration of sea-level rise and coastal processes and assessment of their effects are important aspects of the ESC. Based on qualitative and quantitative evidence, including modelling studies, we have concluded that the site will start to be eroded on a timescale of several hundred to a few thousand years, with consequent disruption of the repository [7]. While this situation may appear unusual for a radioactive waste repository, we observe that in the long term all near-surface disposal facilities are vulnerable to disruption by natural erosion processes, human actions or combinations of natural and human events. This is taken into account by setting limits on the types and activity of waste that may be disposed to a near-surface facility to ensure that the impacts are consistent with regulatory guidance levels at the time of disruption. In the case of the LLWR, the nature and timing of coastal erosion and resulting limits means that there is some LLW that we are unable to dispose of because of the quantities of longer-lived radionuclides it contains. Conversely, some ILW would be safe to dispose of because of the mix and quantities of radionuclides it contains. A summary of the evidence and our arguments on coastal erosion and the vulnerability of the facility to such erosion, and the impacts that will result, are given in Subsections 4.3 and 4.5. Further information on the current understanding of the future natural evolution of climate and landscape in the vicinity of the LLWR is given in the '*Site Evolution'* report [7].

3 Environmental Safety Strategy

This section describes our Environmental Safety Strategy.

3.1 Environmental Safety Strategy Approach

3.1.1 Definition

The GRA and GRR both define (in their Glossaries) an environmental safety strategy as:

> *'An approach or course of action designed to achieve and demonstrate environmental safety'.*

An environmental safety strategy is thus both the process of working towards a facility that is safe and the demonstration that it is safe.

In paragraph 7.2.2 of the GRA, it is stated that an Environmental Safety Strategy:

> *'…should present a top level description of the fundamental approach taken to demonstrate the environmental safety of the disposal system. It should include a clear outline of the key environmental safety arguments and say how the major lines of reasoning and underpinning evidence support these arguments. The strategy should explain, for example, how the chosen site, design for passive safety and multiple barriers each contribute to environmental safety.'*

The GRA definitions are broad: the Environmental Safety Strategy is effectively the complete strategy by which an ESC is developed, including, for example, the strategy for development of the information base and the management framework under which all work related to the ESC is carried out, as well as specific engineering measures. The Environmental Safety Strategy also must include the key environmental safety arguments and evidence.

In this subsection (Subsection 3.1), we describe our approach to developing our Environmental Safety Strategy. An important way of achieving environmental safety, particularly radiological safety, is optimisation. Our approach to optimisation is summarised in Subsection 3.2. The controls developed as part of our Environmental Safety Strategy are reflected in our Site Development Plan, summarised in Subsection 3.3. Subsection 3.4 summarises the controls and their functions and describes how they achieve environmental safety. The demonstration that safety is achieved is completed in Section 4, where the arguments and evidence supporting the ESC are given.

3.1.2 Approach to Ensuring Environmental Safety

Framing and constraints

There are several factors that frame and constrain our Environmental Safety Strategy.

One of our principal objectives, in accordance with government policy and NDA strategy, is to promote and ensure the best use of the LLWR. This means developing plans for the safe and optimised use of the LLWR for disposal of radioactive waste and implementing those plans, subject to necessary regulatory permissions and planning approvals. The development of the ESC has been framed by this objective. It requires optimising the environmental performance of the disposal facility and site both during operations and in the long term. This objective is partly achieved by our supporting the implementation of the waste hierarchy in the management of radioactive waste in the UK, which reduces the volume of waste that needs to be disposed of.

We must demonstrate that the impacts of the LLWR on people and the environment are consistent with regulatory guidance levels at all times.

The LLWR has been operating for over 65 years and hence the history of the site and its current state of development, as well as its environmental context, constrain the Environmental Safety Strategy. For example, the engineering designs for the construction and closure of new disposal areas cannot be considered independently of the operation and closure of the existing trenches and vaults.

Our Environmental Safety Strategy has been developed and implemented taking account of the above factors.

Principles

Our Environmental Safety Strategy identifies the management and engineering control measures that ensure environmental safety.

In identifying the control measures, we have followed several ‘principles’. Some of these principles are derived from the main principles set out in the GRA (see Section 4 in reference [29]) and in the GRR (see Annex A in reference [30]), from which the requirements in the GRA and GRR are derived. The principles of our Environmental Safety Strategy are:

- sound management and safety culture;
- engagement with regulators and other stakeholders;
- firm understanding of the framing and constraints, environmental context, potential hazards posed by the wastes, and the ways in which the hazards might lead to impacts;
- use of optimisation, thus ensuring proportionality;
- application of the waste hierarchy for site wastes;
- according people and the environment in the future the same level of environmental protection as now;
- preference for passive over active controls during the Period of Authorisation and reliance only on passive engineering controls after the Period of Authorisation;
- use of simple approaches, as far as practicable;

- consistency with regulatory limits and guidance levels;
- assurance of protection through monitoring and any required intervention during active institutional control.

Derivation of controls

Our control measures are aimed at ensuring that the impacts that might result from the management of the wastes, including impacts resulting from radionuclides and chemotoxic hazards presented by the waste, are acceptably low.

For the wastes associated with operation of the site, we focus on ensuring optimal management of the wastes including through application of the waste hierarchy.

For the disposal facility, our control measures can include actions to limit the inventory of wastes, the selection of an appropriate design and appropriate operation of the facility.

In practice, we can:

- control the source, that is, the wastes disposed of;
- isolate the source, limiting the potential for its exposure by natural processes and human activities;
- contain the source to minimise the release of contamination from the facility;
- manage any residual releases so as to minimise their effects.

We have identified the control measures through a process of optimisation, described in the next subsection.

3.2 Optimisation

The GRA [29] notes that optimisation is a key principle of radiation protection recommended by the International Commission on Radiological Protection and is incorporated into UK legislation. The GRA defines optimisation as:

> *'…the principle of ensuring that radiation exposures are as low as reasonably achievable (ALARA) in the given circumstances.'*

Paragraph 6.3.58 provides guidance as to what this means, noting that optimisation is '*about finding the best way forward where many different considerations need to be balanced*'. It explains that '*relevant considerations include, for example, economic and societal factors, and the requirement to manage any non-radiological hazards*'. Importantly, it is stated that '*Although reducing radiological risk is important, it should not be given a weight out of proportion to other considerations*', and that '*the best way forward is not necessarily the one that offers the lowest radiological risk'*. The GRR glossary [30] gives a similar definition and makes similar points.

Optimisation is the process we have used to determine a preferred set of management and engineering control measures that are consistent with the goal of achieving radiation doses and risks that are As Low as Reasonably Achievable (ALARA). We have taken into account a range of factors, including the need to ensure adequate protection from the non-radiological hazards presented by the wastes.

Our Site Development Plan has not been derived solely through the process of optimisation in the technical sense of achieving radiological risks that are ALARA. We have also taken into account a wider set of considerations that do not directly affect radiological risk, such as the scheduling of developments and the need to protect workers during the operational period.

The potential controls that we considered in our optimisation process for the disposal facility include the following:

- Controls over waste inventory:
  - What, if anything, should be done about the existing disposals?
  - What controls are appropriate over the acceptance of wastes for disposal in the future?
  - What conditioning and packaging is appropriate for wastes consigned for disposal?
- Controls over design and operation:
  - What control functions are required of the different components of pre- and post-closure engineering, and how are those controls most effectively implemented in terms of:
    - the design specification;
    - the timing of construction or implementation;
  - waste emplacement?
- Controls to ensure that radiological impacts are ALARA with respect to:
  - operational discharges;
  - external irradiation;
- Controls to be implemented during closure of the facility and how long they will need to be effective.

We use our optimisation process to derive waste management plans for our wider site wastes, including some wastes in temporary storage and contaminated land that has resulted from operation of the site as a LLW disposal facility and from its prior use as a Royal Ordnance Factory. We also use the same optimisation process for decisions about uncontaminated waste materials. Where plans have been finalised, the optimal management routes identified have either been management off site or disposal or reuse in the disposal facility.

Consideration of options for the management of the LLWR sits within a wider framework of industry-wide processes ensuring an integrated approach across the waste lifecycle. This includes programmes run on behalf of the NDA. Implementation of the resulting strategies has led to significant changes in projections of disposals to the LLWR, because of waste diversion and treatment strategies. More broadly, the principle of optimisation (demonstrated by applying a process to identify Best Available Techniques, BAT) has become increasingly embedded in the organisation and culture of the industry, as well as at the LLWR.

Within that wider picture, the optimisation process for the disposal facility itself has involved developing, comparing and selecting a set of control measures that will provide optimised environmental protection. In comparing options for the LLWR, our focus has been to make visible the key underpinning evidence and logic that has led us to put forward the proposed set of controls for future management of the LLWR. Our optimisation process is consistent with international and national good practice and regulatory guidance. It provides for a structured, iterative, evidence-based approach to options identification and assessment, with appropriate stakeholder engagement. The process is intentionally flexible to allow its application to focus on the differing nature of controls at a proportionate level of detail.

This flexibility has enabled us to use a range of approaches. Where appropriate, we have carried out a comprehensive evaluation of option performance against attributes that align with industry good practice. We have typically adopted a qualitative, logic-based approach to identifying and assessing differentiating factors, because this lends itself to developing a good understanding of the main discriminating arguments for and against options.

This approach is particularly suited to optimisation assessments of a complex system such as the LLWR and allows greater insights to be gained than a quantitative approach in which option performance against each attribute is numerically evaluated. This is because uncertainties arise when considering long-term environmental management and judgements are required that can be challenging to address efficiently in quantitative optioneering processes. Indeed, it is the logic and arguments underpinning the analysis that are the key outcomes, and the qualitative approach allows them to be presented directly.

Our approach also ensures integration and reconciliation of outcomes to ensure individual studies are aligned with overall repository strategies. In addition, we recognise that iteration is a key aspect of good practice in optimisation, and we ensure that any changes in understanding or context are progressively identified and addressed.

An important aspect of developing, comparing and selecting a set of control measures for the disposal facility has been developing a clear understanding of the safety functions of the different control measures and the qualitative or quantitative effects that they might have on environmental impact. The functions and effects were mainly analysed using the understanding gained through previous assessments of environmental impacts via the pathways for release of hazardous materials to the environment. The pathways are:

- groundwater;
- gas release;

- coastal erosion;
- human intrusion.

For example, the final repository cap will function to:

- limit infiltration into the wastes, to ensure low releases of contaminated leachate from the facility;
- manage bulk and therefore trace gas releases;
- ensure that erosive effects are limited as far as practicable;
- attenuate radiation;
- prevent or discourage human intrusion into the wastes.

The detailed description of the options that have been considered, their evaluation, and selection of a set of compatible and complementary options that form the Site Development Plan is presented in the '*Optimisation and Site Development Plan*' report [9]. Therein, the relevant option assessment studies and their outcomes are grouped together as follows:

- Management controls and interventions relating to the past disposals at the LLWR.
- Management and engineering controls over future waste disposals, including acceptance criteria, treatment and packaging, and methods for waste emplacement.
- Passive engineering controls over the environmental performance of the LLWR during the Period of Authorisation and beyond, taking account of the functional role of engineering features, as well as their design and timing of implementation.
- Active management controls over environmental performance, including for discharges during the Period of Authorisation as well as management and controls exercised over the LLWR site during the period of active institutional control.

A summary of the outcome is provided in the following subsection.

3.3 Site Development Plan

This subsection presents key features of our optimised Site Development Plan for the management of the LLWR. Development of the disposal facility, according to the Site Development Plan summarised in this subsection, would allow the site to continue to operate as the primary destination for disposal of LLW in the UK until 2135, based on current assumptions about future LLW arisings and application of waste segregation, diversion and treatment (see Subsection 2.1). The Site Development Plan, as set out in this report, and in more detail in the '*Optimisation and Site Development Plan*' report [9], will form the basis for future development of the facility. All plans for the use of the LLWR facility, however, are subject to the agreement of the NDA, as owner and strategic authority, and depend on the granting of the necessary planning consents and regulatory permits and permissions. In addition, the future use of the LLWR depends on the requirements for management of radioactive waste in the UK. For the reasons set out earlier in this report, the additions to the Site Development Plan that would be required to dispose of less-hazardous ILW are also summarised.

The Site Development Plan for the use of the site for the disposal of LLW is summarised as follows:

- No intrusive remediation of the trenches is planned, however, active leachate management, the closure engineering that will be constructed, and renewal of the interim trench cap that is underway, will optimise the long-term environmental performance of both the trenches and vaults.
- Waste will only be accepted for disposal and emplaced in the vaults consistent with the requirements of the ESC and our Permit to dispose of radioactive waste. Individual waste consignments will only be accepted for disposal where they meet the WAC or an assessed and agreed variation to the WAC. The quantities of wastes disposed of will not exceed the assessed radiological, non-radiological and volumetric capacities of the facility. The capacity of the repository will be managed to ensure that it is used optimally. Waste will only be accepted for disposal when it has been shown that it is appropriate to dispose of it in an engineered vault, for example, the disposal of VLLW will be avoided unless disposal at the LLWR has been shown to be BAT.
- Engineered vaults will be constructed to allow disposal of those wastes requiring vault disposal. The vaults will be constructed beside and to the south of Vault 9 in the area adjacent to the western side of the trenches.
- A final cap will be progressively constructed over the vaults and trenches. Eventually, the whole area of trenches and vaults will be covered by a single, gently-domed, low permeability engineered cap, designed for stability and resistance to erosion and presenting acceptable visual impact. Suitable long-term vegetation cover will be established on the cap area and periphery.
- A passive gas venting system will be incorporated into the final cap to provide confidence that differential pressures will not threaten the performance of the cap as a barrier to infiltration. Final decisions on the vent design and whether the vent will be closed before the end of active institutional control will be made later, noting that the venting approach does not need to be part of the construction design for the first strip of the cap.
- The vaults will step down in the southerly direction following the natural slope of the site and containerised waste will be stacked in the vaults, utilising as much as possible of the profile volume below the engineered cap.
- Vault areas will be constructed as needed, filled, closed and capped progressively, at the same time capping over the adjacent strip of trench area.

- In Vault 8, we will not pursue higher stacking beyond current stack heights. In the northern portion of Vaults 9 and 9a, which will be filled with ISO containers of the current design, our baseline assumption is that the containers will be stacked to a maximum height of five containers. Stacking beyond that height will require further substantiation. These wastes will be surcharged prior to cap installation to ensure that the wastes will provide a stable base for cap installation. While this will reduce the effectiveness of the barrier the containers provide, this is more than compensated for by increased confidence in long-term cap performance. In Vault 9 and Vault 9a, relevant disposals will be stacked at the northern edge of these vaults and will be closed via an extension of the cap seal over the relevant wastes as soon as practicable after Vault 8 closure. This will provide closure levels of protection of the wastes as soon as is currently practicable.
- We will develop a new stronger ISO container design for wastes not yet committed to a disposal container. Stronger ISO containers will be higher stacked and will be disposed to the southern parts of Vaults 9 and 9a and we expect will comprise the majority of disposals in Vaults 10, 11 and 12. The top-most container of each stack will be fitted with a concrete container protection unit designed to protect the vulnerable container lid from the loads that will be imposed during and after cap installation. These containers will not be damaged during, or after, cap installation and will therefore provide an effective barrier to contaminant transport. The units will also provide some protection from precipitation.
- Interim storage warehouses will be used to protect waste containers in the vaults from local environmental conditions prior to emplacement of the containers in their final disposal positions and construction of the final cap over them.
- During operations, leachate from the trenches and rainwater run-off from the open vaults will continue to be managed by collection, monitoring and controlled discharge to sea via the Marine Pipeline, subject to the requirements of our Permit. The effect of the progressive capping will be to reduce infiltration to the trenches and hence progressively reduce trench leachate. It will also minimise the area of open vaults and hence degradation of the waste containers, reducing contaminant releases to water, as well as reducing overall leachate volumes. The use of warehouses to protect waste containers prior to emplacement in final disposal locations will also reduce the volumes of leachate generated, as the warehouses will prevent the interaction of precipitation with wastes and will allow for separate management of clean run-off waters.
- To promote unsaturated (that is, partially saturated) conditions in the vaults for as long as possible following closure, future vaults will be designed with side walls extending 1 m above the vault base, and incorporating engineered passive drainage arrangements so that, following final closure, residual infiltration through the cap may drain freely.

- An underground, low permeability cut-off wall will be constructed, integrated with the final cap, and the existing cut-off wall at the north-east corner of the site. The wall will extend to 2 m below the bases of the vaults. The wall will be of sufficient depth to limit inflow of surface water and shallow groundwater at the level of the vaults and trenches, and outflow of contaminated leachate close to the ground surface near the facility.
- Active leachate collection and management will continue during operations and after final disposals for as long as required.
- Site wastes will continue to be managed in accordance with our WMP.
- The site will remain under a period of active institutional control, and it is assumed regulatory control, for around 100 years after completion of closure engineering. During this time, measures will be put in place to prevent damage to the closure engineering.
- Monitoring will continue during operations and afterwards during the period of active institutional control. It will provide reassurance that the process of engineering construction is consistent with design requirements for performance and associated Construction Quality Assurance, and after completion, that the repository is performing safely and as expected. It will support the decision on closing the gas vent. Remedial actions, such as addressing any problems with the final cap, will be taken if required.
- Records of the LLWR will continue to be archived at NDA's national facility in Caithness. Other approaches to ensuring knowledge of the disposal facility and site is maintained after the end of the period of active institutional control, such as land covenants, may also be adopted. The 'end state' of the site (the state of the site at the time the NDA relinquish control) will be made consistent with local stakeholders expressed desire for the site to become a sustainable amenity for the local community, thereby, helping to maintain knowledge and lower the likelihood of developments or uses that might lead to adverse impacts.[7]

Additions to the Site Development Plan required for the disposal of less-hazardous ILW are, in summary, as follows:

- We would dispose of all ILW in containers sufficiently strong to withstand the loads imposed during and after installation of the final cap. If the ILW could be handled in the same way as LLW, the containers would be stacked in the vaults alongside LLW (although stacked separately). The exact stacking arrangements would be dictated by several factors, including operational and Nuclear Safety Case considerations. The topmost container of each stack would be fitted with a container protection unit

[7] We do not rely on knowledge retention or amenity use in our demonstration that the regulatory risk guidance level will be met beyond the Period of Authorisation (including a 100-year period of active institutional control).

to protect its lid. Depending on waste receipt rates, containers would be interim stored in temporary warehouses alongside LLW containers prior to emplacement in final disposal locations.

- ILW that gives rise to dose rates necessitating additional shielding would be disposed of in shielded modules, which would be constructed as required in Vaults 10, 11 and 12. We would allow for flexibility with respect to the location and size of the shielded modules in the vaults as this offers a means of managing uncertainty in the volumes of waste that may require such shielding. It also provides flexibility in ensuring that operational and post-closure impacts from wastes in shielded modules are ALARA. Bunding or drain arrangements would be used to isolate waters and leachate associated with the shielded modules from those associated with adjoining vault disposal modules for other categories of wastes. This would include intercepting clean waters shed from the unit roofs during the operational period so they do not become leachate. This is consistent with the principle of minimising overall leachate volumes.
- Appropriate measures (for example, controls associated with the design, protective measures on plant, working patterns) would need to be identified and implemented to ensure that the operational safety impacts from ILW operations would be As Low As Reasonably Practicable (ALARP).
- Consideration would need to be given as to whether wastes would require transport in Type B transport containers. If this were to be needed, then the site would require the capability to unpack disposal containers from transport containers. Buffer storage capability might also be required. Our current assumption is that this capability would be required.

Supporting the Site Development Plan, a structured Requirements Management System ensures that engineering design and optimisation work remains consistent with the ESC. Requirements on the closure engineering are traced through the Disposal System Specification, with linkage into design justification and optimisation studies. The Requirements Management System is described in more detail in the '*Implementation*' report [17].

Figure 2.5 shows the repository today. A schematic plan of the repository with future vaults is shown in Figure 3.1 and representations of the further development of the repository are shown in Figure 3.2 and Figure 3.3.

Figure 3.2 shows the final cap completed over Vault 8 and the adjacent area of the trenches, and the interim cap over the rest of the trench area replaced. Figure 3.3 shows the contours of the final cap completed over the Repository.

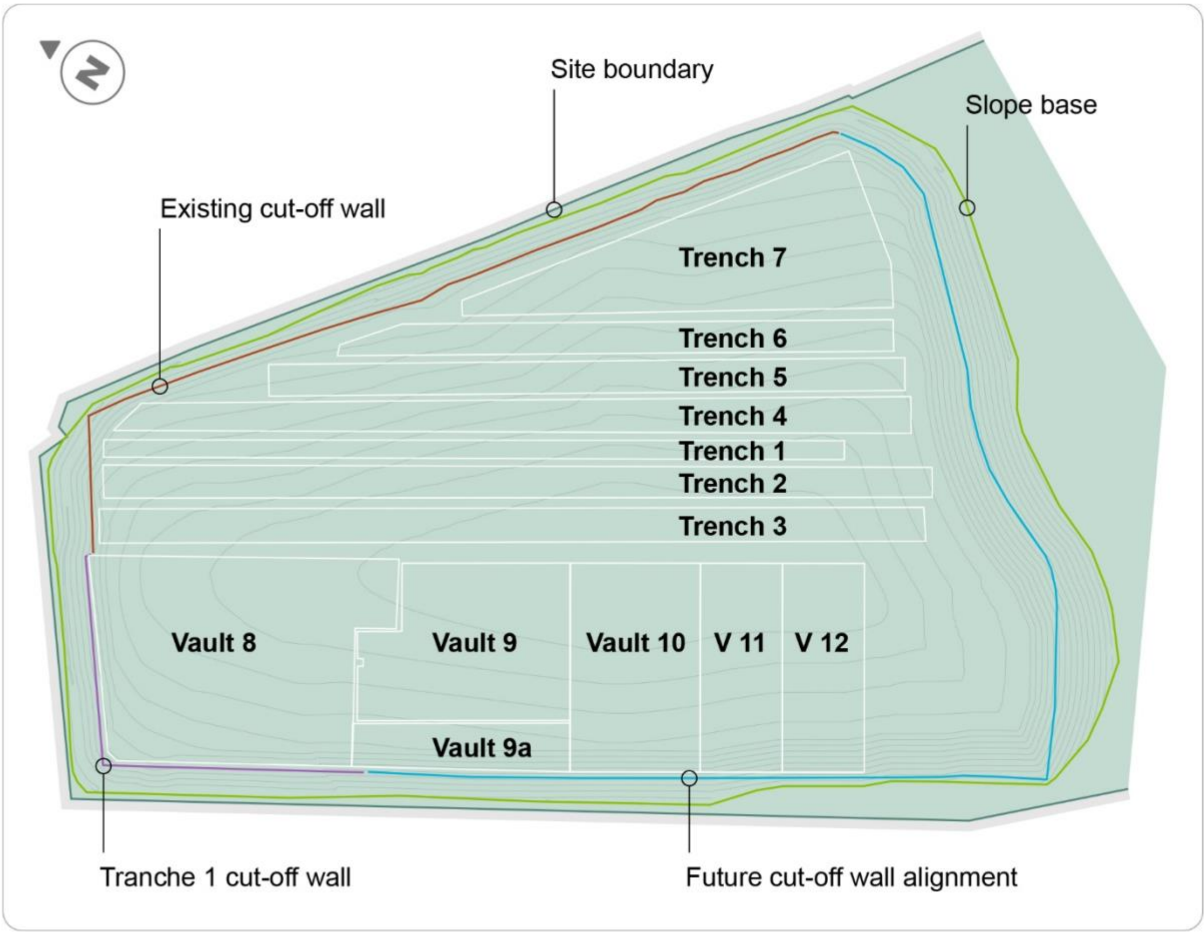

Figure 3.1: Schematic plan of the Repository

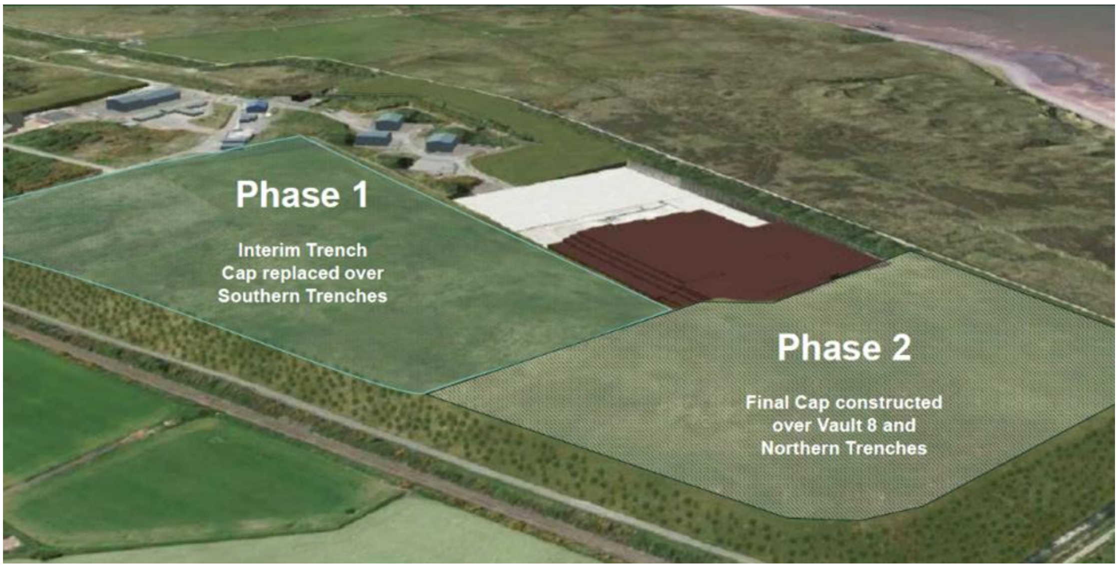

Figure 3.2: Vault 8 final capped

Figure 3.3: Contours of the final cap completed over Repository

3.4 Safety Functions and Controls

In this subsection, we summarise our understanding of how our Environmental Safety Strategy achieves environmental safety. This description is presented in terms of safety controls and functions. Safety controls are the measures applied to ensure that the impact of radioactive waste disposal on environmental safety is acceptably low. They are provided by the components of the disposal system, the way it is managed and the environment within which it sits. The safety functions that correspond to the controls describe the various ways in which the components contribute to environmental safety.

The main pathways by which radionuclides may reach the environment were introduced in Subsection 3.2. We have identified a set of safety functions for each pathway. We have then analysed, either qualitatively or quantitatively those safety functions that we think are key in providing the required performance [11]. In this subsection, we summarise those key safety functions that we consider provide the main contribution to mitigating impacts, in particular, to containment and isolation. A full assessment is provided in the '*Safety Functions*' report [11].

Our approach is necessarily different from approaches pursued in some other programmes as a result of the particular circumstances of the LLWR. The circumstances include:

- The important barriers at the LLWR provide a function at all times of the period of interest to the safety assessment. They degrade gradually and so their efficacy decreases with time. However, unlike in some geological repositories for spent fuel and high-level waste, we cannot identify barriers that provide almost complete containment for different time periods. An exception is the period of active institutional control, which lasts for a specific period.
- The repository has operated since 1959 and so there has been a period of some decades before there was any formal consideration of optimisation, requirements management and a safety functions approach. This means that our safety functions approach has not been integrated with other safety assessment processes until recently.
- There are significant uncertainties in the inventory that will be disposed. It is therefore difficult to identify the characteristics of the site that would be sufficient to enable disposal of that fixed inventory. Rather, our approach is to optimise the design of the system and then set limits on total activity or activity concentration that are consistent with system characteristics. We have not specified a disposal inventory and then designed the system to accommodate that inventory.

Control of disposed inventory

The waste acceptance controls place limits on the quantities of radionuclides and non-radiological contaminants that can be disposed. Capacities are set for each pathway unless the capacities for one pathway are always less limiting than the capacities for another pathway. Such capacities, which are based on the results of assessment calculations, provide assurance that impacts will not exceed the regulatory criteria. They are an important safety control because they provide for safety even if the inventory varies from what is currently anticipated. We identify controls on the physical characteristics of the waste and its biogeochemical characteristics to ensure it does not have significant deleterious effects on the performance of the system. For a small number of pathways, we also identify emplacement strategies, according to which wastes are disposed in locations within the repository that give rise to relatively lower radiological impact, for example, we may emplace wastes at sufficient depth that they would not be disturbed by most forms of human intrusion. Capacity limitation is a strategy that is applied to all exposure pathways. Emplacement strategies have more limited application. Our proposals for capacity controls and emplacement strategies are set out in the '*Implementation*' report [17].

Physical and chemical processes that provide safety functions

An objective of our safety functions approach is to identify how the repository system behaves to limit the impacts of released radionuclides. A discussion of those functions is provided in the following text.

Controls for the groundwater pathway

The most significant potential impacts resulting from the transport of radioactive contaminants in groundwater arise for users of a water abstraction well between the facility and the coast. In terms of the physical and chemical barriers, the following are the key safety functions:

- During the period of operations, repository structures such as the trench interim cap, the final cap to the extent it has been constructed, cut-off wall, waste containers, container protection units and warehouses reduce the potential for water contact with the waste. All leachate that is generated in the vaults is collected but there is some potential for residual water to be released via discontinuities in the trench base layers.
- Over the institutional control period, the lease of land between the repository and the coast by the NDA will minimise the likelihood that that any water abstraction wells will not be constructed.
- After installation, the final engineered cap limits the quantity of water infiltrating the facility and hence limits the flux of contaminants from the near field.
- The vaults are designed so that any water in the vaults is released downwards rather than to any near-surface receptor. The drainage concept ensures that water does not build up at the base of the vaults, which keeps the waste dry and minimises contact between the waste and infiltrating water. As a result of the low infiltration and the drainage concept, the waste remains largely dry, and there is little equilibration between infiltrating water and the waste form.

- Several other near-field safety functions act in concert to limit the flux of radionuclides from the near field. In particular, the containers provide a substantial physical barrier to release, although their function is not represented in groundwater assessment calculations. Slow transport through the wasteform, and high pH conditions, which favour the immobilisation of certain radionuclides, also play a role in limiting fluxes.
- Transport in groundwater through the geosphere is sufficiently slow that significant radioactive decay occurs before many sorbing radionuclides reach any receptor. This means that the most significantly retarded radionuclides do not reach the surface environment.
- Significant dilution occurs within the geosphere underneath the repository, which substantially reduces concentrations of contaminants in groundwater and hence in abstracted well water.

We have undertaken a quantitative analysis of the performance of the different barriers and this is described in more detail in the '*Safety Functions*' report [11]. These calculations show the important role of the engineered cap and other near-field barriers in limiting fluxes from the near field and the importance of dilution within the geosphere.

The identified safety controls and functions ensure that the radionuclide inventory is contained in the system for as long as practicable.

Liquid discharges

During operations and the early part of the period of active institutional control, leachate will be collected from the vaults and trenches and discharged to the sea via the Marine Pipeline. Concentrations of radionuclides in the leachate are reduced by means of the same controls that limit the concentrations for the groundwater pathway during the Period of Authorisation. The Marine Pipeline extends for some distance offshore, which helps to reduce contaminant concentrations in the inshore region.

Gas

Occupants of the cap after the end of the Period of Authorisation may be exposed to radon gas, collected in buildings, and to C-14 as a result of the consumption of crops contaminated with C-14 and inhalation of C-14 bearing gases.

During the Period of Authorisation, controls will prevent agricultural activities on the cap and therefore any doses from C-14-bearing gases would only occur as a result of inhalation. During the Period of Authorisation, there may also be exposures as a result of the inhalation of tritiated water vapour released by the wastes. However, doses are very low and will reduce substantially over the Period of Authorisation because of radioactive decay.

Radon release from the wasteform is a slow process represented using an emanation factor. Radon also decays during advection from the site of generation to the surface environment above the cap. This significantly reduces released fluxes. Only 15% of radon generated is considered to be released from the waste in the trenches and 7% of radon generated is assumed to be released from the waste containers in the vaults [35]. 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 [35]. Thus the delay in radon reaching the surface environment provides an important safety function.

C-14 has a sufficiently long half-life that generated C-14 is assumed to reach the environment. As noted above, during the Period of Authorisation, active management control will preclude agriculture on the cap, which significantly limits the radiation doses that might arise from C-14-bearing gases.

The engineered cap limits infiltration into the vaults and therefore the pH is maintained at a high level. The high pH affects the release of gaseous C-14 by restricting the microbial degradation of cellulosic waste, thus limiting the formation of carbon dioxide and methane in favour of dissolved cellulose degradation products, and also by the reaction between C-14-bearing carbon dioxide and the grout. Even for graphite, for which carbon dioxide is the dominant form of C-14 released, the only releases to the biosphere will initially come from the small fraction of methane . As the dissolved organic molecules are released from the wastes into the gaps between containers, the lower pH in this environment may allow microbial degradation to produce additional gaseous C-14 releases in the form of both methane and carbon dioxide . In the hydrogen-rich atmosphere in the gaps, however, C-14-bearing carbon dioxide is likely to undergo further microbial reaction to methane.

We therefore expect that gaseous C-14 release from the cementitious vaults will be as a methane-rich gas resulting from the combination of abiotic C-14 release processes from the various wastes together with the effect of carbon dioxide gas reactions with grout and later microbial processes occurring outside the waste containers. We expect that carbonation will result in significant retention of C-14-bearing carbon dioxide in grout.

Quantitative analysis shows that only 5% of C-14 is released from graphite waste in the vaults (Figure 3.4). 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 3.5). 95% 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 3.4 for graphite).

The safety functions described above contribute to the containment of C-14 and radon in the repository system.

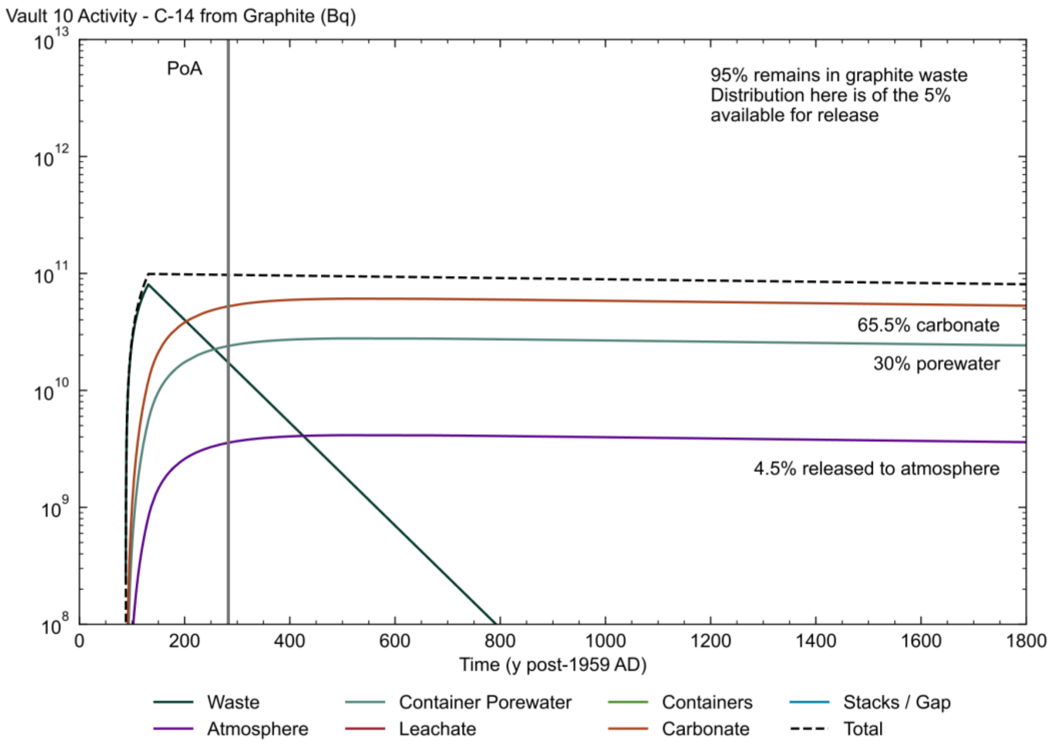

Figure 3.4: Activity distribution of C-14 in Vault 10 from graphite waste

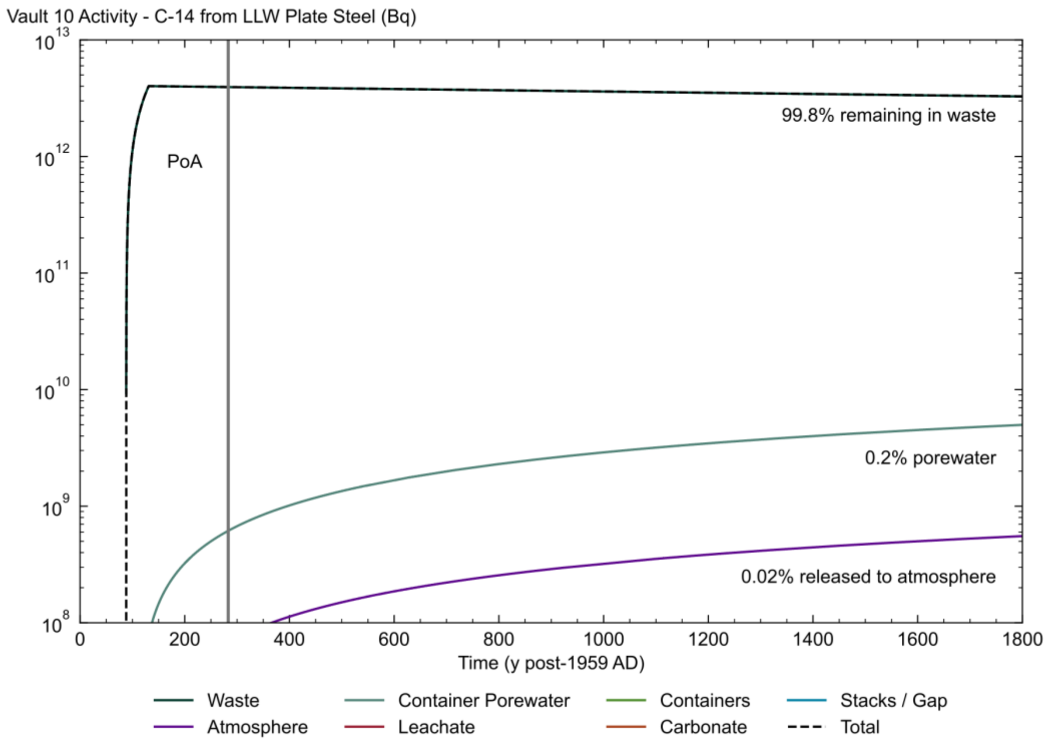

Figure 3.5: Activity distribution of C-14 in Vault 10 from plate steel

Coastal Erosion

We consider that coastal erosion of the facility will occur unless there is future intervention to prevent that happening, such as the construction of coastal defences.

If erosion occurs, those occupying the beach may be subject to radiation exposure.

We have considered the possible function of a physical barrier to erosion but have decided this is not a viable design strategy as erosion would progress around and behind any barrier and we cannot claim that the barrier will be maintained hundreds of years into the future.

The main control is through the implementation of WAC and radiological capacities to ensure impacts from coastal erosion remain consistent with regulatory guidance levels.

A barrier is provided by the Quaternary sediments between the facility and the coast. These sediments prevent erosion for some hundreds of years or more after closure. Over that period, there is significant decay of the radionuclide inventory. This is illustrated by Figure 3.6, which shows the evolution of activity over the period up until the occurrence of coastal erosion. This demonstrates that the geosphere barrier provides substantial containment with respect to this exposure pathway.

Human Intrusion

For the human intrusion pathway, the radiation doses that may arise are a function of radionuclide concentrations in extracted material and the habits associated with any particular intrusion case.

The key safety functions that mitigate impacts are those that prevent human intrusion or which reduce its likelihood. During the Period of Authorisation, active management of the site prevents any intrusion events. After the end of the Period of Authorisation, passive controls such as maintaining records and knowledge of the site reduce the likelihood of intrusion.

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) and by having sufficient depth of cap and profile fill over the wastes that certain sorts of intrusion will not occur.

The prevention of intrusion over the Period of Authorisation means that radioactive decay will significantly reduce the inventory to which any intruder might be exposed. Figure 3.6 shows the effects of the reduction in activity over the Period of Authorisation as a result of radioactive decay. We do not take account of actions to reduce the probability of human intrusion in our calculations because we present radiation doses assuming that the event occurs immediately once the Period of Authorisation ends. However, the measures identified above would be expected to reduce the number of occasions on which exposure would occur.

The measures and functions identified above contribute to isolation of the waste from the human environment.

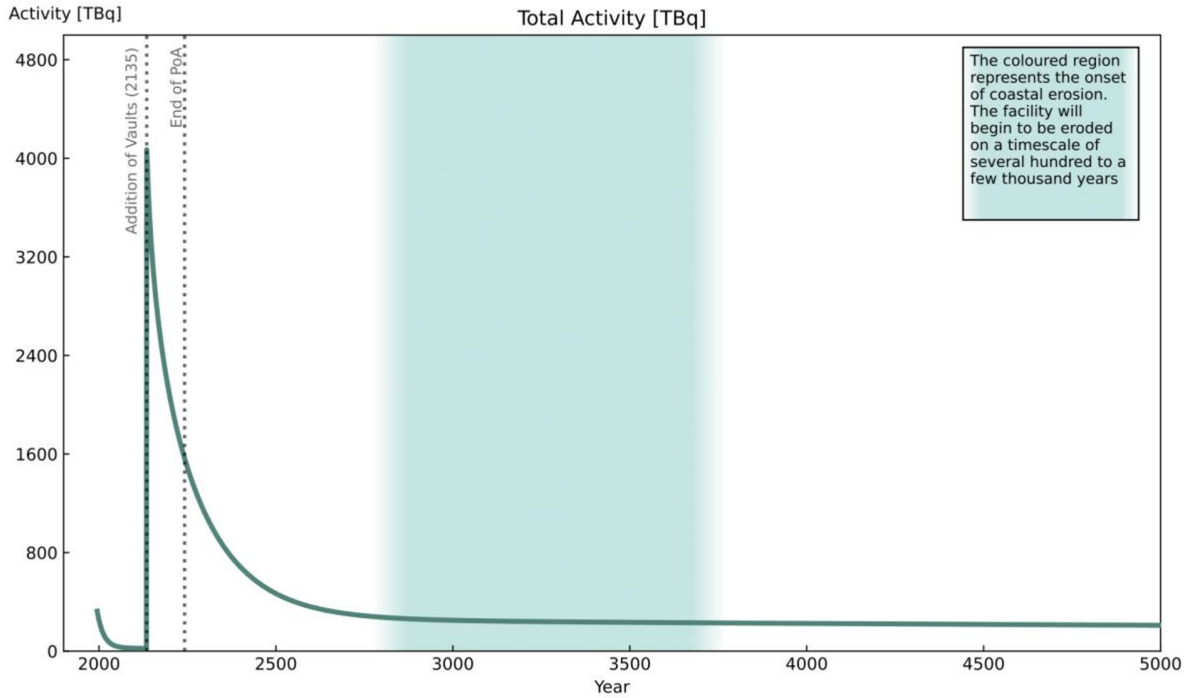

Figure 3.6: Evolution of activity for the reference inventory assuming that the trench inventory is disposed in 1995 and the vault inventory is disposed in 2135

External Irradiation

Occupants of areas outside the site boundary may receive doses from the waste as a result of external irradiation. This exposure pathway may occur up until the time when all of the waste is under a cap. Once the cap is installed, it will provide a sufficient barrier effectively to prevent further doses as a result of external irradiation.

There are a range of physical barriers that are relevant:

- grout inside the containers;
- the physical barriers provided by the metal containers and concrete container protection units;
- the site boundary, which prevents the public being in close proximity to the waste;
- the concrete vault walls;
- the soils and Quaternary sediments around the vaults;
- those parts of the cap that have been constructed at any particular time;
- shielding associated with the shielded modules, for the waste that requires it.

Our quantitative understanding of the potential roles of these barriers is presented in the '*Environmental Safety During the Period of Authorisation*' report [13]. Our current models represent some of these barriers cautiously or do not represent them all. We plan to undertake less cautious and more representative calculations in the future.

The controls and functions identified contribute to the isolation of the waste.

4 Environmental Safety Case Arguments

This section describes the structure of our Environmental Safety Case (ESC) arguments and presents the arguments under five headings:

- management and dialogue;
- system characterisation and understanding;
- optimisation and Site Development Plan;
- assessment;
- implementation.

4.1 Structure of the Arguments

An environmental safety case is a set of claims concerning environmental safety, substantiated by a structured set of arguments and evidence.

At a high level, our case is that:

- we work within a sound management framework and firm safety culture, while engaging in dialogue with stakeholders;
- we characterise and establish a sufficient understanding of the LLWR site and facility, and their evolution, relevant to its environmental safety;
- on which basis, we carry out comprehensive evaluation of options to arrive at an optimised Site Development Plan for the LLWR;
- we assess the environmental safety of the Site Development Plan, to show that impacts are consistent with regulatory guidance;
- we implement our Site Development Plan and ESC to ensure safe and optimal use of the LLWR.

This structure of high-level safety arguments, which together form the ESC, is shown schematically in part (a) of Figure 4.1; parts (b) and (c) respectively of Figure 4.1 show that each of the requirements of the GRA [29] and GRR [30] can be addressed within the structure. This is confirmed in Section 7, which summarises the relation between the GRA and GRR requirements and our arguments in more detail.

The following subsections present the safety arguments in each of the five areas. Each argument is labelled by a letter, corresponding to the area, and the number of the argument within the area.

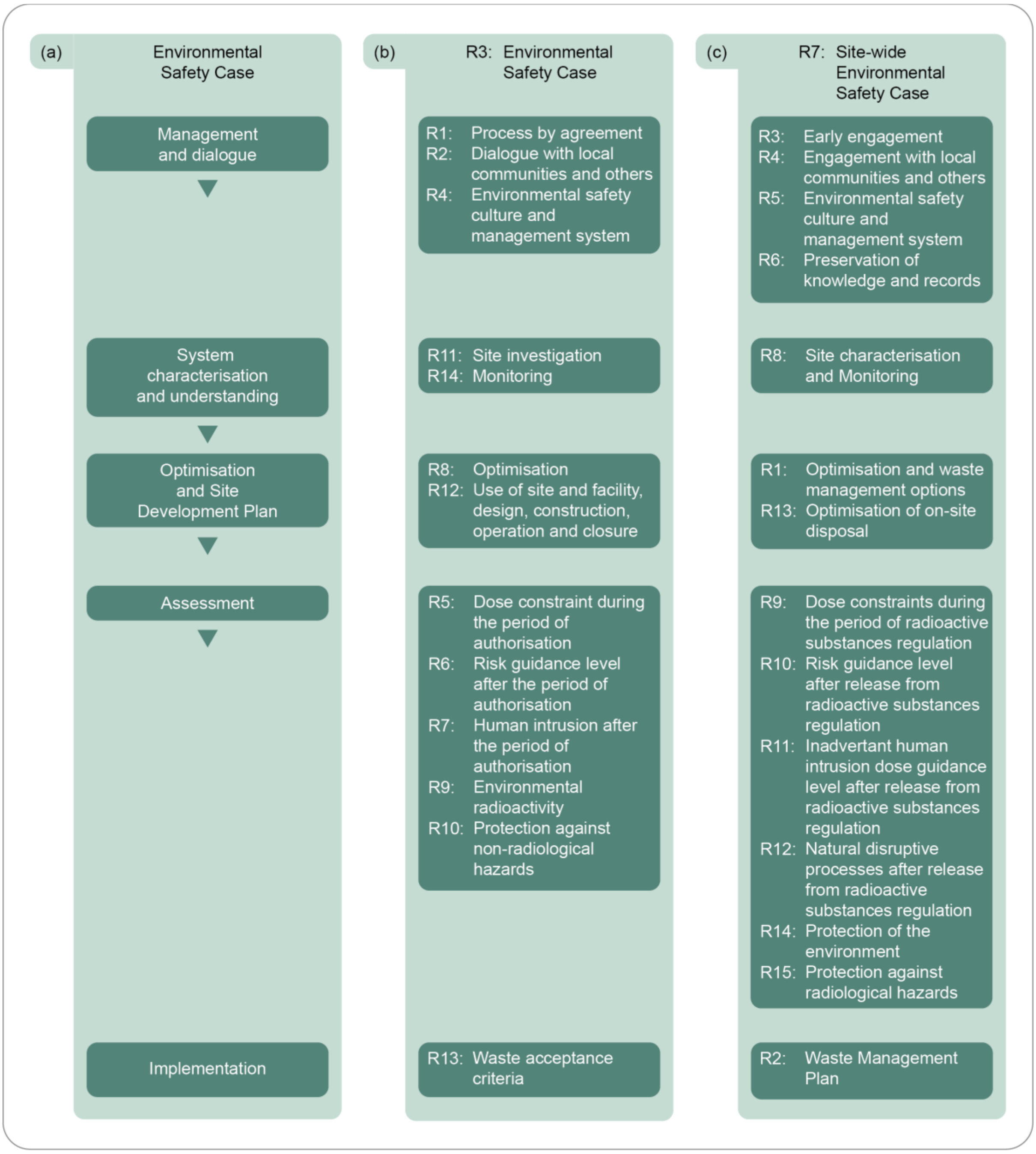

Figure 4.1: Structure of Environmental Safety Case arguments

We observe that:

- sound management, safety culture and dialogue form the essential framework within which all ESC activities are conducted;
- characterising and understanding of all aspects of the system and its evolution form the basis for optimisation and assessment activities that follow;

- Figure 4.1 presents the development of the ESC as a linear process but there will be iteration within the process and the 2026 ESC is itself only one iteration of the Safety Case, following a major review, as the facility develops through its lifecycle;
- at each stage in the lifecycle of the facility, the ESC should be sufficiently developed to support the management decisions necessary at that stage.

Figure 4.2: shows where some of the iterations between different aspects of the development of the ESC can occur. Preliminary assessments inform evaluation of options. Consideration of options and preliminary assessments may identify the need for further characterisation and development of understanding. Implementation of the engineering may require further, more detailed design optioneering. Implementation of waste acceptance controls may lead waste consignors to alter their management plans, affecting the anticipated future inventory of wastes requiring disposal.

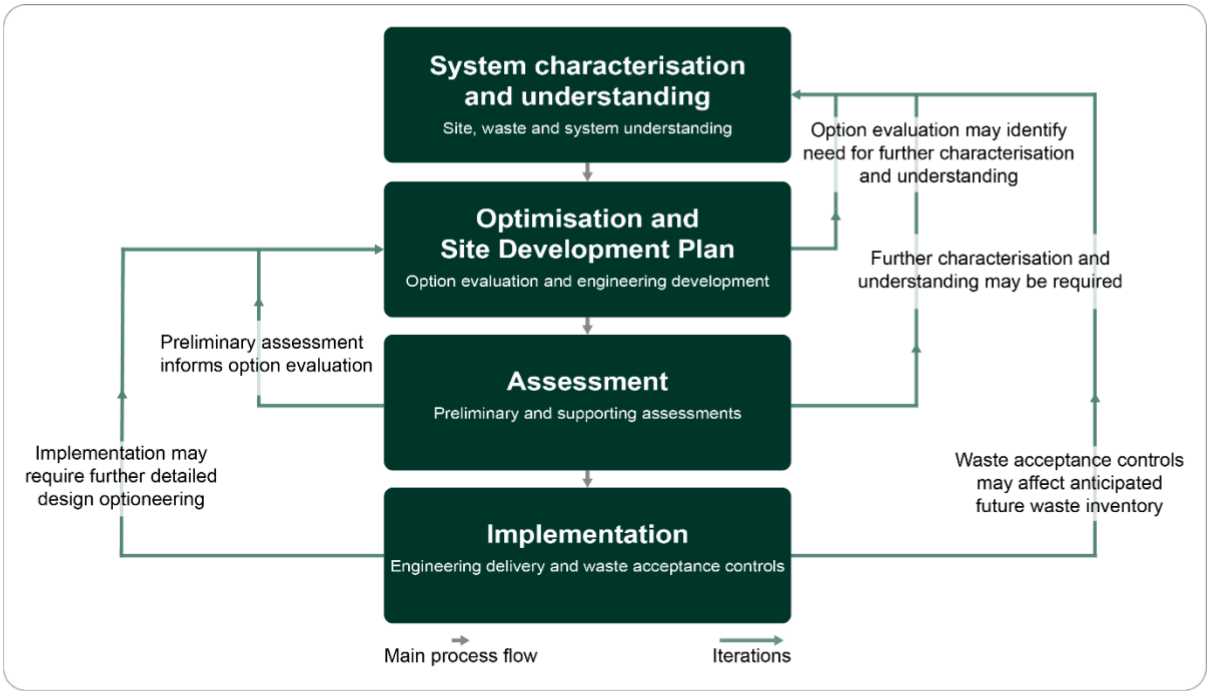

Figure 4.2: Examples of iteration in the development of the ESC

4.2 Management and Dialogue

We have established and implemented a sound management system intended to support a positive safety culture, and are committed to dialogue with our regulators, the NDA, our waste consigners, and other local, national and international stakeholders. The ESC has been produced by the ESC Development Programme. The Programme team planned and undertook a work programme to provide appropriate, accurate and timely information and results to support the development of the ESC, and for Nuclear Waste Services and NDA decision-making. Our work has been subject to peer review by an independent ESC Peer

Review Group including UK and international experts, and thorough review by a team of Nuclear Waste Services staff and contractors.

M1: Management system and safety culture

We have a sound Management System, a positive safety culture and are committed to high standards of environmental safety and quality, as formalised in our Environment, Health, Safety and Quality Policy. The ESC is managed under a dedicated procedure to ensure it is adequately maintained.

This argument relates to GRA Requirement 4 [29] and GRR Requirements R5 and R6 [30]; further support to this argument is given in Section 4 of the '*Management and Dialogue*' report [1].

We aim to achieve high standards of environmental safety and are committed to the protection of the environment and health and safety of workers and members of the public, now and in the future. Our commitment is formalised in our Environment, Health, Safety, Security and Quality Policy [36], which states that '*above all, nothing is more important to us than protecting people and the environment'*. The Policy also sets out our core values and commitments, which are acted upon to encourage a positive safety culture throughout our organisation and across our suppliers and customers. We use a range of media to communicate environmental safety messages, including training courses, meetings, e-mails and posters, as well as formal review and reporting of our performance against key environment, health and safety indicators. We place emphasis on the responsibilities all individuals in the organisation have for safety.

Environment, health, safety, security and quality matters are managed as an integral element of our Integrated Management System (IMS) and responsibility is delegated through our organisation to managers and individuals holding key environment, health and safety roles.

Our IMS, as documented in the '*Nuclear Waste Services Management System Manual*' [37], defines the structured framework of policies, processes, procedures, instructions, guidance, information systems, templates and forms required to deliver the safe, secure, environmentally responsible and cost-effective clean-up of the nuclear legacy, the management of storage and disposal of waste on the LLWR site and the subsequent decommissioning of redundant nuclear plant.

Our IMS has the following scope:

> *'Management of the UK Integrated Waste Programme for radioactive waste; Delivery of a suite of integrated waste management services and solutions; Operation and management of the National Disposal Facility; Development, management and implementation of a programme to deliver new waste disposal facilities including (but not limited to) a geological disposal facility.'*

The IMS applies to all activities we undertake, and compliance with its requirements is mandatory for all employees and contractors. The IMS ensures that we operate in accordance with:

- our documented arrangements;
- the Permit (EPR/YP3293SA) issued under the Environmental Permitting (England and Wales) Regulations 2016 [19], including the associated Compilation of Environment Agency Requirements (CEAR) and other Environment Agency permissions and consents;
- the Nuclear Site Licence, issued by the ONR;
- permissions and consents granted by local authorities;
- the governance framework of the NDA;
- international and national management system standards, including IAEA GS-R-2, ISO 9001:2015 (Quality Management Systems), ISO 14001:2015 (Environmental Management Systems), and ISO 45001:2018 (Occupational Health and Safety Management Systems), as certified by a UKAS-accredited certification body.

The IMS is governed by a comprehensive corporate governance model, with oversight from our Executive and Board Committees, and is structured as a hierarchy of governance, procedural, process-based, and supporting documents. The IMS is managed through a SharePoint-based platform, which ensures configuration control, version management, metadata assignment, access permissions and traceability throughout the document lifecycle. All IMS documents are subject to risk-based periodic review, and retention is managed in accordance with statutory and regulatory requirements.

The IMS is based on the 'Plan-Do-Check-Act' cycle and is subject to regular internal and external audits, management reviews and performance measurement through key performance indicators. These mechanisms drive continual improvement and ensure that the IMS remains effective, fit for purpose, and aligned with our strategic objectives, regulatory obligations and stakeholder expectations. Outcomes from these reviews and assurance activities inform the ongoing development and enhancement of the IMS and are reported through Business Assurance Reviews.

The IMS integrates all aspects of environmental, health, safety, security and quality management, and is designed to support the delivery of our mission to protect people and the environment, now and in the future.

The ESC is managed under a dedicated management system procedure, NWSSOP 40.07.01, which ensures the ESC is maintained and applied effectively [38]. The procedure includes:

- formal arrangements for assessing and responding to new information, implementing changes and change control;

- detailed controls on how our work is planned, managed and recorded, including arrangements for preservation of knowledge and records at the time of release from regulation;
- a tiered approach to review of the ESC, including a requirement for a major review, of which the 2026 ESC is an example;
- arrangements for implementing the ESC on the site.

M2: Management and development of the ESC

The ESC is managed under our IMS. We have carried out our programme of work for this major review of the ESC under the ESC Development Programme, according to an ordered plan that provides appropriate, accurate and timely information and results to support decisions at each stage of development of the ESC. The ESC team interacts with other LLWR teams to ensure the consistency of the ESC with other LLWR activities and to ensure other activities are aligned to meet the requirements and needs of the ESC.

This argument relates to paragraphs 6.2.22 and 6.2.25 of the GRA [29], which support Requirement 4 of the GRA. It also relates to the equivalent provisions of the GRR [30], specifically the requirements on the management of the SWESC, as set out in GRR Requirement R5, paragraph A3.31. Further support to this argument is given in Subsections 4.2 and 4.5 of the '*Management and Dialogue*' report [1].

The ESC Development Programme was established to develop this major review of the ESC, the 2026 ESC, under structured project management processes. The Programme forms part of the Waste Operations portfolio. It has been managed under our IMS, via NWSSOP 40.07.01 [38]. During the development of the ESC, the Programme has been managed by an ESC Programme team, with the ESC Manager reporting to a Programme Board including senior representatives from across the organisation and chaired by the Executive Director of Sites and Operations. This has ensured appropriate focus on the ESC within the organisation and has involved the deployment on the ESC of a team with appropriate resources and technical skills.

A phased programme of work for the ESC Development Programme was developed in 2020. This considered:

- the Environment Agency's review of the 2011 ESC [21], including twenty-nine Forward Issues [22] and 205 recommendations [23, 24, 25, 26, 27];
- Improvement Conditions in our Permit;
- learning from the development and implementation of the 2002 and 2011 safety cases;
- new information gained since the 2011 ESC, from our own work and from international research and development and developing best practice;

- uncertainties identified within the ESC;
- peer review comments on the ESC;
- the need for a SWESC and WMP.

The ESC Development Programme has remained flexible to enable it to adapt to new information and feedback, such as that received via the Process by Agreement (see argument M3) and the Peer Review Group (see argument M5). Status reviews have been held periodically to assess progress, review new information, and identify any required changes to the Programme, which were undertaken in accordance with our change control procedures. A progress report on the development of the Programme has been prepared annually (see reference [39] for the latest report). These reports have summarised progress, risks, changes to the schedule, and interfaces with other work programmes on the site. They were endorsed by the ESC Programme Board and submitted to the Environment Agency as part of the obligations of our Permit.

The ESC Development Programme has been subject to robust assurance, checking and governance [40], applied over several tiers.

- Tasks have been managed under formal quality plans, setting out proportionate arrangements for checking and review.
- Our data management procedure [41] has ensured the use of consistent data across assessments, and that appropriate governance has been applied to that data.
- Our Assessments Manual [42] has ensured a consistent approach to undertaking and documenting impact assessments.
- ESC checking procedures, including the use of a Technical Integrator, has ensured consistency within the wider ESC.
- Key documents have been scrutinised by an independent Peer Review Group, established under formal Terms of Reference.
- A technical review has been conducted by Nuclear Waste Services' Chief of Disposal Safety.
- Nuclear Waste Services' Independent Site Inspector has overseen our adherence to the assurance arrangements.

Nuclear Waste Services' Executive Director of Sites and Operations has approved the submission of the 2026 ESC to the Environment Agency, taking account of the advice of the LLWR's Nuclear Safety Committee. The Nuclear Safety Committee reviewed the top-level document of the ESC, together with the outcome of the above assurance reviews.

Presentations to the Nuclear Safety Committee during the preparation of the ESC, along with other meetings, have been used to ensure that internal stakeholders such as the Executive Director of Sites and Operations, the Design Authority and the Waste Compliance and Customer Management/Support teams are aware of the assumptions and results of the ESC and are ready to implement any required changes following the submission of the ESC.

M3: Dialogue with our environmental regulator

We communicate with our environmental regulator through submissions and reporting required under the terms of our environmental Permit, through regular liaison meetings and via a formal Process by Agreement. In particular, the regular liaison meetings and Process by Agreement have allowed us to present early technical views and findings to discuss these and thus explore the consistency of our arguments and findings with the guidance set out in the GRA as we have developed the ESC.

This argument relates to GRA Requirements 1 and 2 [29] and GRR Requirement R3 [30]; further support to this argument is given in Section 2 of the '*Management and Dialogue*' report [1].

After the review of the 2011 ESC, both we and the Environment Agency undertook 'lessons learnt' reviews. Both organisations agreed that a more formal approach to recording reviews and positions via a Process by Agreement would be beneficial for the 2026 ESC. This entailed submission of documents to the Environment Agency to gain regulatory views on the acceptability of approaches, methods and options as they were developed. We have also held meetings to discuss technical topics with the Environment Agency to brief it on our developing arguments and gain its feedback. The Process by Agreement has provided valuable insight, and led us to change several technical positions, such as our position on climate change scenarios, the definition of representative persons, and several details of our radiological impact assessments.

In addition to the Process by Agreement, we have held regular liaison meetings involving the ESC team, the Environment Agency and the ONR. These meetings also include updates from the LLWR site environmental monitoring team, where any results from the programme that could affect the ESC are also discussed. The ESC Peer Review Group (see argument M5) has also had meetings with the Environment Agency to discuss the peer review process.

We also hold a series of regular formal engagement meetings, structured from Level 4 to Level 1 (the liaison meetings mentioned above are Level 4 meetings). These meetings are held between different members of the organisations and discuss progressively more strategic topics. The ESC Manager attends the LLWR Level 3 and 4 meetings.

Alongside the routine regulatory interactions linked to running a permitted site, such as sharing updates to processes, procedures and management systems, and supporting regulatory inspections, we have also engaged with the Environment Agency on more strategic topics. We have responded to its consultation on the, now issued, GRR (May

2016), the methodology of the Joint Agencies Groundwater Directive Advisory Group (May 2016) and proposed revisions to the GRA[8] (March 2025).

M4: Dialogue with our stakeholders

We attach a high priority to stakeholder engagement and the views of our stakeholders are sought and taken into account. We will continue this dialogue to ensure stakeholders understand the conclusions of the ESC and that any concerns are identified and considered in planning the future development of the ESC.

This argument relates to GRA Requirement 2 and GRR Requirement R4; further support to this argument is given in Section 3 of the '*Management and Dialogue*' report [1].

We engage with a broad range of stakeholders who have an interest in the LLWR site, and our programme of dialogue reflects the differing roles, responsibilities and information needs of each group. Dialogue is maintained throughout ESC development, building on established practices from previous ESC cycles and recognising that the 2026 ESC represents an update to a mature, live case rather than a new submission. Once the 2026 ESC is submitted to the Environment Agency, we will use our established engagement channels to brief stakeholders on the submission and its implications.

Our relationship with the NDA is central to the overall governance of the LLWR. The NDA owns the site, provides funding for its operation and participates in discussions on matters such as waste disposal capacity and national strategy. Engagement takes place through regular meetings and technical exchanges, and the NDA contributes to the West Cumbria Site Stakeholder Group (WCSSG), providing national and policy-related updates. The NDA also interfaces with government departments such as Department of Energy Security and Net Zero, while we respond directly to consultations relevant to the ESC.

Engagement with regulators, including the Environment Agency, is delivered through a structured meeting framework managed by the Environment, Health, Safety, Security and Quality team and supported by participation in community events, WCSSG meetings and liaison with Parish Councils. This ensures that regulatory dialogue is embedded within wider local engagement. Cumberland Council, as the planning authority, is engaged on planning applications, future land use and development of the new Cumberland Local Plan, with liaison meetings held as required and further interaction through an NDA-led working group.

We work closely with waste consignors who rely on LLWR capacity for disposal of radioactive waste. Dialogue is maintained through our Customer Management/Support, Waste Compliance and ESC teams, including assurance work and support on specific consignor challenges. Where changes to waste acceptance arrangements are proposed, early engagement takes place wherever possible, and any changes with potential

[8] The 2026 ESC has been prepared against the requirements stated in the current 2009 version of the GRA.

implications for Permit compliance are managed through the controlled process set out under NWSSOP 40.07.01 [38].

Engagement extends to national and international organisations, including the Nuclear Legacy Advisory Forum, the Radioactive Waste Planning Group, non-governmental forums, and international waste management bodies. These interactions take the form of workshops, site visits, technical exchanges and participation in research programmes, providing opportunities to share information, discuss policy or operational developments and gain insights into international practice.

Local community engagement is supported by the Community Engagement team, who provide updates on site activities and maintain direct channels for enquiries. The WCSSG working group remains an important mechanism for discussing LLWR operations and ESC progress with local representatives, regulators and community organisations. Additional engagement includes meetings with Parish Councils, community drop-in sessions, site tours and outreach in local education. Communication is supplemented by newsletters and targeted notifications for activities that may affect local residents, along with updates via the Nuclear Waste Services community webpage [43].

Certain aspects of the ESC require focused engagement with specific stakeholders, including the understanding of current and future waste inventory, cap design, capacity management and potential changes to WAC, and planning for site development and remediation.

Following submission of the 2026 ESC, the ESC and a Guide to Key Points [44] will be published, with stakeholders notified in accordance with the engagement plan. Substantive feedback will be shared with the Environment Agency and considered in future ESC updates.

Overall, this programme ensures that stakeholders receive information relevant to their responsibilities and that their perspectives are incorporated into the development and communication of the 2026 ESC.

M5: Peer review

The ESC approach and documents have been exposed to extensive internal reviews and independent peer review processes, involving constructive discussions and critical appraisal. Peer review comments have been responded to and taken into account in the development of the ESC.

This argument relates to paragraphs 6.2.40 of the GRA (in support of Requirement 4) and 2.3.14 of the GRR; further support to this argument is given in Subsection 4.4.3 of the '*Management and Dialogue*' report [1].

As part of our arrangements for managing the ESC, a Peer Review Group provides independent challenge of the ESC and constructive advice. The Peer Review Group consists of experts of longstanding experience and strong reputation, with a balance of expertise reflecting the multidisciplinary nature of the ESC. It is formed of individuals from within the UK and overseas, who are independent of the development of the LLWR's ESC. They are established under a formal Terms of Reference [45]. The scope of the Peer Review Group's work focuses on issues that are important to the ESC:

- The environmental risks associated with the LLWR, its operations and post-closure performance.
- The development and evaluation of options that may be available to promote the safe and efficient use of the LLWR.
- The clear presentation of evidence and arguments that must be achieved within the ESC.

The objectives of the Peer Review Group are to [45]:

- provide a timely independent review of key technical approaches, arguments, designs, assessments and documents that form components of the developing ESC and associated stakeholder engagement;
- work in such a way that it can be demonstrated to stakeholders that an effective and proportionate process of independent technical review and scrutiny is operating.

Meeting records, compiled comments, Peer Review Group reports and ESC team responses have been generated as appropriate to provide a clear record of the activities of the Peer Review Group. On a periodic basis, the Peer Review Group issue a summary report, to which we have respond. Peer Review Group comments since the 2011 ESC formed an important input to the Development Programme for the 2026 ESC.

During preparation of the 2026 ESC, the Peer Review Group's role increased. Level 1 and 2 documents were reviewed. For each review, the Peer Review Group submitted detailed written comments, which were formally addressed by report authors and taken into account in the development of the documentation. Meeting records, compiled comments, Peer Review Group reports and ESC Team responses have been generated as appropriate to provide a clear record of the activities of the Peer Review Group. A final report of the Peer Review Group, including the Peer Review Group's view on our response to their comments, has been issued to support the 2026 ESC [46, 47]. The overall conclusion of the Peer Review Group was that the 2026 ESC is of a high technical standard and demonstrates that the facility is presently safe and that future impacts will comply with regulatory guidance. The detailed observations made by the Peer Review Group have either been addressed or will be considered in the development of the future work programme for the ESC.

We also sought peer review and peer input from other NDA group operators on specific topics, including on our WMP, site end state and institutional control approach.

Opportunities have and will be taken to present aspects of the ESC and its underpinning programme of work to a wider technical audience through attendance at conferences. This will result in additional scrutiny and review of aspects of our work.

4.3 System Characterisation and Understanding

Through our programmes of site investigation, measurements, research and detailed modelling, we have developed a sufficiently detailed and reliable description of the waste inventory, engineered system and near field, geology and hydrogeology, and coastal and surface environments to support both our evaluation of options for development of the site and assessments. In particular, this understanding is sufficient to support our estimates of performance required for comparison with regulatory guidance levels, and plans for future acceptance of waste at the facility.

S1: Characterising and understanding the wastes

We have developed a sufficiently detailed and reliable description of the wastes disposed at the site, and wastes that could be disposed of at the site in future, to support our evaluation of options and assessment calculations, and the derivation of controls on the nature and quantities of waste to be accepted at the site.

This includes the consideration of the uncertainties associated with past disposals and future wastes.

The description covers both the radiological and non-radiological components of the wastes.

We have made improvements to the inventory as a result of work undertaken since the 2011 ESC.

The resulting Reference Inventory represents our best estimate projection of the LLW to be disposed of at the LLWR, based on information in the United Kingdom Radioactive Waste Inventory (UKRWI), and an estimate of the ILW that might be accepted if a decision is taken to accept ILW for disposal to make best use of the volumetric and radiological capacities of the site.

This argument relates to GRA paragraphs 5.4.6, 6.2.3, 6.2.34 and 9.9.2 [29]; further support to this argument is given in the '*Disposal Facility Inventory'* report [3].

We have derived a Reference Inventory that provides a best estimate projection of the waste that can be accommodated at the LLWR whilst making best use of volumetric and radiological capacity and ensuring environmental safety. This inventory consists of the existing disposals to the trenches and existing vaults, plus a forward vault inventory developed from the 2022 UKRWI [48]. Future wastes that are included in the Reference Inventory have been assessed against provisional capacity constraints derived from the ESC and take into account assumptions on waste treatment and diversion.

Since the 2011 ESC, we have enhanced the reliability and accuracy of the disposed inventory through a review of the trench inventory, rederivation of the disposed vault inventory, and the introduction of improved tracking systems and waste consignment information, increasing the level of detail, accuracy, and confidence in the inventory and associated uncertainties.

We have based the inventory for future wastes on the 2022 UKRWI, which provides forward inventory information from 1st April 2022, and information on waste streams associated with the nuclear new build programme that were not included in the 2022 UKRWI.

The Reference Inventory for the 2026 ESC has been developed iteratively. The Stage 1 and 2 Inventories were used for different phases of the assessment calculations. The Stage 3 Inventory was developed most recently. It was used, as described in the '*Implementation*' report [17], when considering the practical approach to setting capacities.

The Reference Inventory includes all LLW reported in the UKRWI that could potentially be suitable for disposal at the LLWR, following a systematic screening approach. We consider this to be a cautious assumption. We have excluded waste streams with established alternative disposal routes, specifically: VLLW designated for disposal at authorised landfills, Dounreay and Vulcan LLW routed to local facilities and one waste stream containing contaminated mercury.

Conversely, we have included LLW streams where the LLWR may represent the most appropriate or only available disposal option, including 'Orphan' waste streams where no specific disposal route is identified in the UKRWI. This inclusive approach ensures the Reference Inventory represents a comprehensive assessment of potential waste activities and volumes, enabling evaluation of optimal disposal routes during the waste acceptance process.

We have also included an estimate of the quantities of ILW that might be accepted if a decision is taken to accept ILW for disposal at the LLWR. This allows us to assess the potential impacts of disposal of ILW at the facility and thus informs consideration of adopting the option to dispose of a broader range of waste and make optimal use of the site's volumetric and radiological capacities. If a decision is taken to accept ILW, any ILW considered for disposal would be assessed against waste acceptance controls in place at the time. Some ILW was excluded from consideration in the inventory, including streams covered by the Scottish Higher Activity Waste Policy [49]. We have assessed ILW streams against individual waste stream constraints derived from ESC and Nuclear Safety Case radiological assessment calculations. We have also calculated for each waste stream the fractional use of site radiological capacities. ILW streams were included in the inventory if they passed the waste stream constraints and fitted within the radiological capacities, and would make best use of the disposal volume. Inclusion of an individual waste stream in the inventory does not reflect a position on its acceptance.

The ILW included in the inventory is generally of a similar nature to the LLW included, that is, it has a similar material and radionuclide composition albeit at a higher concentration.

The ESC requires an understanding of the impacts that might arise from non-radiological contaminants associated with the waste. Knowledge of the non-radiological contaminants present in the inventory is less well-developed than for the radiological inventory, although the situation has improved for recent and future disposals given improved characterisation requirements and practices. For the disposed inventory (pre-2022), non-radiological contaminant data are only available from 2016 onwards when systematic data collection began, with no estimates provided for earlier disposals. The disposed vault inventory relies on as-declared values for such components from Waste Consignment Information forms since 2016, while the forward inventory uses data as reported in the 2022 UKRWI for 46 identified materials that may be associated with non-radiological contaminants. We use bulk material data from the Reference Inventory, together with informed assumptions about material composition and declared information on non-radiological contaminants, to derive a source term for use in our Hydrogeological Risk Assessment [15].

Overall, we have developed an adequate knowledge of key disposals to the trenches and the inventories and uncertainties associated with current and future disposals to the vaults to support our optimisation, assessments and development of waste acceptance controls. Certain areas have been identified where the UKRWI could be improved, for example with respect to information on chemotoxic substances. Although uncertainties exist and have been treated, assurance that the disposed inventory will not exceed acceptable limits is provided by the identification and implementation of appropriate capacity constraints (see argument I2). We will also review waste receipts and future national inventories to determine any changes in the projected disposal inventory and where appropriate we will take account of such information in updating the ESC.

S2: Characterisation and understanding of the near field

We have developed a sufficiently detailed description of the near field, including the engineered features, and its possible evolutions, to support our evaluation of options for site engineering and assessment calculations.

This includes detailed quantitative modelling of the geochemical regime as it will change over time.

This argument relates to GRA Requirements 4, 6, 8, 11, 13 and 14 [29]; further support to this argument is given in the 'Engineering Design' [4] and '*Near Field'* [5] reports.

The 'near field' means the engineered features of the repository, all of the materials contained within the repository including the wastes, and any associated soils and sediments within the envelope of the facility. The near field provides several important safety functions limiting the release of contamination via the groundwater and gas pathways:

- The repository cap and other engineered barriers will act to reduce the infiltration of water through the trench and vault regions and contribute to the maintenance of partially saturated conditions for more than one thousand years.
- Chemically reducing conditions will stabilise uranium and technetium in their (IV) oxidation states, leading to lower concentrations in groundwater than would be the case for higher oxidation states.

- Cementitious grout in the vaults is used to reduce voidage. The grout provides an effective substrate for sorption. C-14 is incorporated in the cement grout by carbonation, reducing the release of C-14-bearing species in gaseous and aqueous media.
- During the Period of Authorisation, the ISO containers in the vaults are expected to provide substantial containment against water-borne releases. Any leachate accumulating in the repository outside the containers during the period of active leachate management will be pumped or drained away and disposed via an appropriate authorised discharge route, currently the Marine Pipeline.
- The facility is designed such that, after the end of active leachate management, any leachate is released to groundwater underneath the site, rather than directly to the surface.

Evolution of saturation

The engineered features that will be installed as part of the closure of the LLWR will strongly influence the extent of water flow through the near field and its pathway through the wastes – Figure 4.3 provides a simple schematic of the engineered features. A final cap will be installed, and recharge below it will be very low initially, leading to drying conditions, especially within the vaults, and a lowered water table locally. This cap will degrade over more than one thousand years, recharge will increase, and the local water table will rise within the trenches. Within the vaults, unsaturated conditions in the gaps between the stacks of containers will persist for much longer. We have developed an understanding of the physical evolution of the near field based on several lines of evidence, including detailed groundwater flow calculations and estimates of physical degradation rates for the engineered features, which were elicited as part of our Engineering Performance Assessment [12].

Initially, the vault bases will have low permeability and will degrade only slowly once the cap is installed. After the cap has degraded sufficiently to allow increased infiltration, and saturation of the grout in any failed containers, the water level will begin to rise inside the future vaults. Should it reach the top of the one-metre-high vault walls, this water will flow over the walls to drainage blankets under the vaults and into the underlying geology. Vaults 8 and 9 will be engineered to ensure they behave in a similar way. The slow degradation of the vault bases and walls is expected to allow more flow through these features. The cut-off wall will be extended around the facility. This will significantly reduce groundwater flows to the vaults and trenches.

The trench wastes and the vaults will remain partially saturated for a period of more than one thousand years after closure, most likely to the time of onset of disruption by coastal erosion.

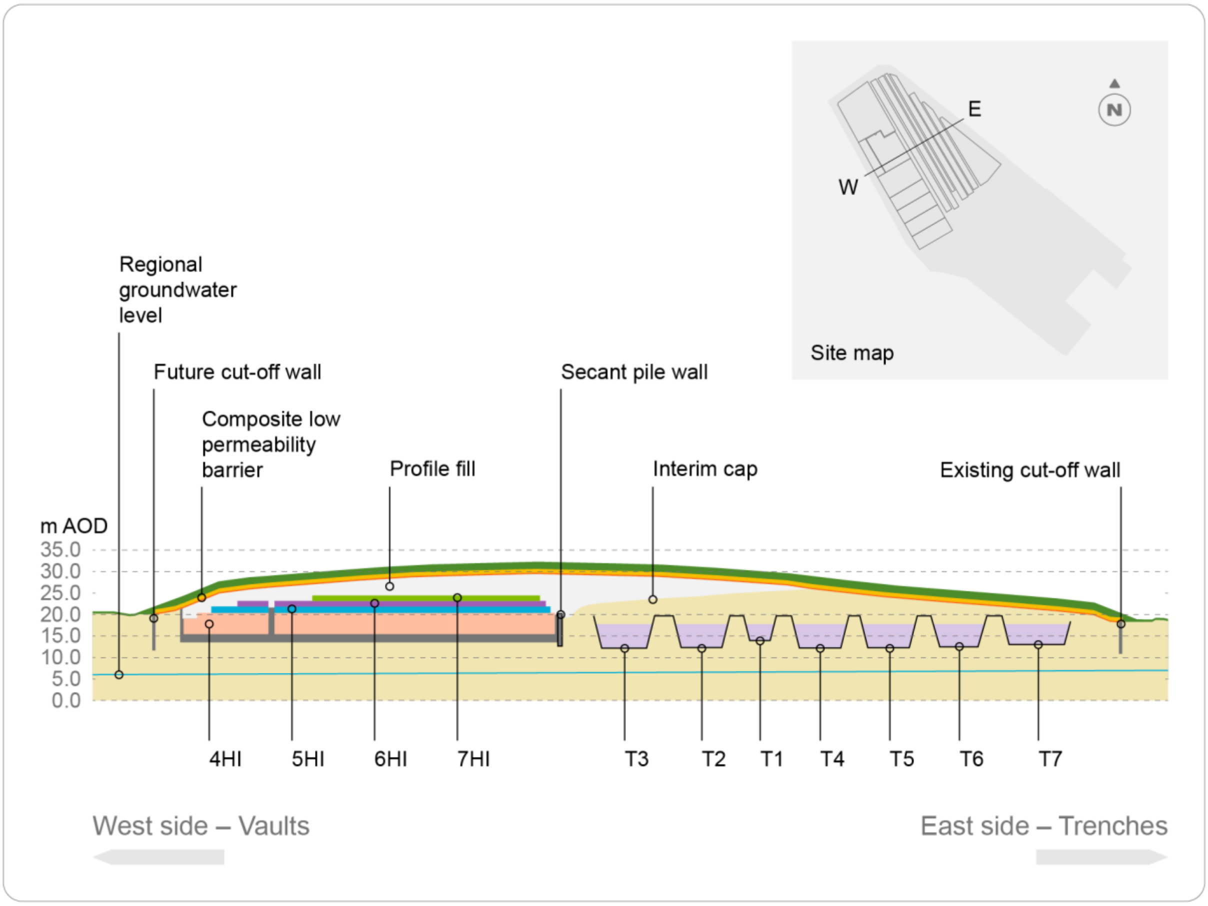

Figure 4.3: Key engineering features

Evolution of chemical processes in the trenches

The main chemical processes and phases of evolution that will occur in the trenches are summarised as follows:

- Degradation of cellulosic wastes in trench disposals will lead to mildly acidic and sulphate-reducing conditions developing early and lasting from around 1,200 years to several thousand years in different trenches.
- Cellulose degradation and metal corrosion will result in the generation of gas, predominantly methane and hydrogen. The large amount of corroding metal in the trenches will ensure reducing conditions are maintained even after cellulose degradation has slowed.
- Once corrosion has largely consumed the metal and cellulose is similarly exhausted, the chemical conditions in the trenches will reflect the infiltration of rainwater, becoming more oxidising.
- Uranium concentrations in the leachate will increase during re-oxidation, although some less soluble trench wastes, such as fluoride residues, will limit uranium release even under oxidised conditions.

- The C-14 in the trenches is mainly released in the first few hundred years in the form of gas.

Evolution of chemical processes in the vaults

The main chemical processes and phases of evolution that will occur in the vaults are summarised as follows:

- Anaerobic corrosion of the containers and waste metals will result in a long period when water consumption exceeds infiltration and releases from most containers are restricted to gaseous radionuclides. The atmosphere of the vaults will be hydrogen-dominated.
- The slow corrosion rate of the containers means that many of the stronger containers with container protection units will have a period of integrity of several thousands of years (in the absence of coastal erosion). Surcharged containers in Vaults 8 and 9 will be damaged but will still present a significant barrier to contact between infiltrating water and the wastes.
- Within the wastes, the grout porewater is initially extremely alkaline with conditions up to pH 13.5. Over time, the pH will fall slightly but, in most of the grout, the conditions are expected to remain at pH 12 or above until the onset of coastal erosion. These hyperalkaline conditions will restrict microbial activity to organic-rich, isolated niches.
- Cellulose degradation will proceed largely by alkaline hydrolysis, with no gas generation from microbial processes. Without microbial degradation, the concentration of ISA (iso-saccharinic acid) will increase within the grout until cellulose is degraded by around 1000 years. The formation of ISA-metal complexes will affect the solubility and sorption of some radionuclides.
- In the unsaturated gaps between container stacks, the composition of infiltrating water will be conditioned by the bentonite in the bentonite enhanced sand layer of the cap. Contact with the containers and iron corrosion products will ensure very low Eh. With limited interaction with the grout, however, the pH will be below 10.
- Under the low pH conditions in the gaps, microbial activity could occur, resulting in metabolisation of cellulose degradation products. This is likely to affect the stability of ISA and EDTA (ethylene-diamine tetra-acetic acid) complexes, particularly where concentrations are highest.
- While the low Eh and high pH conditions in the grout will favour low solubility of uranium in the U(IV) form, the presence of ISA will increase its release rate from the grout due to the formation of ISA complexes. This affects the timing of uranium release, which will be linked to the generation of ISA.
- Technetium will be controlled by sorption processes at low aqueous concentrations below the solubility limit of Tc(IV).

- With C-14 in the vaults, there will be an early peak in gas release but then gaseous releases will fall. Most of the C-14 released from the wastes in the vaults will be retained in the grout as carbonate minerals or in the porewater as dissolved organic species. Microbial metabolisation of dissolved organic C-14 species released into the gaps could result in further gaseous C-14 releases. However, the low carbon concentration means this is uncertain unless there are other organic carbon sources, such as cellulose degradation products, available.

Main uncertainties

A major uncertainty in the trenches is the rate of gas generation. This uncertainty affects the long-term trench evolution, since the rates of gas-producing reactions influence the duration of reducing conditions. It affects the requirements for a gas vent in the cap and related decisions, such as whether the vent can be safety closed at the end of the Period of Authorisation. Probably most importantly, it also affects a key input into the radon gas assessment, since radon is transported by advection in the bulk gas phase. The uncertainty arises from a combination of individual uncertainties such as the inventory of reactive materials, the form of the wastes, for example, the metal surface area available for corrosion, and the rates of cellulose degradation and metal corrosion.

We have deliberately chosen cautious parameters and assumptions in our simplified model of bulk gas generation so that we overestimate gas production. As a result, we are confident that the input to the assessment is also cautious. However, we plan to revisit the gas modelling in future to investigate more fully the impacts of our data choices. This will provide better support for the development of a gas management strategy and future optimisation of the vent system.

The key uncertainty in the vault near-field is the extent of microbial activity in the low pH environment of the gaps. This affects the mobility of uranium and other contaminants that are vulnerable to ISA complexation, as well as the generation of secondary C-14 gas releases.

In modelling uranium mobility, we have cautiously neglected the potential for degradation of the ISA and destabilisation of the uranium complexes, which would reduce uranium releases by allowing retention in the gaps due, for example, to sorption on iron corrosion products.

In the assessment of C-14 gas releases, we have assumed that all dissolved C-14 species released to the gaps are metabolised to maximise C-14 releases to the gas phase. In contrast, in the assessment of C-14 releases to groundwater, we assume there is no secondary C-14 gas generation in the gaps. We acknowledge the inconsistent approach for the two assessments but justify it because we have no information that allows the partition between water and gas phases to be quantified. In reality, the conditions in the gaps will be heterogeneous so that microbial metabolisation will occur in areas where the concentrations of dissolved carbon species, and other nutrients, are high enough to support an active microbial population.

Near-field understanding in support of the assessment models

The understanding we have developed of the evolution of the near field and the engineered barriers is considered an appropriate basis for the assessment models of the near field in the program GoldSim [50]. These models have been used as the basis for determining the release of radioactive gases and dissolved contaminants in groundwater from the near field as well as the impact of human intrusion events.

Our analysis of the near field provides:

- a detailed 3-D groundwater flow model with a representation of the engineered features that was used to investigate the detail of saturation evolution in the engineered system and local geosphere;
- a suite of reactive transport models, from single container to site-scale, that was used to investigate the range of processes involved in the physical and chemical evolution of the near field;
- a model of dissolved contaminant release from the vaults that can account for the effects of heterogeneous flow system with saturated grouted wasteforms surrounded by unsaturated gaps;

models for radioactive gas release to the biosphere that can account for the relevant near-field processes associated with the unsaturated conditions and bulk gas generation.

S3: Characterising and understanding the geology and hydrogeology

We have developed in-depth descriptions and models of the site's lithology, stratigraphy, geochemistry, hydrogeology, and resource potential, and thoroughly assessed dynamic processes such as climate change, sea-level rise, and coastal erosion to support both our evaluation of options for the development of the facility and assessment calculations.

Our work has included the development of conceptual and 3-D geological and hydrogeological models based on a large, high-quality dataset and validated through calibration and iterative refinement, ensuring a robust understanding of the site's behaviour under current and future conditions. We have undertaken explicit uncertainty analysis and management, quantifying the effects of uncertainties in our geological and hydrogeological models and incorporating these into our safety assessment.

This argument relates to GRA Requirement 11 (paragraphs 6.4.7, 6.4.8, 6.4.9, 6.4.10, 6.4.11 and 6.4.13 to 6.4.15) [29] and GRR Requirement 8 (paragraphs A4.12 to A4.15 and A4.17) [30]; further support to this argument is given in the '*Hydrogeology'* report [6].

We have implemented a comprehensive and proportionate approach to site investigation and characterisation, as required by both the GRA and GRR. Our iterative programme has included both intrusive and non-intrusive investigation methods − such as boreholes, trial pits, cone penetration tests, geophysics, LiDAR, and aerial photography − which has enabled us to progressively build knowledge of the site's geological and hydrogeological setting. Although there have been advances in the geological and hydrogeological understanding since the 2011 ESC the basic stratigraphy has not changed. The site is still understood to consist of thick Quaternary deposits (up to ~70 m) overlying Sherwood Sandstone Group bedrock, with the Helsby Sandstone directly beneath the Quaternary sequence.

A 3-D geological model has been developed that provides the framework for hydrogeological modelling. Since 2011, we have incorporated a substantial amount of new hydrogeological data into our understanding and models. This includes from additional boreholes, updated groundwater and surface water monitoring, and new hydrogeochemical analyses. The hydrogeological conceptual model has been reviewed; however, the core elements remain consistent with 2011 ESC. Groundwater flow is still understood to occur primarily within the Quaternary deposits and the upper part of the bedrock, down to less than 100 meters depth. It is divided into Upper and Regional systems. The flow in the Upper Groundwater is predominantly downward through clay rich deposits where it joins the Regional Groundwater. The overall direction of groundwater flow in the Regional system is still from higher ground inland toward the coast, through sand and gravel deposits, driven by the hydraulic gradient between inland recharge and sea level (see Figure 2.8).

Combined with the 3-D geological model, the hydrogeological conceptual model has been used as a basis for the development of hydrogeological models that simulate current and future groundwater behaviour, contaminant pathways, and the impact of engineered features such as caps, cut-off walls, and vaults. The models account for the staged construction and degradation of these features, as well as future site evolution scenarios, including climate change, sea-level rise, and coastal erosion. This enables us to simulate how groundwater pathways and contaminant migration may change over time, and to demonstrate the resilience of the repository's engineering to foreseeable future changes over the next few thousand years. The hydrogeological models provide input data to the groundwater pathway assessment model.

We have undertaken additional work to assess the effects of hydrogeological uncertainties at the LLWR site, including in bulk permeabilities; heterogeneity; bedrock faulting; offshore and internal structure of the confining unit; near-surface and recharge variability; and saline intrusion. Whilst there are variations in flow paths associated with these uncertainties, we can demonstrate that the overall pattern of flow is unaffected and that the representation of the groundwater pathway in the safety assessment is robust.

S4: Characterising and understanding the coastal environment

We have developed a sufficiently detailed and reliable description of the coastal environment, and its possible evolution, to support our evaluation of options for development of the site and assessment calculations.

Our understanding is based on characterisation of the Cumbrian coastal and near-shore environment, monitoring of changes occurring now, preserved evidence of past evolution, and modelling of future coastal recession taking account of an envelope of estimated global and local sea-level rises.

Based on qualitative evidence and quantitative modelling studies, we have concluded that the disposal vaults will begin to be eroded on a timescale of several hundred to a few thousand years, with consequent disruption of the repository, with erosion of the vaults and trenches being complete within one to a few thousands of years.

This argument relates to GRA Requirement 11 and also GRA paragraphs 6.4.14, 7.2.1, 7.3.29 and 7.3.32 [29]; further support to this argument is given in the '*Site Evolution'* report [7].

The LLWR site lies mainly between about one half to one kilometre from the coast. At its north-western corner, the disposal area is only about 350 m from the present-day coastline. The site is vulnerable to coastal erosion; therefore, the characterisation and understanding of the coastal environment is a key concern for the ESC.

Over recent decades, we have undertaken a substantial programme of scientific research and monitoring to characterise the current coastal system and to provide a basis for forecasting its future evolution. Data acquisition and characterisation activities have included:

- Characterisation of the current coastline, the wave regime and its effect on the dispersion of sediments (hydrodynamics) and surveys of the coast (for example, aerial photography, LiDAR imaging and beach surveys).
- Interpretation of paleo-evidence placing bounds on how the coast has developed over the last ten thousand years, including studies of Holocene sea-level change and more recent surveys to understand current rates of change.
- Characterisation of the coastal geomorphology and understanding the constraints placed on future coastal evolution, for example the development of the estuary to the south of the LLWR site.
- Geophysical investigation and geological characterisation of the Drigg spit and the area between the LLWR site and the coast, to aid interpretation of shallow geological stratigraphy and sediments.

We have also undertaken work to understand the implications for sea-level rise of climate change for the LLWR site, using IPCC[9] and IAEA[10] [51], and UKCP[11] studies. IPCC scenarios for global greenhouse gas emissions only extend for a few hundred years in the future, and we have thus extended them to the timescales considered by the ESC. The

[9] Intergovernmental Panel on Climate Change

[10] An international project for assessing the potential impacts of long-term climate change on biosphere characteristics

[11] UK Climate Projections, provided by the Met Office.

scenarios selected for consideration in the 2026 ESC are associated with the following carbon dioxide emissions:

- Reference Emissions Scenario: carbon dioxide emissions remain at current levels until mid-century before declining.
- Low Emissions Scenario: carbon dioxide emissions decline rapidly, reaching net zero after 2050, followed by net negative emissions.
- High Emissions Scenario: carbon dioxide emissions roughly double by 2050, peaking around 2090, with high atmospheric concentrations persisting.

Relative sea-level rise at the LLWR site is projected to reach 10 metres (Reference), 23.3 metres (High), or 0.7 metres (Low) above present in the next 10,000 years [7].

These projections are derived from models that integrate both global and local factors influencing sea level. Global eustatic changes, such as thermal expansion of ocean water due to increased temperatures and the melting of polar ice sheets, are combined with the effects of local isostatic adjustments, diminished to a small degree by expected tectonic uplift of North-west England.

Confirmation that such rapid sea-level changes are credible comes from scientific reconstruction of temperature changes and sea level during the last interglacial (Eemian) period at about 130,000 to 115,000 years before present. In this period, global sea level probably peaked at between 6.4 and 8.7 m above the present-day level and the maximum rate of sea-level rise was large, almost certainly at least 5.6 m per 1,000 years. This arose from contributions from losses from melting of both northern and southern hemisphere ice sheets, showing that both the Greenland and West Antarctic ice sheets are unstable against moderate global warming.

These rates of sea-level rise are outside the range seen in the Holocene (from about 12,000 years ago to the present). Therefore, extrapolation of currently observed recession or reference to local paleo-evidence is only sufficient to estimate future rates of erosion on the Cumbrian coast under the Low Emissions Scenario. Therefore, two coastal recession models have been applied to estimate erosion of the coast adjacent to the LLWR taking account of the estimated range of future sea-level rises:

- An empirically-based coastal recession model, developed to estimate coastal erosion in the context of coastal forecasting, protection and planning.
- A more detailed process-based model, developed as a research model to describe the erosion of coasts comprised of material such as till and soft rock.

Both models are calibrated from coastal recession data, although mainly from the east of England, against lower rates of sea-level rise and periods of only decades. Both models have been applied for the Reference, Low, and High Emissions scenarios. Results from these models indicate the timing of erosion and hence the sea level at such times, which is important in determining whether the disposal facility will be undercut, directly eroded at sea level or inundated. The models have also been extended to inform the timescales and nature of erosion of the repository facility.

The models indicate a range of times for onset of erosion of the facility and completion of erosion that vary with the rate of sea-level rise and coast-to-site section modelled. In summary, contingent upon the greenhouse gas emissions scenario considered, we conclude that the disposal vaults will begin to be eroded on a timescale of several hundred to a few thousand years, with consequent disruption of the repository, with erosion of the vaults and trenches being complete within one to a few thousand years.

The principal processes leading to repository disruption are anticipated to include progressive undercutting of coastal cliffs, direct wave attack on exposed engineered structures, and, particularly under the High Emissions Scenario, episodic or sustained inundation due to rising sea levels. These mechanisms, acting in combination with ongoing coastal retreat, will ultimately result in the gradual exposure, fragmentation, and dispersal of repository materials into the adjacent coastal environment.

As erosion progresses through the vaults and trenches, the adjacent beach environment will evolve as well. It is expected to consist of a mixed assemblage of natural and waste materials, including sand, gravel, eroded concrete fragments from the repository structures, and possibly residual waste items that prove more resistant to weathering and transport. These materials will interact with tidal and storm-driven processes, affecting their distribution along the coastal zone and potentially further afield.

Our understanding of how engineered barriers and waste forms fragment, degrade, and move within a dynamic coastal system has been informed by both laboratory-based studies and observations of sites where similar materials have been released into coastal environments.

It is not considered feasible to guarantee protection from erosion over many hundreds to a thousand years using engineered structures, and we cautiously assume in our assessments that no coastal defences will be present. This position is consistent with regulatory guidance, which requires the repository to be passively safe without ongoing management and maintenance, including provision of coastal defences.

The impacts of the coastal erosion of the disposal facility are addressed in argument A5.

S5: Characterising and understanding the surface environment

Our characterisation of present-day and future exposure pathways and potentially exposed people is based on established approaches and utilises appropriate data on local land and resource use and human habits.

Our assessment of impacts to non-human biota is based on an understanding of the ecosystems present around the LLWR.

This argument relates to GRA Requirement 11 and also GRA paragraph 6.4.9 [29]; further support to this argument is given in the '*Site History and Description*' [2], '*Hydrogeology*' [6] and '*Site Evolution*' [7] reports and the various Level 2 ESC reports that present our assessments [13, 14, 15, 16].

A sufficient understanding is available and has been developed to support our assessments. The following aspects are relevant:

- An understanding of the locations of groundwater recharge and discharge and the location of streams, rivers and estuaries now and in the future [15].
- The location of any natural resources, in particular the potential abstraction of water resources for local use (see below and Section 3 of reference [13]).
- Local activities and behaviour of people in the vicinity of the site, where this is relevant to the definition of representative persons (see below).
- The ecosystems and habitats present, which are a basis for the assessment of impacts to non-human biota (see below).
- General aspects of the site such as climate, soil type, potential erosion rates and topography, which provide a general context to our assessments [7].
- Those changes over time that are relevant to the assessment.

The recognised approach to assessing the consequences of present-day discharges of radionuclides is to assess the consequence to 'representative persons'. When defining a potential representative person in the future, it is appropriate to consider both generic and local behaviour as the characteristics of the site and local behaviour could change.

Habits surveys provide information on present-day human habits that could result in exposure via the main pathways, and this is used to define candidate representative persons for different age groups. In defining the habits of those groups, we have applied 'local profiles' of habits in the same way as applied by the Environment Agency and Food Standards Agency in their annual '*Radioactivity in Food and the Environment*' report. We have supplemented these profiles with our own local knowledge of occupancy patterns. For the first ten years of the Period of Authorisation assessment, it is assumed that habits remain the same as the present day. Doses to candidate representative persons during this period account for all exposure pathways that could apply based on their habits.

Consideration of potential exposures in the future requires an alternative approach in which a wider range of activities is considered (for example, sinking a well into contaminated groundwater and utilisation of the abstracted water). In the assessment of potential radiological consequences during the Period of Authorisation, we have used an alternative approach to define 'potential representative persons' for assessment for the period of ten years hence to the end of the Period of Authorisation. We have used local survey data and national statistics to identify higher rates of consumption and local occupancy patterns, adapting an approach from the National Dose Assessment Working Group to reflect the increasing uncertainty at later times. This systematic approach provides a proportionate mechanism to assess the contribution from all relevant pathways and the dose to different age groups.

After the Period of Authorisation, our potential representative persons are based on a cautious narrative description of potential future human behaviours. This approach provides a balanced and proportionate mechanism for examining impacts from the repository over the longer term. When defining habits for such persons, we have considered both local and national generic habits information but have not been constrained by them if they are not consistent with the narrative description of the potential representative person. For example, limited information is available on behaviours on the coast following the landscape change associated with coastal erosion. We have also considered whether individuals might receive radiological impacts via more than one exposure pathway and have calculated such combined impacts where appropriate. We have considered different age groups and calculated the doses and risks to them if their habits are uniquely relevant to the narrative or they would receive higher impacts than adults.

Of particular importance is the potential for the future exploitation of water resources by use of a water abstraction well between the facility and the coast. We have examined in some detail the potential for such a well and the likely associated behaviours [14, 52, 53].

The habits data, extracted from local surveys, national statistics and local knowledge is systematically documented in our '*Habits Handbook*' [54].

Assessment of the impacts of non-human biota have been undertaken based on a review of the ecological context of the site and its surroundings [16] (see argument A7). The LLWR site is bordered by farmland to the north and east. However, to the west and south the site is contiguous with or lies close to the Drigg Coast SSSI, which is designated both as an SSSI and a Special Area of Conservation. It is also close to the Cumbria Coast Special Area of Conservation. A review of relevant habitat types and species was undertaken in support of the assessment drawing on several surveys and specialist knowledge from our site ecologist.

Environmental change is important to the evolution of the LLWR, particularly in the context of coastal evolution (see argument S3), which will be the major effect on the topography of the system. Rates of surface erosion will not be sufficiently high to modify the local environment or the closure engineering over the timescale of interest [7, 12]. In addition, we have considered the likely evolution of the climate and changes in hydrologically effective rainfall [7]. The climate will maintain a general classification of 'temperate oceanic' in most cases, though with a pattern of wetter, warmer winters and drier summers. Under our High Emissions Scenario, the climate transitions to a 'humid subtropical' classification for a period, similar to present-day Portugal. We assume cautiously that agriculture will continue to be the dominant land use around the LLWR.

The understanding of the surface environment that we have developed is applied in the assessments discussed in Subsection 4.5.

S6: Monitoring

Our environmental monitoring programme provides a fundamental basis for understanding the site and its evolution over time. It provides feedback on the performance of the various barriers to the release of contamination and informs the process of optimising the facility. An appropriate environmental monitoring programme, applying sound science and best practice, is vital to building confidence in successive safety assessments. Similarly, the results of successive safety assessments are used to inform the design of the monitoring programme.

Results from the environmental monitoring programme provide direct evidence that releases of radioactivity from the site at the present day and in the past are low, and that doses to the local population calculated on the basis of monitoring are very low and consistent with regulatory requirements. The results also provide a baseline against which changes due to changes in future operations can be assessed.

An ongoing monitoring programme throughout the Period of Authorisation provides confidence that any unexpected and adverse aspects of performance would be recognised, which would facilitate any appropriate action, including any modification to the Site Development Plan.

This argument relates to GRA Requirement 14 [29] and GRR Requirement 8 [30]; further support to this argument is given in the '*Monitoring'* report [8] with further consideration of the monitoring results given in the '*Environmental Safety During the Period of Authorisation'* [13] and '*Hydrogeological Risk Assessment'* reports [15].

The monitoring programme has gone through a series of changes since data started to be collected systematically in the 1980s, reflecting the increased recognition of the role of monitoring in providing a fundamental basis for understanding the site and its evolution over time. It provides feedback on the performance of the various barriers to the release of contamination and informs the process of optimising the facility. An appropriate environmental monitoring programme, applying sound science and best practice, is vital to building confidence in successive safety assessments. Similarly, the results of successive safety assessments are used to inform the design of the monitoring programme.

The programme not only meets statutory requirements but also adheres to best practice guidelines, ensuring that the methodology is both robust and appropriate. It is managed through a systematic approach, involving regular reviews and updates to incorporate the latest scientific and technical advancements.

Baseline data from prior to commencement of disposal operations or from before the site's use as a Royal Ordnance Factory are not available. Environmental monitoring data are available from the late 1980s through to the present. This allows the longer-term trends to be identified and the effectiveness of engineered barriers assessed, indicating that the LLWR site has minimal impact on the environment and risks to the general public are negligible.

The results also provide a baseline against which changes due to future operations can be assessed.

The results show the following:

- Radiological activities in groundwater and surface water have generally declined over time, corresponding to the construction of the interim cap over the trenches reducing infiltration into the waste. The construction of the cut-off wall has clearly removed the pathway from the trenches to the railway drain.
- In terms of non-radiological impacts, monitoring and assessment evidence shows that LLWR operations have not resulted in significant non-radiological contamination of groundwater or surface water. Where non-radiological substances are detected, concentrations are generally low, consistent with natural background levels, and not localised around the LLWR site.
- Water balance modelling indicated that there was a problem with the interim cap over the trenches. Replacement of the interim membrane is being undertaken at present.
- The environmental risk assessment for aqueous discharge from the LLWR provides evidence that both radiological and non-radiological discharges continue to have a negligible impact on the environment.
- The most recently calculated retrospective annual dose, in 2024, was 25.0 μSv and is considered to be insignificant in comparison to the 2,200 μSv annual average UK dose rate due to natural background radiation.
- No evidence of the migration of contaminants from areas of known ground contamination has been identified.

During the Period of Authorisation, environmental monitoring will provide assurance that the facility is performing as expected [13]. Monitoring data will provide a direct demonstration that the relevant criteria are being met and that the concentrations of any contaminants in environmental media are acceptably low. If any significant changes were observed, then appropriate action would be taken as required. If contaminant concentrations approach a relevant compliance level, then some action would be required. For this purpose, control levels have been identified and trends in the data are examined as part of an annual review process. If control levels were to be exceeded or trends identified, after appropriate technical review, this would lead to consideration of any need for further action, for example, repeat measurements or review of the analytical approach. Ultimately, if performance were deemed to be unsatisfactory, remedial action could be taken based on the monitoring data. This approach provides confidence that the environmental impacts of the LLWR will be kept acceptably low during the Period of Authorisation.

Environmental monitoring data are used systematically within the ESC and are particularly important in providing inputs to, and calibration data for, the 3-D groundwater flow model of the site, near-field evolution, site evolution and as a basis for comparison with assessment model results. The environmental monitoring programme has expanded since 2011, providing more comprehensive data on groundwater levels, quality, and contaminant trends, which has improved our ability to characterise the hydrogeological setting and validate conceptual models.

We recognise the need for a programme of long-term environmental monitoring that will continue throughout the Period of Authorisation. The programme has in recent years been modified to encompass the capping programme. The programme will continue to change as new vaults are built and the site moves from operational to a fully capped and closed repository. The data collected will be an important input into decisions on whether further design optimisation is required. The data collected will also contribute more generally to future updates of the ESC, which is expected to build further confidence in our understanding of system performance and support Permit surrender in the future.

4.4 Optimisation and Site Development Plan

We have carried out a comprehensive evaluation of options for the future development of the facility up to closure and beyond to arrive at an optimised Site Development Plan for the LLWR. This included options related to past disposals, future disposals, future site engineering, waste emplacement, leachate management, wastes associated with the use of the site, and management of the site during closure. Understanding gained from the assessments (Subsection 4.5) has been used, as it developed, to evaluate the environmental safety of alternative options. An optimised Site Development Plan has thus been developed that presents an appropriate combination of implementable options for the development of the site.

A system-wide, integrated approach is used for the optimisation of the LLWR, ensuring that optimised individual aspects are integrated and aligned within an overall optimised disposal model. While optimisation-related arguments are presented individually for clarity, they should be seen are complementary and mutually supportive.

O1: Remediation of past waste disposals

We have examined a range of options for the remediation of past waste disposals at the site, including the retrieval of disposed wastes. We have identified feasible options and evaluated remediation potential, environmental and other impacts from implementation and the costs of each option. We have found that the only options that might have remediation potential involve grossly disproportionate costs as well as other disadvantages including potential risks to workers. Hence, in our Site Development Plan we propose no remediation of the trench wastes.

This argument relates to GRA Requirement 8 [29]; further support to this argument is given in the '*Optimisation and Site Development Plan'* report [9].

One of the main conclusions of the Environment Agency's review of the safety cases submitted in 2002 by a previous operator was that they contained insufficient consideration of optimisation and risk management to demonstrate that impacts would be ALARA. This conclusion was drawn in the context of the then high calculated doses and risks from existing disposals to the trenches that significantly exceeded regulatory guidance levels. Calculated doses and risks from the trench disposals are now broadly consistent with regulatory guidance levels due to the work we have undertaken to improve our assessments and reduce uncertainties (see argument A5). Nevertheless, in order to demonstrate our Site Development Plan is optimised, we have considered a range of actions that have the potential to achieve reduction in the environmental impact associated with past disposals to the LLWR. These options have been assessed from the perspective of the potential reductions in risk they may be capable of delivering, set against the wider implications that would be associated with their implementation.

Consistent with our objective of continuing to provide capacity for the disposal of LLW at the facility, the emphasis in the options analysis has been on the appropriateness of actions that would 'target' the retrieval of wastes from specific areas of the trenches. These are where localised high concentrations of key radionuclides are present that play a significant role in determining overall impacts from the facility. We have, however, considered the implementation of other types of remedial action both targeted and for the whole of the trenches.

Our options assessments demonstrate that the achievable scale of dose or risk reduction is small compared with the costs and disruption, risks to workers and other disadvantages that would necessarily be associated with retrieval or remediation. We do not therefore propose to adopt any such actions within our forward plan for future management of the facility, and this has formed the basis for assumptions adopted in the ESC.

We have undertaken work to understand why the interim trench cap has performed less well than expected and carried out optimisation studies to determine the BAT approach to the interim trench cap. On the basis of these studies, we have concluded that, for those parts of the trenches adjacent to Vault 8, installation of the final cap will provide the required improvement in hydrological performance. For those parts of the trenches that will not be covered by the first strips of the final cap, we are in the process of installing an improved interim cap to provide the required improvement in hydrological performance.

O2: Optimisation of future waste disposals

Implementation of the UK strategy for LLW management has reduced volumes of wastes requiring disposal at the LLWR, through improvements in waste characterisation, segregation and treatment. We will continue to support the NDA in the implementation of UK policy and strategy for managing radioactive waste.

We will continue to work with consignors, the NDA and the wider industry to identify any further innovations in disposal approaches that could enhance the waste management lifecycle for wastes that are disposed to the LLWR.

Should ILW disposal at the site be taken forward, we will similarly work with consignors, the NDA and the wider industry, to produce an optimised approach to container design, transportation, waste receipt and disposal, building on the work already undertaken.

This argument relates to GRA Requirement 8 [29]; further support to this argument is given in the '*Optimisation and Site Development Plan'* report [9].

The NDA operates its overall radioactive waste management strategy [55] within the framework of UK policy and strategy, set out in the UK government policy framework [28], which replaces the previous LLW policy [31] and integrates the previous overall UK strategy. The current policy framework and NDA strategy, like their predecessors, include a focus on optimisation of UK waste management practices across the lifecycle. Priorities therefore continue to include application of the waste hierarchy, and optimisation of use of LLWR as a national asset. Implementation of national strategy since the 2011 ESC has already led to major changes across the industry and in particular at the LLWR, with projections of future disposal volumes having reduced dramatically. The implications of these changes are assessed in this ESC.

We continue to act as a strategic partner to the NDA in the implementation of the UK strategy, for example by supporting its work to engage across the industry to further enhance lifecycle optimisation. We also provide support through processes such as framework contracts allowing cost-effective access to waste management services and facilities by consignors. We are also using our WAC to encourage the use of best practice amongst our consignors.

Proposals for changes to disposal operations will be assessed against the ESC using our change control process. Significant changes will be made in consultation with the Environment Agency. We will also keep under review changes to the wastes we receive for disposal to ensure the assumptions of the ESC remain valid.

O3: Site engineering

We have examined a range of options for site engineering to promote optimised environmental performance, including for capping, vault design, operational and long-term leachate management, and protection of wastes from environmental effects prior to capping. We are constructing an interim cap for the trenches as a response to observations of suboptimal performance of the previous cap. We have further optimised the final cap layers and developed the underpinning understanding of its evolution, to maximise confidence in performance. We have developed optimised plans for closure of Vault 8 and the adjacent strip of the trenches, leading to the cap and cut-off wall design that has been approved for construction. Further optimisation outcomes included recognition of the need for surcharge of the trenches, and of LLW disposals already received at the LLWR or committed to the current container design. This is to maximise confidence in cap constructability and performance. We have also identified options for future waste containers that will be strengthened to support the cap without the need for surcharge.

Following consideration of feasibility, effectiveness, impacts during operations and after closure, and flexibility, we have defined the optimised plans for future vaults and site closure adopted in our Site Development Plan. We have also considered options allowing a broader range of wastes to be accepted for disposal. Together, these plans provide an optimised 'disposal model' that underpins the ESC and will provide a baseline for future optimisation.

Our Environmental Safety Strategy and related site management processes will ensure optimisation continues to underpin design and operation of the LLWR, within an iterative and forward-looking programme.

This argument relates to GRA Requirement 8 [29]; further support to this argument is given in the '*Optimisation and Site Development Plan'* report [9] and the site engineering is described in the '*Engineering Design'* report [4].

In the 2011 ESC, we examined a range of aspects of the pre- and post-closure engineering design that will be employed in future development of the site. Given the uncertainties that are unavoidably associated with providing definitive estimates of long-term engineering performance at the system level, the main emphasis when comparing engineering options for the purpose of design optimisation was whether there was a preference from the perspective of establishing confidence in demonstrating human and environmental safety. Having made such a comparison, we then assessed whether that preference would be materially affected by wider considerations. The conclusions from these studies formed the basis of the Site Development Plan presented in the 2011 ESC.

We have continued to take forward optimisation work using a consistent and integrated process that aligns with regulatory and good practice guidance. Relevant studies have been undertaken within the framework of the overall concept and approach set out in the 2011 ESC but have also served to provide a forum for reviewing and confirming the overall concept. As a result, the continuing validity of the following key conclusions was confirmed.

Future vault design and passive leachate management

Future vault design will be based on the principle of providing comprehensive capture and control of leachate during operations and until such time as active control of leachate is ceased. The vault walls provide containment during the operational period allowing leachate to be managed and protect against uncontrolled overflow during extreme rainfall events prior to capping. This will help to preserve unsaturated conditions over the majority of the waste stacks, minimising interaction between infiltrating water and contaminants within the wastes and reducing the potential for release. Contingency arrangements for the passive discharge of leachate beyond the Period of Authorisation will be provided by horizontally extensive drainage layers beneath the future vault bases. These will be linked to the vaults via laterally extensive drainage features in the walls at the 1 m level.

Closure engineering

The final cap will be the principal component of the overall engineering design for the LLWR. It will play key roles in the passive control of leachate and the protection of disposed wastes from inadvertent disturbance. The components of the engineered cap, shown in Figure 4.4, have been optimised over several design cycles for performance as a hydraulic barrier, consistent with established best practice and experience from landfill disposal design. The design intent is to minimise infiltration to the extent that it is less than the drainage capacity of the underlying geology, thereby creating unsaturated zones beneath the vaults and trenches for as long as reasonably practicable. It also provides effective protection against intrusion by humans, deep rooting plants and burrowing animals.

The profile of the cap is intended to ensure the minimum elevation consistent with providing confidence in long-term performance. The gradient of the cap profile has therefore been minimised to a level that will ensure that its water-shedding and drainage function will persist over the long term under expected rates of settlement. The cap will have a single-dome profile, capable of providing the required structural stability to assure long-term performance. We have analysed the performance of the final cap in our Engineering Performance Assessment [12] and we have a high degree of confidence in its performance.

Profile fill will provide a stable formation for placement of the final cap and will ensure the optimal geometry is implemented. The selection of profile fill material and thickness has been optimised to ensure confidence in cap stability together with consistency with the performance of underlying features including vault drainage systems.

An encircling cut-off wall will be constructed around the whole facility, to a depth of approximately 2 m below the underside of the vault bases, with the aim of preventing the trench and vault wastes and below-slab drainage blankets from saturating. This will be integrated with the cap and will guard against the possibility of near-surface release of leachate close to the facility.

The resulting closure concept is summarised in Figure 4.5.

A passive gas venting arrangement is incorporated in the design of the final cap to prevent pressurisation of the system by bulk gas production or atmospheric pressure changes. The venting approach will also facilitate confirmatory monitoring of bulk gas and radioactive gas production during post-operational control of the site. A decision will be made before final site closure on whether to close the vent. Based upon our evolving understanding of gas generation in the repository, we will develop an optimised design for gas venting.

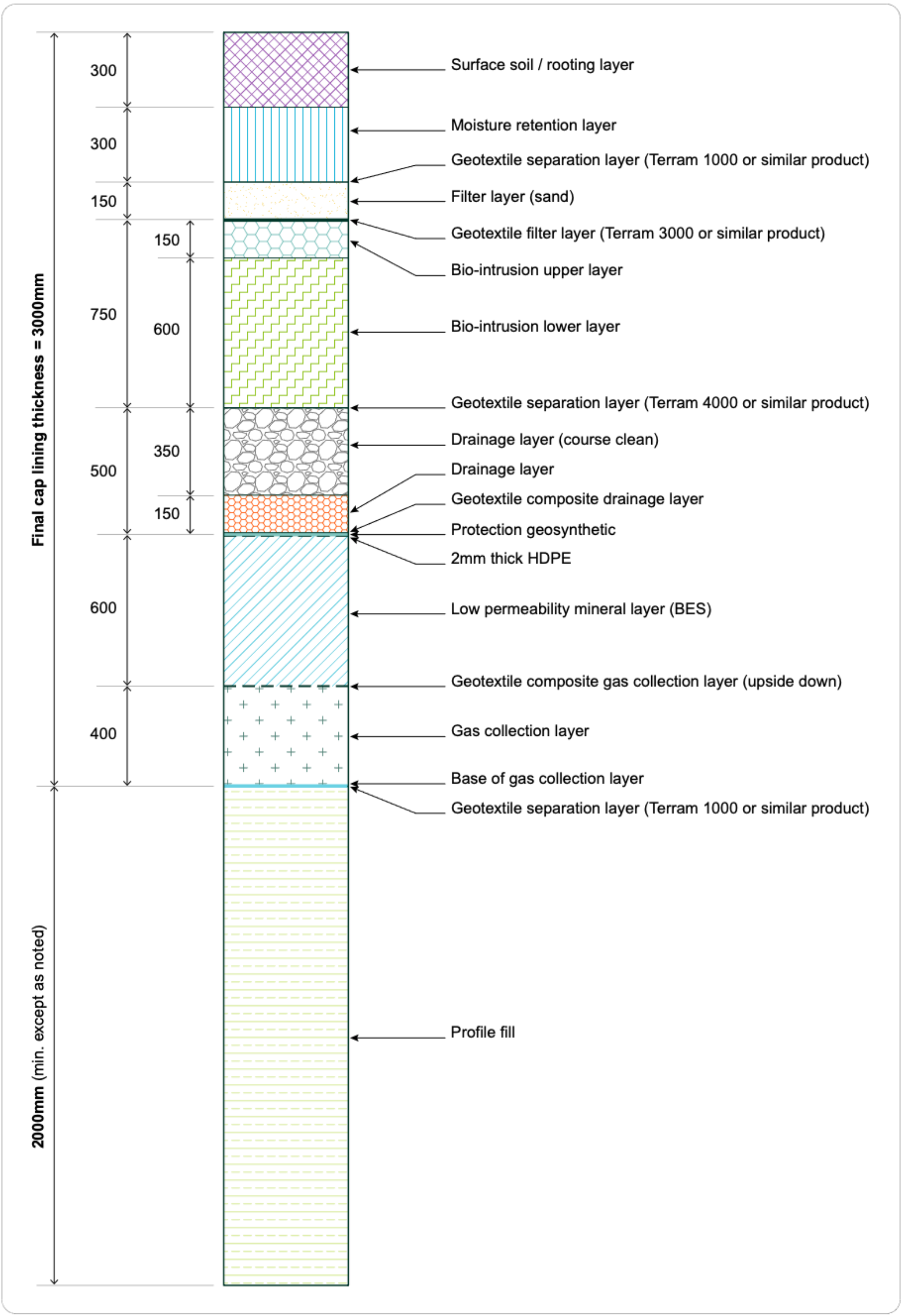

Figure 4.4: Illustration of final cap layers

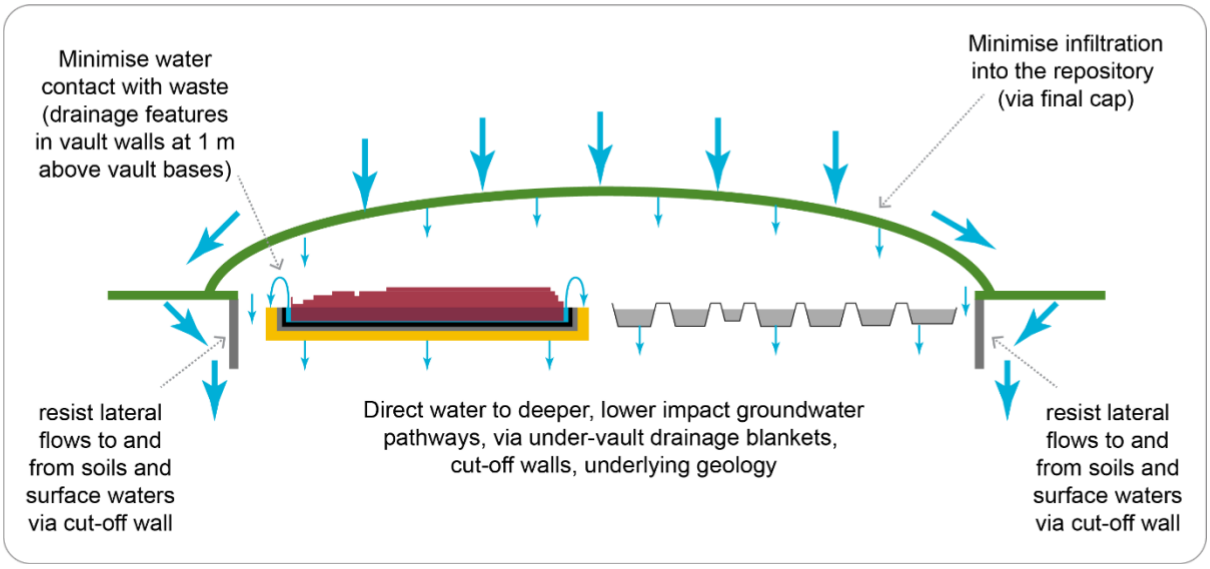

Figure 4.5: Schematic illustration of the optimised closure concept. The schematic focuses on water flows. It reflects evolution of the cap to a point where infiltration has increased sufficient for the vaults to saturate to the 1 m level, resulting in flows to passive drainage arrangements including the vault drainage blankets underlying future vaults. Connections will be engineered from Vaults 8 and 9 to allow access to the drainage blankets underlying future vaults

Closure of Vault 8 and responses to revised understanding of container performance

In the 2011 ESC we assumed that it would be possible to 'higher stack' containers above the as-then four-high maximum stack height in the majority of Vault 8. We argued that this would offer benefits in maximising use of the repository's volumetric capacity.

Our understanding of container load-bearing performance has changed significantly since 2011, on the basis of physical testing and modelling work, and consequently we have undertaken extensive studies to determine an optimised approach to closure of Vault 8. We no longer intend to stack wastes higher than the current stack heights in Vault 8. We have concluded that the BAT approach will be to surcharge the wastes in Vault 8 prior to installation of the final cap. Surcharging will ensure that available settlement has been expressed before cap installation. This will provide a stable base for cap installation, consistent with confidence in the long-term performance of the cap. Surcharging the containers will result in some damage to containers; we expect that this will initially result in only a minor reduction in the level of containment provided by the containers. In the longer-term, however, these containers are likely to provide less containment than the planned new stronger containers with container protection units due to damage to the uppermost container lids, poorer initial condition and accelerated corrosion exploiting the deformation damage.

As the cap is the key control on repository performance, the advantages that this approach offers for long-term cap performance outweigh the minor reduction in the barrier provided by the containers. As the containers in Vault 8 are not considered quantitatively in our assessment models, the reduction in containment will have no effect on assessed impacts.

Optimisation of disposals to the future vaults

We have continued to optimise the repository engineering in response to revised understanding of container performance, rates of waste receipt, and the potential to accept less-hazardous ILW.

Drawing on our experience of Vault 8, we have considered a range of engineering options for disposals to and closure of Vault 9 and design and closure of future vaults. We have concluded that the optimised engineered design is as follows.

For wastes that are already emplaced in Vault 9, or will be disposed of in Vault 9 and 9a in an existing container design, we will surcharge the containers prior to emplacement of the final cap. Relevant disposals will first be stacked at the northern end of Vaults 9 and 9a and will be closed via an extension of the cap seal over the relevant wastes as soon as practicable after Vault 8 closure. This will provide closure-levels of protection of the wastes as soon as is currently practicable; surcharge will occur later at the time of final cap emplacement over Vaults 9 and 9a.

For wastes where there is potential to change the container design, we will modify the existing ISO container design to strengthen them. The adoption of a strengthened half-height ISO container will ensure protection of the multi-barrier concept, without disproportionate cost or wider industry impacts. To ensure that the weaker lids of the containers are protected from loads imposed during and after capping operations, the top container of each stack will be fitted with a container protection unit. These will comprise a reinforced-concrete structure which will span across the container and will transfer loads to the load-bearing elements of the container. Wastes in these stronger containers will be disposed of in the southern parts of the Vault 9 and 9a and will be disposed of in future vaults. These containers will be higher stacked consistent with the required cap gradient and specified minimum levels of profile fill under the cap.

To ensure that containers are protected from environmental effects, they will be stored in interim storage warehouses prior to emplacement in final disposal locations shortly before installation of the relevant strips of the final cap. These warehouses will be similar to standard industrial warehouses and will be built away from disposal operations; for example, warehouses in Vault 10 (or another location on the site) could be used to support disposals to Vaults 9 and 9a. A fully sealed, climate-controlled design is not anticipated and the warehouses will not provide shielding. We consider this to be proportionate to the level of protection required. The warehouses will be removed prior to vault closure. They will ensure that the containers are in a good condition at the point of disposal. This will maximise the contribution of the containers to the multi-barrier system.

Potential for ILW disposal

The above outcomes, together with those that remain valid from the 2011 ESC, are the basis for our revised Site Development Plan.

In addition, as part of work to support the NDA to make optimal use of the LLWR, we have assessed a range of engineering options that would allow the site to accept less-hazardous ILW. Based on our optimisation and supporting engineering studies, our conclusions are as follows.

All ILW would be disposed of in mild steel containers that would be sufficiently strong to withstand loads that would be imposed during and after cap installation. We recognise that there are uncertainties as to whether ILW would require Type B transport containers for transport from consignor sites to the LLWR. We have assumed, therefore, in our work, that a Type B container would be required. The container we have considered in our work would fit within a Standard Waste Transport Container, if transport within a Type B container were to be required. The capability to accept Type B containers would then be needed on site. We will continue to support ongoing optimisation and design work in this area, aligned with wider NDA programmes, and, working with consignors, to identify updated optimised designs. The final outcomes will ensure the containers deliver the functions already identified, but the options process is intentionally flexible and the outcomes may vary in detail from the approach assumed in this ESC. The current assumptions nevertheless provide a firm and appropriate basis for the assessments presented.

ILW that may be handled as LLW (that is, low dose rate ILW) would be disposed of in the southern parts of Vault 9 and 9a and in the future vaults. No modifications of the vault design would be required to accept such wastes. Containers would be stacked to a height consistent with the required cap gradient and specified minimum levels of profile fill under the cap. The top container of each stack would be fitted with a container protection unit to transfer the load of the overlying cap and profile fill to the load-bearing elements of the container, thus protecting the weak container lid. Prior to emplacement in final disposal locations, these containers would be stored in interim storage warehouses alongside LLW containers.

For ILW that cannot be handled as LLW (that is, requiring consideration of shielding on account of higher dose rates), we would construct reinforced concrete structures ('shielded modules'), which would provide the required degree of shielding. The shielded modules would only be constructed in Vault 10 onwards. The shielded modules would provide protection from the environmental processes as soon as the wastes are emplaced; there would be no need to place higher dose rate containers in the interim warehouses prior to emplacement in the shielded module. If ILW were to be disposed of at the LLWR, there is some uncertainty as to the volume of waste that would require emplacement in shielded modules. Our approach recognises that flexibility with respect to the location and size of the shielded modules in the vaults offers a means of managing this uncertainty. The design of the shielded modules is intentionally simple, consistent with the vault disposal approach and the level of hazard involved.

The use of different approaches for different waste categories necessitates a 'modular' approach. This approach is also consistent with the wider benefit of allowing flexibility in future vault size and construction timeframes, aligned with timeframes for implementing strips of the cap. This is of value given uncertainties in future inventory projections, and recognition of the importance of timely protection of disposed wastes from environmental effects.

If ILW disposal at the LLWR were to be pursued, the Site Development Plan would require revision to include these optimised measures.

O4: Waste emplacement strategies

We have examined the advantages and disadvantages of waste emplacement strategies. Since emplacement criteria add complexity to disposal operations, we only implement them where necessary. We adopt a proportionate strategy for stacking waste packages in the vaults to reduce cap degradation through settlement and to optimise the potential for reducing impacts in the future. We also implement controls to ensure the emplacement strategy remains practicable.

This argument relates to GRA Requirement 8 [29]; further support to this argument is given in the '*Optimisation and Site Development Plan*' [9] and '*Implementation*' reports [17].

We have developed and implemented a proportionate emplacement strategy that controls emplacement of packages to limit the impacts that might result from future human intrusion or coastal erosion, loads on materials containing absorbed liquids, and the effects of settlement on the cap. As part of the 2026 ESC, we have updated this strategy and are additionally proposing that waste packages containing relatively large amounts of radium are placed away from the top of the waste stacks, to limit the potential for impacts from the release of radon through a damaged cap.

The success of diversion of routine LLW to other routes is leading to the typical activity concentration of waste being consigned to the LLWR being of a higher activity concentration. This may mean that the proportion of consignments with emplacement requirements will increase. The number of consignments requiring consideration against the emplacement strategy is kept under review as part of the ESC Annual Review, to ensure it remains practicable. At present, approximately a quarter of consignments require consideration under the emplacement strategy.

We identify consignments requiring specific emplacement as part of the waste acceptance process. We use a calculation tool to optimise the emplacement of waste packages. Our current emplacement strategy places restrictions on activity concentration in consignments that would be within 5 m of the surface of the cap. We have updated these calculations on the basis of the 2026 ESC.

Operating Instructions in the Environmental Clearance Certificate require that waste consignments are to be disposed of in their final positions in accordance with the emplacement strategy derived from the ESC and with the agreement of the ESC Manager.

If ILW disposal at the LLWR were to be pursued, the emplacement strategy would require revision because at present it relies on the activity concentration definition of LLW. We have explored an approach using a screening threshold to demonstrate the implications of accepting ILW on the emplacement strategy. The majority of ILW that might be considered for disposal at the LLWR would have to be excluded from upper stack positions or placed in areas where the profile fill is deeper. A proportion of this waste would have to be disposed of in shielded modules (if accepted) due to higher dose rates.

O5: Management of run-off and leachate

We have examined the options for run-off and leachate management and the progressive transition from active towards passive control. As part of our Site Development Plan, we are implementing a plan to continue to manage leachate and run-off safely.

This argument relates to GRA Requirement 8 [29]; further support to this argument is given in the '*Optimisation and Site Development Plan'* report [9].

During operations, rainwater run-off from the open vaults and leachate from the trenches and capped vaults will continue to be managed by the collection, monitoring and controlled discharge to sea via the Marine Holding Tanks and Marine Pipeline, subject to the terms of our Permit. We plan to construct the final cap (and associated cap seal) progressively in strips, which will reduce infiltration to the trenches and run-off from the vault slabs. This will ensure that the current leachate management system remains capable of handling run-off other than from extreme events and does not need to utilise the back-up of release to Drigg Stream.

The upgrade to the interim trench cap, with associated drainage features, will ensure that run-off will be effectively managed and that trench leachate volumes will be minimised. Our surface water management system will continue to evolve as the final capping of the facility progresses.

The leachate management system will be maintained for a period after completion of the installation of the final cap, until it can be demonstrated via monitoring that it is no longer needed (that is, there is little or no volume of leachate being generated).

Whilst leachate in the vaults is currently actively pumped, optimisation work has identified the potential to move to a passive gravity-based system during operations.

The assumption of continued active management and monitoring is consistent with established practice for landfill operations.

After the final cap is installed over the trenches, infiltration of rainwater will be greatly reduced. This will lead to a gradual drying out of the trench waste. For the vaults, water consumption by corrosion will exceed infiltration, so the vaults will dry out quickly within a decade of capping. The volume of leachate is then expected to be minimal. Monitoring will continue into the post-operational period with the objective of confirming performance in relation to leachate management.

O6: Wastes associated with the use of the site

Various wastes and areas of contamination have resulted from the use of the site for the storage and disposal of radioactive waste and its prior use as a Royal Ordnance Factory. In some cases, optimised waste management options have been identified and have or will be implemented. In other cases, further work will be required, at an appropriate stage in the life of the site, to identify and implement optimised waste management options. An integrated WMP for these 'site wastes' and contamination has been developed as part of the 2026 ESC. Continuing monitoring of the site indicates that leaving contamination on the site in situ for the time being is not having an adverse impact on people or the environment.

This argument relates to GRR Requirement 2 [30] ; further support to this argument is given in the '*Optimisation and Site Development Plan*' [9] and *'Waste Management Plan'* [10] reports.

The wastes in the disposal facility form the main environmental hazard but other wastes and areas of contamination have resulted from the use of the site for the storage and disposal of radioactive waste and its prior use as a Royal Ordnance Factory. These are characterised and recorded under our processes [1, 8], are set out in the integrated *'Waste Management Plan*' [10], and include the following:

- Solid, liquid and gaseous wastes generated from operation of the site.
- Future arisings of decommissioning wastes including in situ structures that will eventually become radioactive waste (for example, the Leachate Management System, the Marine Pipeline) and non-radioactive decommissioning wastes.
- Contamination arising from:
  - the legacy from the Royal Ordnance Factory operations and buildings including asbestos;
  - the legacy from historical LLWR operations including radiologically contaminated concrete slabs (for example, B749 and B741);
  - storage of Plutonium Contaminated Material in the magazines and elsewhere on site;
  - contaminant migration from authorised LLW disposal areas (Trenches 1 to 7 and Vaults 8 and 9);
  - contamination arising from other site operations including road, rail and site drainage.

- Waste that may be generated from the clean-up of contamination.

Together, our Site Development Plan and established processes consider when and how to clean-up radioactive contamination and ensure we optimise waste management over the lifetime of the site [9, 10]. Our optimisation decisions consider all relevant factors, working within the constraints of past land use and disposal decisions [9]. We balance many considerations including radiological and conventional safety, and implementation of the waste management hierarchy. The process ensures that radiological risks to the public are kept ALARA. Radiological impacts on other living organisms are also considered in the process.

The primary aim is to ensure optimised waste management is carried out across the site's lifecycle to work towards the regulatory criteria defined for release from regulation [30]. Given the stage of the site's lifecycle and the remaining planned operating period, there are further assessments and decisions that will need to be made in relation to 'site wastes' and areas of contamination. However, our processes for optimisation are established, we undertake the assessments and decision-making process at the appropriate time, and have documented previous examples of this in the WMP.

Options for management of radioactive waste arising on the site include:

- disposal in the LLWR vaults;
- disposal off-site by transfer (for example, to landfill or other permitted facility);
- 'disposal for a purpose' (for example, using lightly contaminated decommissioning wastes for void filling);
- 'disposal in situ' of below-ground structures that become waste.

If 'disposal for a purpose' or 'disposal in situ' is selected as the optimised waste management option for any radioactive waste on site, we will apply to the Environment Agency for a permit variation as set out in the GRR [30].

Options for management of non-radioactive waste arising on the site include:

- 'deposit for recovery' (for example, reuse of site-won material in the profile fill layer);
- transfer off-site to a suitably permitted facility for disposal or re-use.

We take an integrated approach with radioactive and non-radioactive waste where appropriate, for example by applying the waste management hierarchy and taking opportunities to re-use material on site [10]. Examples of this approach where decisions have already been taken include where clean demolition material is to be used as profile fill in the construction of the final cap.

Radioactive and non-radioactive contamination may be left in situ if it is safe and optimised to do so. No decision has yet been taken to leave contamination in situ. Our ongoing monitoring programme and site characterisation activities will continue to build our understanding of potential waste or contamination on the site. The WMP will be updated as more knowledge is gained about potential future waste arisings or contamination is identified.

These decisions all take into account the next planned use of the site, which is 'waste management and recreation or nature conservation'. This has been agreed with our stakeholders, including the local community.

Continuing monitoring of the site indicates that leaving contamination on the site in situ for the time being is not having an adverse impact on people or the environment [8, 10, 13, 15].

O7: Management during closure

Our Site Development Plan sets out arrangements for management of the site, including for the period of institutional control after waste emplacement has been completed and the facility capped, such that, at an appropriate time, and subject to regulatory agreements, it will be possible to release the site from management control and direct regulatory supervision.

This argument relates to GRA Requirement 8 [29] and the GRR [30]; further support to this argument is given in the '*Optimisation and Site Development Plan'* report [9].

Following the end of waste emplacement, the cap will be completed and a period of active institutional control will follow in which the facility will continue to be monitored and managed. The site will continue under regulatory control during this period and hence the Period of Authorisation will finish when we have demonstrated the criteria for release from regulation have been met [30].

The next planned use of the site, agreed with the local community, is 'waste management and recreation or nature conservation'. Following the end of operations, closure engineering will be completed and controlled public access is anticipated to be possible.

It is not appropriate at this stage to define detailed, or to conduct a detailed optimisation of, arrangements for management during the period of active institutional control for a site that we expect to continue to receive wastes for many decades. Nevertheless, it is important to provide assurance that the facility can be safely closed and released from control, and to understand what actions need to be undertaken now, such as records retention, to help in the future. Hence, our Site Development Plan outlines arrangements for the institutional control period, covering aspects such as leachate management, monitoring and preparations for release of the site from control.

Our assessment calculations demonstrate that intrusion hazards associated with shorter-lived radionuclides are expected to fall substantially over the first 100 years following the end of disposals and much less rapidly thereafter. Our assessment (see argument A5) suggests that, from this perspective, the site could be safely released from control after 100 years. Our assessment over the Period of Authorisation of the groundwater pathway has produced estimates of dose consistent with guidance levels (see argument A4). Similarly, our assessment of the gas pathway has determined impacts from C-14-bearing gases and radon are consistent with guidance levels assuming a 100-year period of active institutional control (see argument A5).

We consider that the best way of reducing the likelihood of damage to the facility in the future is to ensure that knowledge is retained about the nature of site and wastes, and the hazards that the wastes present. This would be assisted by involvement of the local community in making decisions on the future of the site. We believe sufficient control could be provided by land covenants, planning controls and beneficial ownership by the local community.

4.5 Assessment

We have carried out assessments of the performance and safety of the LLWR during disposal operations, while under management following completion of disposals, and after the end of management and regulatory control of the site. Radiological risks and doses to members of the public, the impacts from chemotoxic substances and radiation doses to non-human species have all been considered. The final assessments were undertaken on the basis of the Site Development Plan (see Subsection 3.3). We have thus demonstrated the environmental safety of the disposal facility under the Plan. The assessments undertaken largely address the impacts from the wastes emplaced in the disposal facility, although their results do suggest that the impacts from any residual contamination on the rest of the site would be very low. This is true currently, as shown by the LLWR's environmental monitoring programme.

A1: System understanding and safety functions

We have developed a thorough understanding of the evolution and performance of the existing disposal facility and its planned development in terms of the:

- potential radiological and non-radiological hazards;
- safety functions, for example, the function of waste containers in limiting the release of radionuclides;
- features, events and processes that provide, promote or reduce those functions.

This has supported our consideration of options and definition of the Site Development Plan and provided the basis for quantitative modelling and assessments.

This argument relates to GRA paragraphs 7.2.6 and 7.3.3 [29]; further support to this argument is given in the *'Safety Functions'* report [11].

The safety controls and safety functions provided by the wastes, engineered disposal system and the surrounding geological materials are discussed in Subsections 3.4 and 4.3. Under this argument, A1, we provide a narrative setting out the operation of the key pathways and safety functions.

The function of the LLWR, as any near-surface disposal facility for radioactive waste, is to contain and isolate the emplaced wastes and associated hazardous materials. Some discharges are planned during the period of operations and site control and some releases to groundwater are inevitable.

We have used our judgment and system understanding, developed over the course of several assessments, to identify the impacts associated with the migration of contaminants to people and the environment, and to identify key safety functions and relevant features, events and processes. We have undertaken several steps to ensure that our analysis is comprehensive. We have:

- developed and reviewed conceptual models for each pathway and/or system component;
- audited our assessment models against a standard list of features, events and processes;
- undertaken a bias audit of each assessment model;
- drawn on information from numerical models, including variant calculations to explore key process and parameter sensitivities;
- in identifying safety functions, drawn on understanding developed during design optimisation, modelling, the engineering performance assessment and while creating the Requirements Management System;
- drawn on information from a comprehensive monitoring programme.

On this basis, we set out an account of the impacts that are relevant over the lifetime of the disposal facility.

Period of Authorisation

At the present day, aqueous and aerial discharges are made under the terms of our Permit. Releases of contaminants, mainly tritium but also some other mobile radionuclides, to groundwater have occurred in the past and are continuing. We expect the magnitude of such releases to decrease over time as a result of radioactive decay (for tritium), leaching and the effects of engineering measures such as the installation of a final cap.

Aqueous discharges are made, via the Marine Holding Tanks and Marine Pipeline, of leachate from the trenches and run-off from Vaults 8 and 9. Leachate from the trenches is limited by the interim trench cap, which limits rainwater infiltration, and the current cut-off wall, which limits groundwater inflows to the trenches and also prevents migration of contaminants towards the railway drain (as occurred before the interim trench cap and cut-off wall were constructed). The containerisation and grouting of wastes in the vaults limits contact of water with the waste and hence limits the amounts of contaminants in vault run-off. Drains intercept and collect groundwater, which is directed to the Marine Holding Tanks.

Discharges occur of gases (notably radon and C-14-bearing gases, but also tritium) from the disposed waste in the trenches and vaults. The release of radioactive dust is insignificant.

The Grouting Facility includes dust abatement and control features. Discharges of radon are reduced as a result of decay during transport from the wasteform to the surface environment. Discharges of C-14-bearing gas are kept low as a result of slow release from certain wasteforms.

Radiation is emitted from wastes. The trench cap attenuates radiation from the trench wastes to effectively zero. Alpha and beta radiation cannot penetrate container walls. Gamma radiation is attenuated to an extent by the grout and container walls but penetrates the containers. The vault walls prevent direct irradiation from containers not stacked higher than the walls but there is potential for external irradiation of offsite receptors.

After completion of disposals to each vault, or potentially part of a vault, a cap section will be constructed over the filled vault and adjacent trench area. This cap will attenuate gamma radiation to negligible levels, further reduce infiltration to the trenches (and hence leachate volumes), and also reduce radon releases, as the cap is extended progressively southwards. The cap over the vaults will limit infiltration to the vault wastes and, together with the drains, will promote relatively dry (unsaturated) conditions in the wastes, which will limit waste degradation and contaminant leaching.

After filling of the last vault, the final cap will be completed. The cap includes a vent to allow the dissipation of any gas overpressure from waste degradation. This vent may be removed at site closure. A cut-off wall will be constructed around the rest of the disposal area to below the depth of the vault bases, to limit shallow groundwater inflow to the disposal area and prevent contaminant migration from the disposal area to shallow groundwater. Trench and vault leachate and drainage management will continue, as required, to reduce the potential for release of leachate to groundwater.

A key feature of the LLWR, and other near-surface disposal facilities, is that substantial radioactive decay of shorter-lived radionuclides, and hence diminution of radiological hazard, occurs between the time of disposal and the end of the period of management control. During this time, human intrusion into the waste and deleterious actions or uses of the site area are all prevented. The reduction in activity for the LLWR is shown in Figure 3.6.

Long-term – evolution of barriers and the site, and safety functions

In the trenches, degradation of waste and leaching of more mobile and accessible contaminants began at the time of waste disposal. The interim cap over the trenches and the north-east cut-off wall have limited water infiltration and lateral flow into the waste, and the trench base drains have collected contaminated leachate, which is managed as described above. A small proportion of the contaminated leachate will, however, have passed through the trench bases and percolated downwards to groundwater.

The final capping and complete cut-off wall will limit water inflows to the trenches for a substantial period. When the cap has degraded, some hundreds of years or more after the present, there is a potential for water levels in the trenches to rise and loss via the trench bases to become the main route for migration of leachate. By this time, the waste will be substantially degraded, shorter-lived radionuclides will have decayed and a fraction of the more mobile, longer-lived radionuclides will have been collected and discharged to the sea. Oxygen will be consumed by corrosion of metal and organic degradation, so that the trenches will be fully anaerobic. Release of contaminants from the waste will then be controlled by degradation of the waste forms, sorption of contaminants on wastes and trench fill materials, and for a few contaminants by solubility limitation.

In the vaults, the wastes are largely protected during the ‘open’ period by the containers and grout. Nevertheless, some degradation, especially of soft organic waste forms, will have begun and the ISO containers will have begun to corrode externally. After each vault is capped, the drainage arrangements will ensure that the majority of the wastes remain unsaturated. As conditions in the vaults become anaerobic, corrosion rates of the ISO containers will reduce. Conditions within the ISO containers will be anaerobic and conditioned to high pH by the cement grout.

Migration in groundwater

The cap will ensure that the repository remains substantially dry for hundreds of years and releases will be very low. The cut-off wall will ensure that any contaminant movement from the trenches and vaults is downwards to the water table. Contaminants moving down to, and in, groundwater flowing in the drift and sandstones beneath the site may be sorbed, especially to clay minerals, but the primary safety function for mobile contaminants is the dilution provided in groundwater flowing beneath the site. The groundwater that passes beneath the disposal area flows towards the coast to discharge to the marine environment below low water with some possibility of discharge through the foreshore sediments. In either case, large dilutions occur.

A key possibility is that a well for domestic or agricultural use could be constructed between the disposal area and the coast, with consequent potential for exposures via drinking water and agricultural paths (animal products or vegetables and fruit). No such well exists at present and most of the land between the disposal area and the coast is part of the SSSI so that housing or agricultural developments are unlikely in this area. Additionally, the land is now leased for 999 years by the NDA. Nevertheless, the possible sinking of a water abstraction well in the future is important as it provides the most direct access and exposure to potentially contaminated groundwater from the site.

Migration with gas

Methane and carbon dioxide will be generated from the degradation of organic wastes in the trenches, mainly within the first several hundred years after disposal, after which readily degradable organic material is exhausted. The restriction of microbial activity in the vaults, as the result of the high pH in the grout, means that there will be very little generation of gas from degradation of organics. In both the vaults and trenches anaerobic metal corrosion will result in a bulk gas phase dominated by hydrogen. Bulk gas can provide a vector for release of C-14-bearing gases as well as radon.

The restriction of microbial activity in the vaults means that generation of C-14-bearing gases from organic wastes will be substantially limited at early times. C-14-bearing carbon dioxide released from graphite, ion exchange resins and surface contaminated wastes will be taken up as carbonate within the cement grout, so mainly C-14-bearing methane will be evolved. Soluble C-14 species, mainly small organic molecules, will remain in the container porewater until released to the lower pH environment in the gaps between container stacks. Here microbial degradation reactions may result in further C-14-bearing gas generation. Both methane and carbon dioxide will be evolved in the trenches, but the inventory of C-14 in the trenches is much less than that in the vaults.

C-14-bearing methane is expected to migrate to the biosphere by a combination of processes and will diffuse through the cap or will be released from any vent that is retained after site closure.

Methane is expected to be metabolised to carbon dioxide by soil microbes. The carbon dioxide then emanating from the soil can then be fixed into vegetation via photosynthesis. If the cap is being used for agricultural purposes, then C-14 will be incorporated into fruit and vegetables grown on the cap or animal products from animals grazing on the cap.

The hydrogen-dominated bulk gas phase will also be instrumental in transporting radon generated from radium-bearing waste. Radon will be released as a result of bulk gas advection through a vent or through defects in the cap. Without advection, the radon would mainly decay before diffusing through the layers of the cap.

Radon might also cause an impact if the cap were substantially damaged, radium-bearing waste were excavated by human intrusions, or a house were built with a deep basement that intersects the gas collection layer. We assess such cases and also other exposure modes resulting from human intrusion (see argument A5).

Hydrogen gas produced from metal corrosion may contain tritium; but tritium is of little concern in the long-term because of its relatively short half-life (12.3 years).

Longer-term evolution and coastal erosion

The rate of coastal recession is related to the rate of sea-level rise, that is, more rapid sea-level rise will lead to more rapid erosion. Thus, although there is uncertainty about the rate of sea-level rise and timing of erosion, our understanding and modelling (see argument S4) indicates that the vaults are most likely to be disrupted by undercutting, with consequent distribution of engineered materials and wastes onto the beach. Such erosion would occur mainly during storm events. As erosion proceeds and sea level continues to rise, the trenches are also most likely to be undercut, but with a possibility of direct erosion at sea level for the more inland trenches.

Sections of vault base and large waste items may remain on the beach below the cliff for years to decades, but most contamination is associated with materials (corrosion products, degraded residues from organic wastes, mineral sands etc.) that are liable to be dispersed and mixed with natural beach gravel, sand and sediments. Contaminated sediment of the local foreshore will mix with the larger reservoir of sediment offshore. Contaminants will be released from the wastes and foreshore sediments into marine water solution and be sorbed on natural sediments.

Coastal studies indicate that there is little transfer of sediment into or out of the coastal cell between St Bees and Walney Island (near Barrow). Hence, the fate of all solid material eroded from the LLWR will be distribution along this coast, and, in the longer term, dispersion and burial in the Irish Sea. Contaminated sediments from the offshore may also be deposited back on beaches along the length of the coast and in local estuaries and embayments. More mobile contaminants will be carried in marine solution and dispersed into the Irish Sea and beyond.

Human Intrusion

After the Period of Authorisation, there is a possibility that people may intrude into the facility without knowledge of its contents. For example, a trial pit might be dug as part of a site investigation. However, the final engineered cap is designed to deter human intrusion and information on the hazards associated with the site will be recorded to deter such inadvertent human intrusion.

A2: Quantitative analysis and modelling

To provide clear quantitative understanding of the key processes and results we develop separate models to assess different ‘pathways’ by which contaminants are released, migrate and give rise to exposure: migration in groundwater; migration in gas; natural disruption and dispersion (coastal erosion); human actions.

We assess these pathways and interactions between them for defined scenarios, focusing on the expected evolution of the disposal facility and its environment. We apply appropriate models to analyse each of the above pathways for defined scenarios. Our assessment models often incorporate cautious assumptions, for example, where a particular process is difficult to represent in the model. We compare assessment results from each pathway, consider the timing and location of impacts, and hence determine whether an individual could be exposed via multiple pathways.

This argument relates to GRA Requirements 5 to 7 and 9 and 10 [29]; further support to this argument is given, in particular, in the ‘*Environmental Safety During the Period of Authorisation*’ [13] and ‘*Assessment of Long-term Radiological Impacts’* [14] reports.

As indicated in argument A1, at any one time many processes will be operating and radionuclides or other contaminants may be being released, migrating and giving rise to exposure by multiple routes. To develop representations that provide clear quantitative understanding of the key processes and results, and to make the analysis tractable, we choose to develop separate models to assess different ‘pathways’ by which contaminants may be released, migrate and give rise to exposure.

For assessments in the Period of Authorisation, the degree of uncertainty over conditions and evolution is less than in the long term, and we generally use results from monitoring and conventional models, as developed for modelling of routine discharges and releases. The approach to analysis, and the addition of impacts via different pathways, are discussed in argument A4.

For longer-term assessments, we identify four pathways:

- migration in groundwater;
- migration in gas;
- natural disruption and dispersion (coastal erosion);
- human intrusion.

When considering the Period of Authorisation, we also consider external irradiation.

We recognise that there is interaction, correlation, and the potential for addition, between the pathways. For example, changing vault or environmental conditions will simultaneously affect migration in more than one pathway, damage due to human intrusion might affect releases by other pathways, and an individual could be simultaneously exposed to more than one pathway. We have developed a revised methodology based on Environment Agency guidance to address the habits of individuals over different assessment periods. For calculations of impact during the Period of Authorisation, we base our calculations on the habits of groups of individuals from different areas around the LLWR. These habits are based on local surveys and account directly for the likelihood that occupancies and behaviours may result in exposure by more than one exposure pathway.

We have defined three alternative climate scenarios as a basis for our assessment calculations (see argument S4).

We have then developed appropriate models or a model chain to analyse each of the above pathways and represent the uncertainties related to each pathway.

Each of the pathways is analysed and modelled independently, taking account of the range of uncertainties for the defined scenarios and uncertainties related to the contaminant release, migration and exposure processes for each pathway. Models present a cautiously realistic representation of the features and processes. That is, we apply our knowledge to develop models of physical and chemical processes that are realistic where possible, but may be cautious when assumptions are required, for example where processes are difficult to represent in assessment models. We also check for interactions and correlations.

The assessment calculations for human intrusion and coastal erosion begin with the complete contaminant inventory in place, not allowing any depletion due to prior loss or change except due to radionuclide decay and in-growth. We also define representative persons with location, habits and diet such that their exposure is cautiously estimated in the context of the given scenario and pathways.

Finally, we compare assessment results from each pathway, the timing and location of impacts, and hence consider whether an individual could be exposed via multiple pathways.

Over the long term, we find that this is not the case because of differences in timing of peak impacts via different pathways, and because the cautious assumptions on habits of representative persons make it unlikely that an individual could simultaneously be undertaking the assumed activities or habits representative of more than one pathway.

A3: Uncertainty management

We have identified and taken account of outstanding uncertainties and open decisions with the potential to materially affect our assessment and related ESC arguments, and outlined the work needed to better understand the key uncertainties to support future assessments and decisions.

This includes the development of a register of significant uncertainties.

This argument relates to GRA Paragraphs 7.2.4 and 7.3.10 [29]; further support to this argument is given, in particular, in the '*Near Field'* [5], '*Hydrogeology'* [6], '*Site Evolution*' [7] and '*Assessment of Long-term Radiological impacts*' reports [14].

Uncertainty originates from lack of knowledge of parts of the studied system and from the random nature of some phenomena. This lack of knowledge can arise from limited measurements, uncertainty in interpretation of measured data, insufficient understanding of processes, spatial variability and the uncertain occurrence of events. In the context of the LLWR and its assessment, uncertainties arise from:

- uncertainties concerning past and future waste disposal operations, for example, the radiological inventory, future engineering and operational choices;
- uncertainties in the characteristics of the waste disposal facility and its environment, for example, due to measurement uncertainty, measurement interpretation, applicability of literature values rather than measured values, and variability of parameters in time and space;
- uncertainties about the long-term evolution of the waste disposal facility and its environment and concerning future events that may have an impact on the disposal facility and its environment;
- uncertainties concerning future human behaviour.

It is necessary to recognise the relevant uncertainties and analyse them to the extent that is helpful in guiding the development of the facility and assuring its safety and compliance with regulatory requirements. At a given step, the treatment of uncertainty may be constrained by limited data, the models that are available and uncertainty over the future waste arisings and future decisions over management of the facility. The treatment of uncertainty within safety assessment aims at:

- identifying priorities for further work to reduce uncertainty where it is important;
- enabling regulatory and management decisions to be taken on the development of the disposal facility that account for the presence of uncertainty.

Some uncertainties will remain unresolved, but this does not prevent an assessment of the safety of the disposal facility taking account of the outstanding uncertainties. As stated in the GRA: *'Uncertainties themselves are not obstacles to establishing the environmental safety case, but they do need proper consideration and including in the structure of the environmental safety case as appropriate.'* We have adopted a classification of uncertainties that is conventional in radioactive waste disposal assessment, focusing on their mode of treatment in the safety assessment:

- Scenario uncertainty – are the (safety assessment) scenarios considered sufficiently complete in their representation of the possible evolutions of the disposal facility and its environment?
- Model uncertainty – do the models describe the real-world features and processes in an adequate way (in safety assessments we aim at not underestimating impact)?
- Parameter uncertainty – what impact do possible variations of the parameter values have on the results of the safety assessments?

As part of this ESC, we have:

- defined three scenarios that are considered to span the range of potential climate evolutions [7];
- considered whether alternative models of the system are appropriate, for example, in relation to the conceptual hydrogeological model [6];
- identified the key uncertainties relating to different parts of the system [5, 6, 7];
- explored the implications of those key uncertainties in terms of estimated radiological impacts by undertaking variant calculations for a range of calculation cases or by means of system understanding [13, 14, 15, 16];
- explored other uncertainties by undertaking underpinning technical studies [5, 6], for example, in relation to heterogeneity in the wastes and in the geosphere;
- undertaken probabilistic calculations for radiological impacts for the groundwater pathway, based in part on a set of elicited probability density functions for key parameters [14];
- used our understanding of the key uncertainties as a major input to the development of the technical programme that we have put in place in support of the ESC;
- identified those uncertainties and biases that still warrant further work (see Section 6);
- established a register of significant uncertainties, which indicates how uncertainties have been addressed and the extent to which further data gathering, calculations or decisions are needed [56].

Key uncertainties, based on judgment and our understanding of the system, include the following:

- inventory of disposed wastes and management and characterisation of future wastes that may be disposed of;
- the time at which the facility will be eroded by the sea, sea level at the time of erosion and rate of release of radionuclides from eroded material into marine waters;
- the rate of gas generation in the trenches and extent of microbial activity in the vaults and hence uncertainty in the generation rate of C-14 from key wasteforms;
- the evolution of the properties of the engineered cap over time;
- the evolution of gas pressures in the repository, which is relevant to vent design.

The implications of these key uncertainties are explored in the '*Assessment of Long-term Radiological Impacts*' report [14].

We have made substantial progress since the 2011 ESC in resolving or characterising some key uncertainties, including:

- the implications of alternative geological and hydrogeological interpretations [6]
- the properties and evolution of the cap and other engineered barriers [12];
- the processes governing the generation and release of radioactive gases [5];
- rates and processes in the near field taking account of the low rates of infiltration that are expected through the cap [5].

A4: Radiation doses during the Period of Authorisation

Environmental safety during the Period of Authorisation is managed, and impacts controlled and monitored, through the Site Development Plan, such that doses to members of the public are ALARA.

We estimate potential radiation doses to members of the public in the vicinity of the site based on local habit data, taking account of the fact that the same individual may receive doses by more than one exposure pathway. We have estimated such radiation doses based on monitoring data and assessment calculations. These estimates take account of present-day conditions and site developments up to the end of regulatory control of the site, including the effect of uncertainties in releases to the environment.

Present day doses and modelled doses after capping is completed are less than the applicable dose constraint. Modelled doses during future operations are dominated by external irradiation. Our assessment indicates that wastes with higher external dose rates than are currently received may arise in future. If waste with higher external dose rates does arise in future, our monitoring arrangements will enable us to identify any adverse trends and we would implement any controls needed to ensure that doses were below the applicable dose constraint and were ALARA.

This argument relates to GRA Requirement 5 [29]; further support to this argument is given in the '*Environmental Safety During the Period of Authorisation*' report [13].

The Period of Authorisation means the period during which a Permit (it was an Authorisation under previous legislation) is held. For the LLWR, it encompasses the present-day situation, the period of continued disposals at the site (operations), the period in which site engineering is being completed, and continued monitoring and phased cessation of active controls (closure).

Site Development Plan

Environmental safety in this period is managed through an optimised Site Development Plan (see Subsection 3.3) derived under our Environmental Safety Strategy (see Subsection 3.1). The Site Development Plan provides for:

- engineering to minimise the generation of contaminants in effluents, and collection and controlled discharge of those that arise, using existing engineered measures, appropriate future vault design, interim trench cap replacement and early implementation of closure engineering features such as the final cap and the cut-off wall;
- the use of site management controls, including prevention of access during operations and in management controls to prevent human intrusion into the engineered barriers or waste during the institutional control period;
- the collection of information on effluents, discharges, dose rates and environmental concentrations, which provide information on the functioning of the engineered barriers and management controls, as well as providing a baseline against which future performance can be gauged.

The current Site Development Plan is based upon the disposal of LLW only and does not, therefore, include the provision of capability required for less-hazardous ILW disposal. If ILW disposal were to be pursued at the LLWR, modifications would be required to the Site Development Plan. This would include construction of shielded modules for disposal of ILW with higher dose rates. We would allow for flexibility with respect to the location and size of the shielded modules in the vaults as this offers a means of managing uncertainty in the volumes of waste that may require such shielding. It also provides flexibility in ensuring that operational impacts from wastes in shielded modules are ALARP.

Sources, Pathways and Receptors

During the Period of Authorisation, members of the public may be exposed via the following pathways or sources:

- permitted discharges of leachate and vault run-off via the Marine Pipeline;
- external irradiation (outside the site boundary) from receipt and emplacement operations, and emplaced waste;
- discharges of radioactive gases (H-3 and C-14-bearing gases, Rn-222) to air;

- radioactivity in the Drigg Stream, which relates to discharges to the stream prior to upgrading of leachate collection and discharge arrangements;
- radioactivity in groundwater if abstractions were to occur, although no abstraction well exists at present and should be prevented in future through NDA control of land between the disposal facility and the coast.

We have assessed each of the above pathways or sources using a combination of monitoring data (in respect of present discharges via the Marine Pipeline, release of tritium to air and residual radioactivity in the Drigg Stream), results from long-term assessment models (in respect of projected releases to groundwater and releases of C-14-bearing gas), and models specific to the Period of Authorisation assessment (in respect of discharges of radon and external irradiation).

Members of the public could be exposed simultaneously by multiple pathways. We have developed an approach to defining 'representative persons' for consideration during the Period of Authorisation. Our approach takes account of guidance that applies to impacts from permitted discharges from nuclear sites and results of previous Period of Authorisation assessments and retrospective dose assessments. These indicate that exposures during the Period of Authorisation are dominated by external irradiation while the vaults are operational, and atmospheric releases after the cap is completed. Proximity to the LLWR is therefore the most significant characteristic of an exposed group.

We take a cautiously realistic approach for assessments in the near future (considered to be the next ten years) and apply increasing caution at later times to reflect increasing uncertainty in human behaviours. We have therefore defined two sets of habits.

- For prospective assessments of up to ten years in the future, we apply a modified ‘local profile’ approach. The approach makes use of ‘local profiles’ defined in habits survey reports, which are based on local survey data. These are supplemented with local knowledge of specific dwellings and other buildings near the LLWR and associated occupancy times. Members of these exposure groups are termed ‘candidate representative persons’.
- For assessments of prospective dose from ten years hence to the end of the Period of Authorisation, we apply a more cautious ‘modified top two’ approach. In this method, high-rate intake rates are assumed for two foodstuffs that contribute most to the dose, with mean intake rates used for other foods (which are all assumed to be locally sourced). The high-rate intake rates are selected from the greater of those calculated using locally-derived or generic data. Members of these exposure groups are termed ‘potential representative persons’.

Several exposure groups are considered during each time period. Where groups could be exposed via multiple pathways, combined doses are calculated.

Assessment and Management

At the present day, the cautiously estimated maximum annual dose related to the LLWR is less than 0.05 mSv. Future annual doses depend on assumed future habits and locations, but are dominated by external irradiation until the final cap is completed. The peak total annual doses to the representative person calculated between now and completion of capping were 0.35 mSv for the Reference inventory (which includes ILW) and 0.14 mSv when only LLW is considered. Dose from radon inhalation contributes less than 0.005 mSv and all other pathways contribute 0.001 mSv or less to the total assessed doses to the representative person from the Reference inventory. Our model of external dose uses cautious assumptions. Our monitoring and management arrangements and, if necessary, waste controls, would ensure that doses were ALARA and below the applicable dose constraints (0.3 mSv).

External doses from uncapped vaults are likely to be higher than present day doses as the projected future inventory contains higher activities of Co-60 and Cs-137, which are the main contributing radionuclides to external doses. Our Reference inventory suggests there could be some higher dose rate LLW from Sizewell B and new build reactors in the longer term (likely to be disposed in Vault 10 onwards). There is uncertainty in the volume and activity of wastes that might arise from the nuclear new build programme. Improved inventory information would be available closer to the time of design development for future vaults that would inform our approach to both vault design and waste emplacement plans. We undertake quarterly monitoring of dose rates offsite, which would enable us to identify any adverse trends in dose rate. Should dose rates measured offsite start to increase or if consignors propose higher dose rate waste for disposal, there are several actions we could take to ensure that doses to members of the public offsite were ALARA and consistent with the dose constraint. Our ESC and Nuclear Safety Case teams would consider the optimised strategy for managing high dose rate waste at the time. As such, we have not committed to a specific management approach for higher dose rate LLW, if it were to arise and be accepted for disposal at the LLWR. If a decision was taken to accept ILW for disposal, high dose rate ILW would be disposed in shielded modules. We would undertake further work to improve our modelling approach and understanding of the inventory prior to any decision to accept ILW. We would also undertake work to develop our approach to handling higher dose rate ILW alongside our Nuclear Safety Case team. We will ensure that our operational approach and future vault designs keep doses to members of the public ALARA and below the dose constraint.

The number of offsite individuals that could be exposed to higher levels of external irradiation is very small, a few to tens at most walking or dwelling very close to the operating disposal area. A larger number of individuals may be exposed as a result of marine discharges, although only a few will have habits such as to experience the calculated doses from this pathway based on the habits of potential representative persons and assessed doses are very low.

The cap will reduce external dose rates to negligible levels. Following completion of the final cap, doses are dominated by inhalation of radon, and annual doses will be less than 0.005 mSv.

Thus, we are confident that the annual effective dose from the LLWR to a representative member of the critical group will not exceed a source-related dose constraint of 0.3 mSv, as demanded by Requirement 5 (paragraph 6.3.2 of the GRA).

A5: Radiation doses and risks in the long term

We have assessed the radiation doses and risks to potentially exposed individuals in the long term (after the Period of Authorisation) for the scenarios and pathways discussed in argument A2, including natural degradation and release pathways, and human intrusion.

The assessments focus on a broadly expected evolution of the local environment, uncertainties in the properties of the wastes, engineered barriers and hydrogeology, and uncertainties in radionuclide release, migration and exposure processes. We have considered a range of cautiously-defined potential representative persons, to identify the persons representative of those at greatest risk, or who may receive the highest doses.

For releases in groundwater, gas and coastal erosion, we calculate risks and conditional risks to those exposed that are consistent with the risk guidance level of 10^{-6} y^{-1}.

For realistic and foreseeable human intrusion events, we calculate doses to the intruders and those exposed in the longer term as a result of prior intrusion events that are consistent with the dose guidance level range of 3 to 20 mSv y^{-1}.

This argument relates to GRA Requirements 6 and 7 [29]; further support to this argument is given in the '*Assessment of Long-term Radiological Impacts*' report [14].

From our detailed characterisation and understanding (see Subsection 4.3), we have developed an integrated understanding of the evolution of the LLWR and its environment (see argument A1) and developed models to assess the pathways by which contaminants are released, migrate and give rise to exposure: migration in groundwater; migration in gas; natural disruption and dispersion (through *coastal erosion*); and human actions (see argument A2). We have carried out the assessments of each pathway taking account of the range of uncertainties (see argument A3) related to:

- the waste inventory, engineering and operational choices;
- the characteristics of the disposal facility and its environment;
- the long-term evolution of the facility and its environment;
- radionuclide release, migration and exposure processes;
- future human behaviour and activities.

Table 4.1 presents a summary of the assessed risks via groundwater and gas pathways, which may be compared with the risk guidance level of 10^{-6} y^{-1}. Results are presented for the groundwater well probabilistic case and for reference deterministic cases and exposed groups. We present results for the coastal erosion pathway primarily as annual dose to emphasise that the cases relate to conditions or evolutions, the probabilities of which are not quantified. We identify, however, the cases that we consider most representative or ‘central’ and therefore most appropriate to compare with an annual dose of 20 µSv, i.e. a dose corresponding to the risk guidance level. Human intrusion is assessed against a dose guidance level range and not included in the table. All calculations have been based on the Stage 2 inventory, which includes some less-hazardous ILW. Further details are provided in the text below.

Table 4.1: Summary of assessed risks from reference cases

Pathway	Case	Risk, y^{-1} Dose, µSv	Key radionuclides
Groundwater	Well user – probabilistic case	$4\ 10^{-7}$	Ra-228, Th-232, Th-228
	Well user – deterministic case	$2\ 10^{-9}$	I-129, Tc-99
Gas	Smallholder, vent closed, geomembrane intact	$8\ 10^{-8}$	Rn-222
	Smallholder, vent closed, geomembrane degraded	$1\ 10^{-7}$	C-14
	Smallholder, open vent	$1\ 10^{-9}$	C-14, Rn-222
Coastal Erosion	Recreational beach user	22 µSv (trenches) 11 µSv (vaults)	Th-228, Ra-228 for trenches Nb-94 for vaults
	Inshore fisherman	19 µSv	Th-228 / Ra-228
	Marine foodstuff consumer	15 µSv	Pu-239

Groundwater pathway

The hydrogeological models have been used to consider the long-term behaviour of the site taking into account the expected evolution of climatic conditions and the possible long-term performance of the engineering components. We have undertaken a range of deterministic calculations and a probabilistic calculation based on numerical models of groundwater flow and transport. Our hydrogeological model is computationally intensive and, also, not suited to capture the full range of behaviours that may occur, given the significant uncertainties in the evolution of the engineering components. A simplified Compartment Flow Model has therefore been developed to carry out the large numbers of probabilistic cases required. The Compartment Flow Model allows the simulation of flows and water levels in hundreds of alternative realisations.

Several changes have occurred since the 2011 ESC in our understanding of the evolution of the near field (see argument S2), in particular, in relation to infiltration through the cap and the evolution of pH. New information on the properties and evolution of geomembrane properties and evolution of geomembranes leads to an updated view that there will be low infiltration through the cap for a much longer period than was assumed in the 2011 ESC. This means that the pH will remain high at around 13 for an extended period of time. We have investigated the potential effects of uncertainties in these findings.

We have assessed the impact from the groundwater pathway using models with varying degrees of complexity. Our reference case model is similar to that used in the 2011 ESC in which the near field is represented as a series of homogeneous compartments with uniform flow. We have investigated the potential impact of slow transport of contaminants to gaps between the containers in which most water flow is considered to occur. The results for the reference case and this dual porosity model are found to be very similar. We have also used a scoping model that is intended to capture the key processes controlling release, but in a simplified manner. The scoping model provides assurance that the results obtained with the detailed assessment models are correct, and provide a credible basis for understanding the potential hazards from the well pathway.

The biosphere pathway giving rise to the greatest impacts is the well pathway, based on the assumption that there is a water abstraction well between the disposal facility and the coast. We have also considered potential impacts from estuary, stream and marine discharge paths and from delayed coastal erosion. Potential representative persons receive external exposure, inhale and ingest dust, and consume contaminated products, for example, drinking water, and eating garden produce, marine foodstuffs, animal products etc.

In the reference case, deterministic case peak risk from the well pathway is about 2.3 10^{-9} y^{-1} occurring around 2250 (that is, about 100 years after completion of the final cap); the key radionuclides are I-129 and Tc-99. In the corresponding probabilistic calculation case, the peak mean radiological risk is 4.2 10^{-7} y^{-1} with the largest contributions arising from Th-232 chain radionuclides. The mean is dominated by a small number of realisations with low radium or thorium sorption coefficients.

The reference case is based on the reference climate evolution scenario. We have calculated cases for the two alternative climate scenarios identified above. Results are very similar for each climate evolution scenario.

In order to investigate the effects of cap performance less good than assumed in the reference case, we assessed a variant with the infiltration rate through the cap increased to its 95th percentile value and the time of cap degradation reduced to its 5th percentile value; this calculation case represents the cap performing significantly worse than anticipated. Results were about two orders of magnitude greater than in the reference case, but still well below the risk guidance level.

The calculation of risk for the well biosphere path includes an estimate of the annual probability for the presence of the well between the disposal area and the coast. This was derived taking account of possible future domestic, agricultural land and leisure uses of the land. The number of persons that could be exposed at the levels calculated is of the order of a few to a few tens.

Gas pathway

The gases of key concern are:

- C-14-bearing methane and carbon dioxide, generated from C-14-bearing wastes;
- Rn-222 (radon) generated from Ra-226-bearing wastes.

Some of the potential exposure situations considered in this assessment are likely to occur (probability close to one) whilst others are less likely (probability much less than one).

Ordnance Survey map data have been used to calculate the spatial density of buildings on the West Cumbrian coast. The results are fed into a statistical analysis to calculate the probabilities of different exposure situations.

Carbon-14

Wastes are assigned to one of five material categories for which specific release rates and C-14 speciation are applied. Release rates may be experimentally determined, as for graphite, or based on corrosion rates, degradation rates, or cautious assumptions where there are no other data.

Any primary releases as methane are assumed to reach the biosphere. In the trenches, C-14-bearing carbon dioxide is also lost directly to the biosphere along with methane. In the vaults, inorganic carbon in the form of carbon dioxide gas or dissolved carbonate is assumed to react with the grout, forming immobile carbonate minerals. The soluble C-14-bearing organic molecules remain in the container porewater until released into the gaps between containers, where it can undergo further reaction to form C-14-bearing gas.

The biosphere model takes fluxes of C-14 gas from individual repository compartments and then represents the processes of mixing of C-14-bearing carbon dioxide in the plant canopy atmosphere and uptake into vegetation by photosynthesis. Different vegetation heights or crop types can be represented. Specific concentrations (Bq $kg[C]^{-1}$) of C-14 in plant foodstuffs or animal fodder and hence animal products, and doses via consumption of these products, are calculated. The potential representative person is a smallholder self-sufficient in vegetables and fruit grown on the cap, and with milk from goats grazed on the cap.

The reference case assumes the cap vent is closed at the end of the Period of Authorisation. With the geomembrane intact, infiltration is too low for any significant release of C-14 in solution from the containers. The pH in the containers is expected to be too high for significant microbial activity. This limits the amount of C-14 gas generated and released. The peak risk is 5.5 10^{-9} y^{-1}, which occurs immediately after the Period of Authorisation. This is more than two orders of magnitude below the risk guidance level. A key assumption in the reference case is that the cap geomembrane does not fail before the repository is disrupted by coastal erosion. There is potentially greater than 50% likelihood the cap geomembrane would still be intact when the repository starts to be disrupted by coastal erosion. However, there is also a substantial likelihood that the cap geomembrane would fail before the repository starts to be disrupted by coastal erosion. With earlier than expected degradation of the cap geomembrane, at 1,000 years after placement, the calculated peak risk increases to 1.2 10^{-7} y^{-1} and occurs immediately following geomembrane failure.

With early failure of the cap geomembrane, there is sufficient infiltration for small C-14-bearing organic molecules to be transported out of the containers by diffusion and leaching, into the gaps between container stacks and the bases of the vaults where the pH is lower. There, microbes are expected to be active and metabolise the small organic molecules forming C-14 gas. Small organic molecules are expected to ‘build up’ in the container porewater while the cap geomembrane is intact. Once the geomembrane fails, there is a peak in releases of small organic molecules from the containers, leading to a peak in generation and releases of C-14 gas.

Irradiated graphite wastes are the main sources of C-14-bearing gas from LLW and ILW after the Period of Authorisation. In the early geomembrane failure case, gas generated from degradation of soluble organic C-14 species from organic and 'other' wastes are the dominant contributors to the peak after geomembrane failure. In the 2013 assessment [57], irradiated graphite and irradiated steel wastes were the main sources of C-14 gas. The C-14 gas fluxes per unit inventory have decreased significantly from these waste types compared with the 2013 assessment. This is due to slower steel corrosion rates, improved understanding of the form of release from steels, and improved understanding of the availability and rate of release from graphite. The slower corrosion rates reflect updates to the near-field conceptual model (pH in the containers) and significantly updated information on steel corrosion rates under different conditions.

If the cap vent is left open at the end of the Period of Authorisation, releases of C-14 gas are focused through the vent. Potential doses to users of smallholdings on the vent are higher than in the reference case, which considers smallholdings anywhere on the cap. However, because the probability of at least one smallholding on the vent is lower than the probability of at least one smallholding on the cap, the risk from C-14 is lower for the open vent case than the reference case. The risks for the open vent case depend on the layout of the smallholding over the vent, that is, whether the house and its kitchen garden are located directly above the vent or not. Peak risks vary between 9.3 10^{-10} and 3.4 10^{-9} y^{-1} depending on the layout.

Overall, the results provide confidence that with appropriate control of the use of the radiological capacity, the potential risks after the Period of Authorisation from C-14 gas can be limited to the levels described in the GRA.

There are significant uncertainties in the model for release from the containers following failure of the cap geomembrane. These uncertainties affect the calculated capacities. However, the model includes several cautious aspects, including accumulation of C-14 in solution in the containers prior to failure of the cap geomembrane. Once the cap geomembrane fails, the C-14 is released from the containers over a comparatively short period and rapidly microbially metabolised to C-14 gas. Therefore, there is limited scope for a realistic model that leads to higher release rates and lower calculated capacities.

The capacities for future stronger containers are significantly greater than for current containers. Capacities for existing containers are expected to be underestimated due to cautious simplifying assumptions in the calculations. However, it is difficult to justify robustly less cautious assumptions.

Radon

Changes to our understanding of the performance of the engineered cap mean that advection of radon by bulk gas is expected to be an important transport process. In contrast, transport of radon was expected to be dominated by diffusion in the 2011 ESC. We have therefore developed a new model for the transport of radon gas.

The cap geomembrane is expected to have a lifetime of hundreds of years to a few thousand years. While the cap geomembrane is intact it will be a barrier to release of bulk and radon gas. With the cap vent closed, a small gas overpressure is expected to develop in the repository, with bulk gas flowing through defects in the cap geomembrane to discharge at the cap surface. Bulk gas could also flow through or under the cut-off walls to discharge at the perimeter of the cap. The proportions of bulk gas, and associated radon, that discharge at the cap surface compared with the perimeter of the cap are uncertain. The reference case cautiously assumes all discharge is to the surface of the cap. This gives the shortest travel time and least decay of radon, and therefore higher risks than discharge at the perimeter of the cap.

With the cap vent closed and the geomembrane intact, the peak reference case radon risk to houses developed on the cap is $7.4\ 10^{-8}\ y^{-1}$, which is below the GRA risk guidance level.

If the cap geomembrane fails before the repository starts to be disrupted by coastal erosion, then bulk gas velocities will decrease leading to slower transport of radon by bulk gas, greater decay of radon, and lower risks. Risks are around a factor of 12 to 17 lower compared with the geomembrane intact. However, advection is still a significant process. If advection is removed from the assessment model, so transport of radon is only by diffusion, then risks from radon are negligible, consistent with the assumptions and results of the 2011 ESC.

The case where the cap vent is left open and a house, or houses, are built on the vent results in slightly higher doses than the reference case. However, assuming there is no preference for constructing houses on certain areas of the cap, the risks from this case ($4.5\ 10^{-10}\ y^{-1}$) are significantly lower than from the reference case. While there is high probability there would be at least one house on the cap, the probability of there being at least one house on the vent is considerably lower.

The results provide confidence that with appropriate WAC, and control of use of the radiological capacity, the potential risks from radon gas can be limited to the levels described in the GRA after the Period of Authorisation.

Initial work is being undertaken to identify credible alternative vent designs. Options have been identified that should reduce radon fluxes from the vent and reduce the probability of a house (or houses) being built on the vent.

Combined risks from Radon and C-14-bearing gas

People living in smallholdings on the cap may be exposed to radon gas in the house and C-14 from consumption of produce from the smallholding. The peak risks from radon and C-14 gas do not occur at the same time in all cases. Therefore, the risks are added for each future time and the peak found. The peak risks for the Stage 2 inventory are given in Table 4.2. They are all below the risk guidance level.

Table 4.2: Combined doses from C-14 and radon to a small-holder occupying a house on the cap

	Vent closed, geomembrane intact	Vent closed, geomembrane degraded	Vent open
Risk y^{-1}	$7.9\ 10^{-8}$	$1.3\ 10^{-7}$	$1.4\ 10^{-9}$
Radon contribution %	93%	3%	33%
C-14 contribution %	7%	97%	67%

Natural disruption – coastal erosion

Coastal erosion is identified as the mode by which the LLWR will be disrupted by natural means. As discussed in argument S4, we conclude that the repository will begin to be eroded during a period of several hundred to a few thousand years after present. Other possible modes of natural disruption, for example, cap erosion or glacial scouring, will be of little effect or will not occur before coastal erosion disrupts the facility. We consider that onset of coastal erosion before 300 years after present is very unlikely; by this time the radiological hazard from direct exposure to the vault wastes will have declined by an order of magnitude.

The consolidation of scientific and monitoring work related to coastal characteristics and processes, and description of potential future coastal development (see argument S4), have been used to develop a detailed numerical model for the assessment of the radiological impacts of coastal erosion. Notable features of the model are its capability to represent the spatial heterogeneity of the wastes, and the explicit treatment of the erosion of wastes and their dispersion from the eroding cliff, through the storm beach and foreshore, and into the marine environment. The model has considerable flexibility, which has enabled a range of uncertainties to be explored.

The calculated concentrations of radionuclides in different parts of the shore environment change with time as different parts of the LLWR, containing different wastes, are eroded. The calculated concentrations reproduce the dilution of waste with co-eroded materials and the foreshore-offshore sediment tidal mixing. Assessed annual doses to potential representative persons take account of exposure to the different parts of the local coastal environment and more widely dispersed radionuclides. Locally, the dominant exposure pathway is external irradiation to wastes present on the beach and foreshore; along the coast, external exposure to more generally dispersed contamination and doses via marine foodstuffs are important. Three reference potential representative persons are considered as being present at all times:

- a locally-based recreational user of the shore adjacent to the LLWR site, for example, a dog walker or beachcomber;
- an occupational group of inshore fishermen basing its activities anywhere on the coast between St Bees and the Ravenglass Estuary;
- a group of high-rate consumers of marine foodstuff harvested from the local coastal water between St Bees and the Ravenglass Estuary.

The reference case considers erosion of the vaults by undercutting, beginning at about 1,250 years after present, and passing through the facility on a front aligned parallel to the general alignment of the coast, and hence parallel to the line of the vaults and then each trench in turn.

The reference calculation case yields a peak annual dose of 22 µSv for the locally-based recreational exposure group, principally due to progeny from Th-232 in Trenches 4 and 5. The peak annual dose to this group from LLW and ILW in the vaults of 11 µSv occurs earlier. The peak annual dose to the inshore fisherman potential representative person, assuming the disposal of LLW and ILW is 19 µSv. Calculations of potential dose from the ingestion of marine foods, again assuming the disposal of LLW and ILW lead to an annual dose of 15 µSv.

If ILW were not included in the inventory, calculated peak doses from the vaults reduce to 2 µSv for the recreational user, 3 µSv for the occupational user and 5 µSv for the marine foodstuff consumer.

The marine model has been improved for the 2026 ESC, so it now represents progressive burial of eroded materials and associated radionuclides in the sediment sink. The marine model is used in the calculation of doses to the inshore fisherman potential representative person, and the high-rate marine foodstuff consumer potential representative person. The improved marine model provides a more realistic representation of the system than the 'well mixed' representation used in the 2011 ESC. This change results in slightly higher peak radionuclide concentrations, per unit inventory disposed, in surface sediments in the regional sediment sink cell, and along the wider coastline, compared with the 2011 ESC approach. Therefore, it results in slightly higher doses, per unit inventory disposed, compared with the 2011 ESC approach.

The peak calculated doses to occupational potential representative person and marine foodstuff consumers potential representative person are broadly consistent with the dose corresponding to the risk guidance level (20 μSv), assuming exposure occurs. Doses again show a peak associated with erosion of the shielded modules and peak doses from marine foodstuffs occur when erosion of the shielded modules finishes. The key radionuclides are Pu-239 and to a lesser extent C-14 and Pu-240. Doses to the inshore fisherman potential representative person also show a peak at the same time due to Nb-94 and Pu-239 in the shielded modules, however, the highest doses to the occupational potential representative person occur during erosion of the trenches. This is due to Ra-228 and Th-228 ingrown from Th-232 disposed in the trenches, plus an additional dose contribution from Nb-94 and Pu-239 disposed to the vaults that remain in the surface sediments of the regional sediment sink when the trenches are eroding. Where doses arise from future disposals, we will consider reducing them either through emplacement or capacity measures, as set out in the '*Implementation*' report [17].

The results of variant calculation cases show the most significant biases and uncertainties are associated with:

- the radionuclide inventory and spatial distribution of radionuclides in the vaults;
- the amount of relative sea-level rise, and therefore the elevation of the back of the storm beach, at the base of the cliffs, when the trenches are eroded;
- radionuclide – particle size associations, which affect the radionuclide transport velocities compared with bulk materials; and sorption distribution coefficients for radionuclides in the coastal and marine environment.

The timing of erosion is a less significant uncertainty for the dose calculations because the additional radioactive decay (and ingrowth) of the key radionuclides is small, when comparing the longest timescale for erosion with the shortest.

We have also assessed situations in which the waste attracts specific interest. Such situations are, in accordance with Environment Agency guidance [30], assessed against the same 3 mSv and 20 mSv annual dose guidance levels appropriate for human intrusion. These cases are assessed as part of our human intrusion assessment (see below).

If coastal erosion at the LLWR is assumed not to take place, the 3 mSv y^{-1} dose guidance level would be exceeded for the occupier and smallholder events, the earliest time at which this occurs being 25,000 AD. This is due to the ingrowth of radon from decays of U-234 and Th-230 via Ra-226. However, this variant is not considered credible and is included only to explore the hazard profile over time.

In terms of the potential for deterministic health effects, none of the assessed effective doses exceed the relevant threshold.

Overall, the results provide confidence that with appropriate measures, the potential impacts from coastal erosion of the vaults can be limited to the levels described in the GRA. Disposals of some of the Pu-239 bearing ILW streams included in the Reference inventory may need to be limited to ensure peak calculated doses to high-rate marine foodstuff consumers remain at or below 20 µSv.

Human intrusion

The guidance in the GRA [29] requires that human intrusion into a near-surface disposal facility after the end of management control of the site is to be assessed on the basis that it occurs, and against a dose guidance level in the range of around 3 mSv for exposures continuing over a period of years to around 20 mSv for exposures that are only short term.

We have identified a range of possible human intrusion events and subsequent more prolonged exposure situations, based on geotechnical practices and credible future uses of the site, assuming the site is no longer protected under planning procedures and/or the presence and nature of the disposal facility is forgotten. We have reviewed the events addressed and added to the list that was used as a basis for the 2011 ESC assessment. We have assessed these qualitatively, and selected for quantitative assessment those that we consider are representative and have potential to cause radiological exposures. This includes cases that occur while the repository is still intact, and cases that could occur when the facility is eroding and wastes are more directly accessible at the coast. We have characterised the selected events and exposure situations based on geotechnical practice and cautious assumptions concerning the fate of excavated material and subsequent use of any contaminated environment created. We have also examined the impact of heterogeneity of waste activities in past and projected disposals at a trench section and vault scale.

For geotechnical investigation intrusion events, exposures following borehole drilling or trial pit investigations, the maximum assessed dose is 3.7 mSv, which occurs from existing waste disposals in the trenches. This is below the 20 mSv dose guidance level.

For exposures to those involved in the construction of a housing development, the maximum dose is 0.08 mSv, significantly below the 20 mSv dose guidance level.

For events involving prolonged occupation of a house or the use of a smallholding, both on land previously contaminated as a result of human intrusion, the maximum dose is below the 3 mSv dose guidance level (2.1 mSv and 1.8 mSv).

In terms of the potential for deterministic health effects, none of the assessed effective doses exceed the 100 mSv threshold, above which deterministic effects become increasingly likely. In addition, an assessment of absorbed doses for the building occupier indicate that severe deterministic effects are very unlikely to occur.

We have considered deliberate interactions with the waste that may occur after coastal erosion. As noted above, we assess radiation doses to an informal scavenger and to an organised scavenger/retriever. Maximum annual doses to the informal scavenger are calculated to be 1.8 mSv, which is below the guidance level of 3 mSv. The organised retriever/scavenger event gives rise to a maximum annual dose of 1.4 mSv, which is below the 20 mSv guidance level.

Criticality

We have undertaken a criticality assessment for the repository and concluded that the possibility of criticality is so remote that it can be discounted [58].

A6: Non-radiological impacts

We have designed and will manage the facility to ensure a standard of protection against non-radiological hazards that is no less stringent than that provided by disposal to a landfill of wastes that pose a similar non-radiological hazard.

We have made estimates of the non-radiological impacts to groundwater in the Period of Authorisation, and thereafter. During the remainder of the Period of Authorisation and thereafter, the estimated non-radiological impacts are demonstrated to be very low and significantly below relevant groundwater standards. The level of protection provided by the LLWR is significantly greater than that provided by a typical landfill.

We have also considered the potential for exposure to asbestos in the wastes following human intrusion into the repository or following disruption of the facility by coastal erosion and sea-level rise. The assessed impacts from exposure to asbestos are comparable to the radiological impacts arising from exposure to the wastes. The level of protection provided by the LLWR is significantly greater than that provided by a hazardous waste landfill, which would be used to dispose of non-radioactively contaminated asbestos.

We have considered the potential for the generation of, and impacts from, chemotoxic and flammable gases. Based on our near-field understanding, significant quantities of chemotoxic and flammable gases will not be released from the wastes.

This argument relates to GRA Requirement 10 [29]; further support to this argument is given in the '*Near Field*' [5] and '*Hydrogeological Risk Assessment*' reports [15]. The regulatory guidance notes that standards for the disposal of hazardous waste may not be suitable to apply to waste that presents both radiological and non-radiological hazards. It goes on to say that, '*Accordingly, these standards need not necessarily be applied, but a level of protection should be provided against the non-radiological hazards that is no less stringent than would* *be provided if the standards were applied.*' The argument in relation to this requirement is presented below.

The relevant standards to consider when demonstrating that disposals of solid radioactive waste at the LLWR address Requirement R10 are the following:

- The European Union Water Framework Directive 2000/60/EC and its daughter directive, the Groundwater Daughter Directive 2006/118/EC. Both directives are concerned with the protection of groundwater against pollution, the prevention and limitation of inputs of pollutants to groundwater and the prevention of deterioration of status of groundwater bodies.
- The requirements on acceptance of asbestos to a disposal facility set in Environment Agency guidance *Landfill Operators: Environmental Permits*. This is based on EU Council Decision 2003/33/EC establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC on the landfill of waste.

In England, the Water Framework Directive and the Groundwater Daughter Directive are implemented by:

- the Water Environment (Water Framework Directive) (England and Wales) Regulations 2017;
- the groundwater provisions in Schedule 22 of Environmental Permitting Regulations 2016.

To ensure protection of groundwater quality, the Water Environment Regulations 2017 place a '*prohibition of direct discharges of pollutants into groundwater*'. Environment Agency guidance [59] limits the duration that demonstration of compliance with the 'prohibition' requirement is required to the anticipated life of the site Permit.

The groundwater provisions in Schedule 22 of Environmental Permitting Regulations 2016 place obligations on an operator to take '*all measures deemed necessary and reasonable to:*

- *prevent the entry of hazardous substances to groundwater;*
- *and limit the input of non-hazardous pollutants to groundwater so as to ensure that such inputs do not cause pollution of groundwater.*'

However, it is noted that there is '*a practical limit to what can realistically be achieved ...*', '*... when considering what measures are 'reasonable', the radiation protection principle of optimisation should be observed*' and that '*... absolute and indefinite containment of pollutants within a disposal facility will not be achievable*' [60].

In their review of the 2011 ESC, the Environment Agency noted that while Requirement R10 necessitates a level of protection against non-radiological hazards that is no less stringent than would be provided if the hazardous waste standards were applied, a hazardous landfill operator would not normally be required to assess non-radiological impacts arising from the coastal erosion and human intrusion pathways [21]. Following this guidance, we have not conducted assessments of non-radiological impacts for these two pathways in the 2026 ESC.

Design Aspects

Our design for the vaults is more effective in limiting releases of non-radioactive contaminants than would be the case for a landfill in the following respects:

- the waste in the vaults is in containers, which will provide substantial containment during the Period of Authorisation;
- given the persistence of the containers, and low permeability of the vault bases, pumping of leachate will be highly effective in limiting releases to groundwater during the Period of Authorisation;
- the low sidewalls in the future vaults [4] will make local discharge to the surface environment much less likely than would be the case with a landfill;
- wastes in the vaults are grouted to reduce voidage, promoting the stability of the cap, as well as providing a chemical barrier reducing the release of contaminants and providing a substrate for sorption;
- the period of active institutional control will be substantial, far longer than is planned for any landfill, allowing monitoring of the evolution of the engineered features.

The vaults and trenches will be covered by an engineered cap, which will be resilient to anticipated settlements and will include a geomembrane and bentonite-enhanced sand layer, which will work together to provide a highly effective barrier to infiltration of water for a substantial period of time. The cap will provide a higher level of performance than a landfill for a hazardous waste facility.

For the trenches, post-emplacement engineering included the installation of an interim cap and a cut-off wall, which act to reduce the non-radiological impacts of the disposed inventory by limiting release of both gaseous and aqueous contaminants into the environment. In response to water balance data, which suggested that the interim cap has not performed as well as expected, we are currently installing an improved interim cap over the southern trenches. For the northern area of the trenches, the required improvement in hydrological performance will be provided by installation of the first strip of the final cap.

Groundwater Assessment Approach

In assessing the impacts from non-radiological contaminants, we have drawn on data from the current monitoring programme [8] and on the results of assessment calculations.

We believe that it is appropriate to assess the potential non-radiological impacts arising from the LLWR in a manner that is consistent as possible with the approach that we have followed with respect to radiological impacts. Consideration has been given to the use of approaches involving LandSim [61], but these are considered inappropriate because:

- they need to be based on measurements of leachate concentrations, which are not available for the vaults (or for any suitable analogue);
- the approach is not consistent with the range of contaminant transport pathways that are relevant to the chosen design after the end of the Period of Authorisation;
- there would be an inconsistency between the approach for radiological and non-radiological impacts.

We have assessed non-radiological impacts for the groundwater pathway using a systems assessment model developed using the program GoldSim [50]. This model is very similar to that used to assess radiological impacts.

Concentrations of contaminants in groundwater have been calculated at compliance points consistent with those which would be used when undertaking a hydrogeological risk assessment for a conventional landfill. These compliance points are as follows:

- For hazardous substances, there is one compliance point located directly below each trench and its immediate surrounding geology, in the regional aquifer adjacent to the edge of the discharge area for that particular trench or vault. Inclusion of the immediate surrounding geology ensures that all possible discharges to the regional aquifer are captured. In calculating hazardous substance concentrations at these compliance points, account is taken of immediate dilution occurring after discharge into the regional aquifer. Full dilution in the regional aquifer is not accounted for.
- For non-hazardous pollutants, we calculate concentrations directly below the site boundary (in more detail we use the maximum concentration at any given time across all such points lying below the site boundary).

Calculated concentrations are compared with LLWR Assessment Standards. For hazardous substances, these are taken to be the most restrictive of:

- the Environmental Quality Standard;
- European Union Drinking Water Directive standards;
- the Minimum Reporting Values, which are taken, where possible, from official Environment Agency guidance, otherwise we use the relevant Limit of Detection.

For non-hazardous pollutants, the Assessment Standards for non-radiological contaminants are currently based on the most restrictive Environmental Quality Standards for fresh water or salt water [15]. Where no Environmental Quality Standard is available, the European Union Drinking Water Directive standards [15] have been used. Assessment Standards are reviewed on an annual basis to ensure they align with any changes to the respective standards.

We have followed a more comprehensive approach to the assessment of non-radiological hazards than would often be the case for a landfill. In particular:

- we consider in detail the evolution of the engineered barriers during the Period of Authorisation and after the end of management control and the implications for assessed non-radiological impacts;
- we consider alternative evolution scenarios to explore the effects of uncertainty in the timescales for coastal erosion and sea-level rise on assessed impacts.

Impacts during the Period of Authorisation

Monitoring data for non-radiological contaminants in groundwater have been reviewed [62, 63]. The levels of non-radiological contaminants leaving the LLWR at present are sufficiently low that their impact is indiscernible from background concentrations. Where concentrations exceed the relevant assessment standards, these substances are considered to be present in groundwater as a result of natural processes or agricultural activities up-stream of the site. Monitoring will continue during the Period of Authorisation to provide reassurance that concentrations of non-radiological contaminants remain low.

We have assessed the impact of the release of non-radioactive contaminants from the wastes during the Period of Authorisation. Assessment calculations suggest that there will no future exceedances of the relevant standards during the Period of Authorisation. The combined effects of a cap, the waste containers and leachate collection will ensure that releases from the vaults are not significant.

Impacts after the Period of Authorisation

Our reference case shows that calculated concentrations of non-radiological contaminants after the Period of Authorisation are many orders below LLWR Assessment Standards. Our other assessment case calculations indicate that, even if key barriers perform significantly less well than anticipated, there is no significant risk of hazardous substances or non-hazardous pollutants entering the environment as a result of disposals at the LLWR.

In work carried out after the 2011 ESC was submitted, we assessed the impacts of encountering asbestos either as a result of human intrusion into the repository or following disruption of the repository by coastal erosion. We assumed that around 80% of future asbestos waste would be friable. We assumed that, during intrusion, a receptor would interact with a waste container with high asbestos content. These assumptions are cautious because only a small proportion of containers are likely to have high asbestos content and our WAC now limit the quantities of friable asbestos which may be disposed in a container.

Assessed impacts from inhalation of asbestos fibres following coastal erosion are low. This is because the inventory of asbestos is low and also because asbestos fibres would be rapidly dispersed by tides and by wind action. The greatest impacts from asbestos would arise following intrusion into a container with large quantities of untreated asbestos in friable form. Our WAC will limit the potential for such exposure situations to arise. We note as well that the LLWR provides a higher level of protection than landfills which would be used for the disposal of non-radioactively contaminated asbestos.

We considered the impacts that might arise from toxic gases and concluded that such impacts will be very low. We have also considered the impacts that may arise from flammable gases. The main flammable gas of interest is hydrogen. We have examined, as part of our radon assessment, the quantities of hydrogen gas which could enter a house built on the open vent on the cap. Cautious calculations suggest that levels of less than 0.2% hydrogen could occur, compared with the 4% hydrogen usually taken as the lower explosive or flammable limit for hydrogen in air at 25 °C. These calculations are cautious because they assume:

- that the bulk gas is comprised entirely of hydrogen;
- that all bulk gas will leave the repository via the gas vent, whereas our programme of gas modelling work suggests that bulk gas may not overpressure to the extent that it leaves the repository via the vent;
- that all bulk gas discharged from the vent under the house footprint enters the house.

If the gas vents were sealed at the end of the Period of Authorisation, then the level of hydrogen which could build up inside a house built on the cap would be lower. We will undertake work following the submission of the 2026 ESC to consider whether it will be necessary to retain an open vent after the end of the Period of Authorisation. We will also consider how to optimise the vent arrangements, which will offer benefits in terms of reducing impacts from hydrogen.

We do not consider it likely, therefore, that potential impacts from hydrogen would be significant.

A7: Impacts on non-human biota

We have made estimates of the radiation dose rates to the non-human biota on and in the vicinity of the LLWR at the present day and into the future. In almost all cases, the absorbed dose rates are below a cautious screening level of 10 $\mu Gy\ h^{-1}$ recommended by the Environment Agency, for which no significant radiological effects are expected in even the most sensitive types of organisms present, and hence do not require more detailed consideration.

During the Period of Authorisation, all exposure routes are shown to be below the screening level, except for a short period in the future when Vault 11 is full and uncovered. During this time, external exposure only exceeds the screening level within 90 metres of the vault. However, this situation is temporary, affects only a small area, and occurs while site work is already taking place, so it is not expected to harm wildlife populations.

After the Period of Authorisation, exposure to wastes on the cliffs and storm beach, arising as a result of coastal erosion and disruption of the facility, led to calculated dose rates for several representative organisms exceeding the 10 $\mu Gy\ h^{-1}$ screening dose rate. However, these exposures were not considered significant either because of the low radiosensitivity of the species concerned, because the contaminated area was not likely to host the relevant species, or because the relevant species occupied a much larger area than would be contaminated. Hence, we have concluded that there will be no significant impacts from the repository on non-human biota populations.

This argument relates to GRA Requirement 9 [29] and GRR Requirement 14 [30]; further support to this argument is given in the '*Assessment of Radiological Impacts on Non-human Biota'* report [16].

Although there is no evidence that there might be a threat to populations of non-human biota from the authorised release of radioactive substances if people are protected (see paragraph 6.3.72 in reference [29]), we must also protect biota in areas and habitats that are not extensively exploited by people, or where no people are present. Furthermore, it is necessary to demonstrate that non-human species are protected under legislation related to conservation, for example that derived from the European Commission Habitats Directive (EC 1992) [64]. Therefore, we have assessed the impacts of waste disposal at the LLWR on non-human biota that are present in the vicinity of the LLWR today, or that could be present in future.

Assessment approach

We have carried out the assessment using the internationally recognised ERICA methodology and ERICA Tool software package [65], which is a method supported and used by the Environment Agency.

The ERICA Tool considers representative organisms characterised by their dimensions, the concentrations of radionuclides that they exhibit relative to the environmental media in which they reside, and the fractions of the time that they are present within, or at the surface of, these media. The whole-body absorbed dose rate to each selected representative organism is calculated based on radionuclide concentrations in the environmental media in which they reside. These dose rates are compared with a screening dose rate below which no significant effects are observed in populations of the most sensitive types of organisms. The Environment Agency has advised that evaluation against a generic screening dose rate of 10 $\mu Gy\ h^{-1}$ will generally be sufficient.

If dose rates exceed the screening value, a more detailed assessment is required. We have a structured approach for doing this including looking at specific organism behaviour and conditions of exposure, and evidence of radiosensitivity for the organisms exposed.

As described in Subsection 2.5, the western boundary of the northern part of LLWR site is contiguous with the Drigg Coast SSSI, which is also designated a Special Area of Conservation, and to which we pay special attention in the present day. For this area, detailed evaluations of the implications of observed radionuclide concentrations have been published in the literature[12], including an assessment using the ERICA Tool and a

[12] Although the radioactivity in this area today is due to natural radionuclides, global fallout and historical discharges from Sellafield, and is not LLWR related.

comparative assessment using ERICA and the other biota assessment models [66]. These studies conclude that dose rates to non-human biota are generally less than 1 μGy h^{-1} and are very unlikely to exceed the screening dose rate of 10 μGy h^{-1}.

To assess impacts to non-human biota, we have estimated dose rates to representative organisms due to radionuclide concentrations calculated by the same models as used to assess human exposures (and, during the Period of Authorisation, determined by the same monitoring data as used to assess human exposures). We have considered the environmental concentrations arising as a result of releases via groundwater and gas pathways, and as will occur during erosion of the facility in the long term. During the Period of Authorisation, we have also considered permitted releases of leachate to the sea and the Drigg Stream, historical contamination of the Drigg Stream and direct and scattered radiation from uncovered vaults. We do not consider environmental contamination that may arise during and following human intrusion cases, because the contamination would be localised, and thus present little potential for ecological harm. Dose rates to individual non-human biota following human intrusion will be bounded by those that occur during coastal erosion.

During the Period of Authorisation

Dose rates from permitted discharges to both the Marine Pipeline and, exceptionally, to the Drigg Stream during the Period of Authorisation are below the screening dose rate. Dose rates from historical contamination of the Drigg Stream are higher than those from current and future permitted discharges, but still below the screening dose rate. Dose rates from direct and scattered radiation from uncovered vaults are only above the screening dose rate at 30 metres from the waste stacks when Vault 11 is full at 2113 AD. At that time, the assessed dose rate at 30 metres is 28 μGy h^{-1}; and falls below the non-human biota screening value within 90 metres of Vault 11. These dose rates will be highly localised and only a few individual organisms are likely to incur them. In addition, there are pessimisms in the way that the direct and scattered radiation dose rates are calculated, and the area affected would be impacted by operations and emplacement of the final cap, making it disruptive for most non-human biota. Therefore, we conclude that non-human biota would not be adversely impacted by this potential exposure pathway. The direct and scattered radiation results for all other vaults remain below the 10 μGy h^{-1} ESC screening dose rate at a distance of 30 metres from the waste stacks.

After the Period of Authorisation

For the groundwater pathway, the highest dose rates are assessed for land hypothetically irrigated by contaminated groundwater from a well after the Period of Authorisation. The maximum dose rate to non-human biota is more than three orders of magnitude below the screening dose rate.

For the gas pathway, the principal consideration is the release of C-14 and its uptake in vegetation by photosynthesis. Assuming a relatively enclosed canopy typical of heath and scrub, represented by calculations for fruit bushes, a dose rate below the 10 μGy h^{-1} screening level is calculated for plants and animals permanently resident on and receiving all sustenance from the cap areas over the vaults and trenches. Dose rates from gaseous releases of tritium and radon are also below the screening dose rate.

In the case of coastal erosion, dose rates depend on the activity of the wastes exposed, which varies spatially and temporally. The radioactivity on the beach and foreshore represents a more averaged source due to mixing with clean materials but still varies over time. Absorbed dose rates to organisms associated with the foreshore, marine sediments and waters all are below the 10 µGy h^{-1} screening level. Absorbed dose rates above the screening level are calculated in the case of biota residing permanently and gaining all sustenance on the cliff and storm beach.

Following coastal erosion, the highest calculated dose rates (970 µGy h^{-1}) are to lichens and bryophytes on the cliff. However, literature effects data show that dose rates would likely need to be two orders of magnitude greater than this to negatively impact lichen. Moreover, we do not think it credible that populations of lichens and bryophytes will reside in this location.

Small mammals and reptiles on the cliff have assessed dose rates between 20 and 28 µGy h^{-1}. However, their habits and sources of sustenance mean that the actual dose incurred is likely to be lower. This is because mammals and reptiles will spend time on, and gain their sustenance mainly from, the foreshore or inland heath. The assessed dose rates for small mammals and reptiles are below the upper bound of the applicable ICRP derived consideration reference level. Other terrestrial organisms on the storm beach and cliffs have assessed dose rates above the screening value. However, consideration of radiosensitivity using the ICRP-derived consideration reference levels shows that populations of these organisms are unlikely to be harmed by assessed dose rates.

The cliff and beach are, furthermore, transient environments with continual turnover, migration and movement of organisms between the potentially contaminated area adjacent to the LLWR, other areas of beach and further afield. Thus, even if there is potential for radiological detriment to individual organisms, there is no potential for significant harm to local populations.

We also considered the potential for harm to non-human biota from contact with high-activity particles as there is potential for some of the radioactivity in the LLWR to be released in particulate form in the long-term through coastal erosion or human intrusion. Our assessment showed that even if non-human biota encountered such particles, any effects would be very localised and limited to individual organisms that may come into direct contact with a particle.

A8: Protection of groundwater

We have considered the protection of groundwater as a receptor in its own right and assessed the possibilities of direct discharge to groundwater and the requirement to prevent the release of hazardous substances to groundwater. These assessments have considered both radionuclides and non-radiological contaminants.

No direct discharge will occur because of the presence of natural and engineered barriers between the waste and the groundwater and the release of hazardous substances to groundwater is prevented according to the criteria for radionuclides and non-radiological contaminants. The release of non-hazardous pollutants is limited according to the criteria for non-radiological contaminants.

The impacts from radionuclides are addressed under arguments A4, A5 and A7 and the impacts from non-radiological contaminants are addressed under argument A6.

This argument relates to Schedule 22 of the Environmental Permitting (England and Wales) Regulations 2016 and the Water Environment Regulations 2017. Disposal of solid radioactive waste in a near-surface disposal facility constitutes a groundwater activity and it is therefore necessary to demonstrate that we comply with the relevant groundwater protection regulations. Further support to this argument is presented in '*Environmental Safety During the Period of Authorisation*' [13], '*Assessment of Long-term Radiological Impacts*' [14], '*Assessment of Radiological Impacts on Non-human Biota'* [16] and '*Hydrogeological Risk Assessment'* [15] reports.

As discussed under argument A6, the groundwater provisions in Schedule 22 of Environmental Permitting (England and Wales) Regulations 2016 place obligations on an operator to take '*all measures deemed necessary and reasonable to prevent the entry of hazardous substances to groundwater and limit the input of non-hazardous pollutants to groundwater so as to ensure that such inputs do not cause pollution of groundwater.*'

However, it is noted that there is '*a practical limit to what can realistically be achieved...*', '*...when considering what measures are 'reasonable', the radiation protection principle of optimisation should be observed*' and that '*...absolute and indefinite containment of pollutants within a disposal facility will not be achievable*' [60].

To ensure protection of groundwater quality, the Water Environment Regulations 2017 place a '*prohibition of direct discharges of pollutants into groundwater*'. Environment Agency guidance [59] limits the duration that demonstration of compliance with the 'prohibition' requirement is required to the anticipated life of the site Permit.

All vaults at the LLWR either have been, or will be, constructed from the surface [4] and will not extend below the regional groundwater table. Over the lifetime of the site's Permit, the regional groundwater will remain below the level of the vaults, as demonstrated in our hydrogeological studies [6]. Any releases from the facility are therefore indirect as they must percolate through the underlying geology before entering the regional groundwater.

Radiological impacts

Although groundwater is a receptor in its own right, we demonstrate that we protect groundwater by calculating radiological impacts to members of the public and non-human biota who potentially interact with groundwater during the Period of Authorisation and thereafter. The Environment Agency advises that an input of a radioactive substance to groundwater during the Period of Authorisation is considered to have been prevented if:

- the radiation dose to members of the public incurred via the groundwater pathway is consistent with, or lower than, 0.01 mSv y^{-1}; or,
- if the radiation dose exceeds 0.01 mSv y^{-1}, to demonstrate that:
    - the dose to a representative person through all pathways during the Period of Authorisation is less than 0.3 mSv y^{-1}; and,
    - doses are ALARA, taking into account economic and social factors (that is, the repository and the waste management arrangements are optimised); or,
- the concentration of radionuclides (in Bq l^{-1}) attributable to the discharge in groundwater immediately down-gradient of the discharge zone is consistent with background concentrations in this or a similar geological formation.

In addition to these criteria, it is necessary to demonstrate protection of non-human biota inhabiting groundwater-fed ecosystems. Dose rates via the groundwater to biota in such ecosystems should be well below levels considered to result in adverse effects for the type of organism concerned [59].

As discussed under argument A7, we use an ESC screening dose rate of 10 µGy h^{-1} when assessing radiological impacts to non-human biota. Environment Agency guidance on groundwater protection endorses a more restrictive screening dose rate of 1 µGy h^{-1} for groundwater protection assessments. Assessed dose rates lower than this value are not expected to harm organisms inhabiting groundwater fed ecosystems. The assessed dose rates to non-human biota arising from releases to groundwater are all below the more restrictive 1 µGy h^{-1} screening value.

There are currently no abstractions of water undertaken between the LLWR site and the coast and the designated SSSI is currently under a 999-year lease to the NDA, which ensures that we have control over future development of the SSSI, including the installation of groundwater abstraction wells. It is unlikely, therefore, that a well would be sunk up to the end of operations to abstract contaminated groundwater.

The relevant receptor when assessing protection of groundwater now and during the rest of operations is therefore a marine foodstuffs consumer. Our assessment model demonstrates that annual doses to a marine receptor are very much less than 0.01 mSv. Doses to non-human biota are calculated to be very low.

Our monitoring data show there are locally elevated concentrations of tritium and C-14 in groundwater between the LLWR and the coast. We cannot infer how much tritium or C-14 has reached the marine environment to enable us to calculate a dose to a marine receptor based on monitoring results. We have therefore carried out a 'what-if' calculation in which a hypothetical well is sunk between the LLWR site and the coast. Although it is not credible for a well to be sunk during operations, this provides an upper bound on present day dose, as concentrations in the marine environment will be lower than those observed at our monitoring points.

Our monitoring data indicate that, for the present day, assessed annual doses would be around 0.17 mSv for localised regions between the site and the coast. These doses largely arise from tritium disposed of in the trenches, with annual doses of around 0.002 mSv arising from C-14, which has migrated from the trenches via low dilution pathways.

The monitoring borehole locations have been chosen to provide information on areas of higher contaminant concentrations. They therefore do not provide a representative view of contaminant concentrations over the full areal extent of groundwater flows between the LLWR site and the coast. We expect that doses from the consumption of groundwater further from the site (for example, on the SSSI) would be lower.

The environmental significance of these locally elevated concentrations in the groundwater is very low because it is not credible, as discussed above, that a member of the public could interact with this groundwater. Similarly, non-human biota would principally interact with water resources recharged by uncontaminated groundwater, rather than interact with the elevated concentrations at greater depth in the groundwater.

As part of our optimised Site Development Plan, we will, over the course of the Period of Authorisation, implement the following engineering measures to ensure that impacts to groundwater are ALARA:

- installation of a new interim trench cap membrane over the southern portion of the trenches;
- installation of the final cap, initially over Vault 8 and the adjacent strip of trenches and, subsequently, over the remainder of the vaults and trenches;
- extension of the existing cut-off wall.

These measures will reduce the inflow of water into the trenches and hence the production of leachate and release of radionuclides to groundwater. This reduction in releases, together with the short half-life of tritium, will result in concentrations of tritium (and hence assessed doses) reducing significantly over the next few decades.

During the active institutional control period, there would be a much smaller presence on site. We expect that the NDA will still hold the lease on the land between the LLWR and the coast during this period, although there is greater uncertainty for this longer timescale. We cautiously assume, for the purpose of demonstrating protection of groundwater, that a well might be sunk between the LLWR and the coast during the active institutional control period. It is inappropriate to rely on monitoring data to assess impacts in this period. This is because the future evolution of the plume is uncertain and cannot be inferred from monitoring data. We therefore use our assessment model to calculate doses for the remainder of the Period of Authorisation. We calculate annual doses from the ingestion of contaminated groundwater to be less than 0.01 mSv throughout this period.

We expect, therefore, that assessed annual doses to relevant receptors for the duration of the Period of Authorisation will be less than 0.01 mSv and will not lead to adverse effects in biota inhabiting groundwater-fed ecosystems. Even if we were to consider our 'what-if' well for the near term, assessed annual doses would be less than 0.3 mSv and our optimised Site Development Plan would ensure that these doses would be ALARA.

We conclude on this basis that we have taken all necessary and reasonable measures to demonstrate that we prevent the input of radionuclides to groundwater during the Period of Authorisation.

After the end of the Period of Authorisation, the Environment Agency advises that an input of radionuclides to groundwater would be considered to have been prevented if:

- the radiological risk to members of the public through the groundwater pathway after the end of the Period of Authorisation is consistent with, or lower than, an assessed risk of 10^{-6} y^{-1}; or,
- the assessed risk through the groundwater pathway exceeds 10^{-6} y^{-1}, risks are ALARA, taking into account economic and social factors (that is, the repository and the waste management arrangements are optimised); or,
- the concentration of radionuclides (in Bq l^{-1}) attributable to the discharge in groundwater immediately down-gradient of the discharge zone is consistent with background concentrations in this or a similar geological formation.

As discussed under argument A5, we have assessed the radiological impacts from our optimised repository design for different evolution scenarios. Our assessment calculations indicate that assessed risks would be consistent with the risk guidance level for all evolution scenarios considered. We conclude on this basis that we have taken all necessary and reasonable measures to demonstrate that we prevent the input of radionuclides to groundwater after the end of the Period of Authorisation.

Non-radiological impacts

As discussed under argument A6, during the Period of Authorisation and thereafter, the estimated non-radiological impacts in our reference case are demonstrated to be very low and significantly below relevant groundwater standards. The level of protection provided by the LLWR is significantly greater than that provided by a typical landfill. We consider, based upon the assessed impacts and our optimised repository design, that we have taken all necessary and reasonable measures to prevent the input of non-radiological hazardous substances to groundwater and to limit the input of non-hazardous pollutants to groundwater.

4.6 Implementation

We have implemented the ESC to ensure that the site is managed safely and optimally in accordance with the safety case. Implementation of the ESC in relation to installing the optimised engineering for disposal of wastes consigned to the site and management of site wastes has already been addressed in our arguments relating to optimisation. WAC, emplacement strategies, and site capacities have been derived as part of the ESC and implemented into our management arrangements. This ensures that only types and quantities of wastes that are safe can be disposed of at the repository. Changes resulting from the development of the 2026 ESC will be implemented in accordance with our current Permit and with the agreement of the Environment Agency where necessary. Changes allowing the safe disposal of some ILW will be implemented if and when a decision is made to pursue this option and the necessary permissions are obtained. We will continue to develop our Site Development Plan and ESC to ensure safe and optimal use of the LLWR.

I1: Waste Acceptance Criteria

We have systematically derived and implemented WAC consistent with the assumptions and results of the ESC. The derived radiological criteria are consistent with our Permit and the limits and guidance levels for dose and risk given in the GRA. Our WAC also take account of other waste characteristics, including chemotoxic properties. 'Disposability assessments' can also be undertaken to assess whether new wastes are consistent with the assumptions and results of the ESC. Our WAC are revised as new information becomes available.

This argument relates to GRA Requirement 13 [29]; further support to this argument is given in the '*Implementation*' report [17].

We have systematically derived WAC consistent with the assumptions and results of the ESC. Our approach to waste acceptance is in accordance with regulatory guidance and requirements, and follows best practice guidance based on international experience. We have taken into account any requirements and guidance specific to the LLWR provided by the Environment Agency. Where possible, our WAC are quantitative. The derived radiological criteria are consistent with our Permit and the limits and guidance levels for dose and risk given in the GRA. WAC for radionuclides are based on the application of the 'sum-of-fractions' approach, which is recognised as a safe way of dealing with contributions to radiological impact from potentially more than one radionuclide.

An important requirement of our WAC is the need to use BAT in the selection of waste for disposal at the LLWR and in the preparation of waste for disposal.

Radiological aspects addressed in the WAC include:

- total specific activity – currently, only LLW can be disposed of;
- heterogeneity, including Discrete Items, Low-activity Sources, and Active Particles;
- fissile content.

Non-radiological aspects addressed in the WAC include physical properties, ability to affect biogeochemistry and containment, potential to create voidage because of degradation, and chemotoxic properties.

The control of the impact of complexing agents on the release of materials and of other hazardous substances and non-hazardous pollutants is largely achieved through the management of repository capacity (see argument I2).

There is a potential for asbestos to become exposed on the beach because of coastal erosion or through human intrusion. Given the hazard associated with the potential exposure of asbestos on the beach, following the 2011 ESC, we introduced a waste acceptance control to ensure that disposed asbestos is limited, conditioned or treated in such a way that it presents an acceptable hazard when present on the beach.

Our published WAC also include necessary controls derived from our Nuclear Safety Case and operational constraints, as well as those derived from the ESC.

Procedures are in place to ensure that consigned wastes are compliant with our WAC, or an agreed variation, and Permit. Verification procedures are in place to ensure the wastes received match their declared characteristics. 'Disposability assessments' can be undertaken on the suitability for disposal of new wastes or assess waste streams or consignments that may challenge our different safety cases or Permit conditions.

After submission of the 2026 ESC, detailed finalisation of the revisions to the WAC implied by the new ESC will be undertaken. We will consult with our waste consignors and the Environment Agency as appropriate. These changes will be implemented along with those required to emplacement strategies (see argument O4) and capacity management arrangements (see argument I2).

We have also systematically considered the WAC in the context of potential acceptance of ILW. Many areas of the WAC would not require different measures for ILW acceptance (for example, criteria on voidage or materials). The defined capacities would also remain the same since they do not depend on the waste types or inventory. However, changes would be required to the WAC for specific activity limits, and dedicated emplacement strategies might be required. These changes to allow the safe disposal of some ILW will be implemented if and when a decision is made to pursue this option and the necessary permissions are obtained.

I2: Radiological and non-radiological capacity

We have used our assessments and the limits and guidance levels for dose and risk and other criteria to derive the safe radiological and non-radiological capacities of the disposal facility. The design will also impose a finite volumetric capacity. Procedures have been implemented to ensure that the quantities of wastes accepted for disposal do not exceed the safe capacities. The procedures also ensure that the capacities are used optimally to support the NDA's mission.

This argument relates to GRA Requirement 13 [29]; further support to this argument is given in the '*Implementation*' report [17].

We have used our assessment models coupled with the radiological limits and guidance levels set out in the GRA to calculate different total radiological capacities. These results have been analysed to derive an overall safe set of total radiological capacities. A sum-of-fractions approach has been used. Radiological capacities calculated based on the results of the 2011 ESC and some subsequent work [57] are now stated in our Permit from the Environment Agency. We will seek to update those controls to align with the 2026 ESC findings.

A similar approach has been used for hazardous substances and non-hazardous pollutants but in this case regulatory guidance levels are not stated in the GRA and other criteria have been used to set total non-radiological capacities. The calculated capacities are generally for single substances.

A similar approach has also been taken to calculating the safe quantities of complexing agents that can be accepted at the LLWR.

The design of the LLWR, assumed in the Site Development Plan, also sets a limit on the physical volume of waste that can be disposed of at the facility.

Appropriate procedures have been put in place to allocate repository capacity for waste streams consignors wish to dispose of at the LLWR and ensure that the capacity is not exceeded. Decisions on the allocation of capacity are taken at different management levels in Nuclear Waste Service and the NDA, depending on the amount of capacity that is being requested.

The WAC and controls on the quantities of wastes that can be disposed of at the LLWR ensure that both the types and amounts of wastes are safely limited.

The revised capacity controls that have been derived from the 2026 ESC will be assessed for whether the controls are more restrictive than the current ones. A decision will then be made on whether to work to the more restrictive controls prior to any Permit made by the Environment Agency.

Although the derived radiological and planned physical capacities of the repository are finite, the amount of LLW in the UKRWI requiring the levels of environmental protection provided by the LLWR's engineering is not expected to exceed the capacities. This would not be the case if the decision was taken to dispose of less-hazardous ILW at the LLWR. In that case, the amount of ILW arising in the UK meeting the WAC would be expected to exceed the calculated capacities (provided consignors were able to demonstrate that disposal of the wastes at the LLWR was BAT). Were this situation to arise, consideration would need to be given by the NDA, Nuclear Waste Services and waste consignors on how to make optimal use of the capacity of the LLWR.

I3: Operating the site

We have implemented procedures to ensure that the LLWR is operated in accordance with the assumptions and results of the ESC. A key aspect of this implementation is the use of an Environmental Clearance Certificate setting out the necessary controls. The implementing procedures address ‘change control’ on the site, as well as ensuring wastes are only accepted and emplaced for disposal consistent with the ESC, WAC and derived capacities. The change control procedures ensure that no changes are made to the operation of the site or facilities constructed or altered without an assessment made by competent individuals of the implications of the changes for the ESC.

This argument relates to GRA Requirements 4, 12 and 13 [29]; further support to this argument is given in the '*Management and Dialogue*' [1] and '*Implementation*' reports [17].

An Environmental Clearance Certificate is used to implement the ESC on the LLWR site. A clearance certificate is how the Nuclear Safety Case is implemented on the LLWR site and the same approach was adopted for the ESC for consistency.

An Environmental Operating Rule stated in the Environmental Clearance Certificate limits the wastes that can be accepted for disposal to those allowed by the Permit, that is, within the LLW limits of 4 GBq t^{-1} alpha and 12 GBq t^{-1} other radionuclides, and in quantities not exceeding the radiological capacities set out in the Permit. In addition, there are three Environmental Operating Instructions. The first limits the acceptance of wastes for disposal to those meeting the WAC or an approved variation to the WAC. The second Environmental Operating Instruction requires waste consignments to be disposed of in their final positions in accordance with the emplacement strategies derived from the ESC and with the agreement of the ESC Manager. The third Environmental Operating Instruction ensures that non-radiological capacities and capacities for complexing agents are not exceeded. The implementation of WAC and capacity controls have already been discussed under arguments I1 and I2. Optimal emplacement of wastes in their final disposal locations has been discussed under argument O4.

The Environmental Clearance Certificate also states several Environmental Operating Assumptions. An environmental monitoring programme is required, along with regular reviews of the ESC, to ensure appropriate account is taken of new information. The importance of assessing the implications for the ESC of proposed changes to the operation of the site or new facilities constructed is also recognised in the Environmental Operating Assumptions. The site's change control procedure − the 'Plant Modification Process' − requires that changes that might be significant for the assumptions and outcomes of the ESC are assessed by the ESC Manager prior to the changes being implemented. The Environmental Operating Assumptions require the consideration of BAT in developing changes to existing systems or designing new systems.

An asset inspection and maintenance programme is also an Environmental Operating Assumption. The Environmental Clearance Certificate also identifies the 'Environmental Equipment' on site, necessary to meet the requirements of the Permit and ESC, helping to ensure that the significance of the equipment is understood and that the equipment is properly maintained, inspected and tested.

Supporting the Environmental Clearance Certificate, a structured Requirements Management System ensures that engineering design and optimisation work remains consistent with the ESC. Requirements on the closure engineering are traced through the Disposal System Specification, with linkage into design justification and optimisation studies.

I4: Optimising the use of the LLWR

Operating the LLWR in accordance with the Site Development Plan, WMP and capacity usage plan all contribute to ensuring that safe and optimal use is made of the LLWR, in accordance with government policy. The 2026 ESC has been developed to show the types and quantities of ILW that could be safely disposed to the LLWR were it demonstrated that it was BAT to do so. Disposal of ILW at the LLWR would require a decision to pursue this general option and the necessary permissions to be obtained.

This argument relates to GRA Requirements 4, 8, 12 and 13 [29]; further support to this argument is given in the '*Management and Dialogue*' [1], '*Optimisation and Site Development Plan*' [9] and '*Implementation*' reports [17].

In their new policy framework for managing radioactive substances and nuclear decommissioning, published in May 2024, the UK government and devolved administrations have stated that they wish to ensure that the best use of disposal capacity is made across the UK and expect the NDA to ensure the optimal use of the LLWR. We operate the LLWR in accordance with the site's Site Development Plan, WMP and capacity usage plan. These plans were developed using optioneering processes. Operating to these plans helps to ensure that optimal as well as safe use is made of the LLWR, in accordance with government policy.

The 2026 ESC assesses the disposal of LLW at the LLWR, demonstrating that it is safe to continue to dispose of LLW at the facility. The new government policy also states that the NDA should explore with relevant stakeholders, including regulators, local authorities and the local community the potential for optimising the existing near-surface facility, the LLWR, to take less-hazardous ILW. For this reason, the 2026 ESC also assesses the types and quantities of less-hazardous ILW that could safely be disposed of in the vaults at the LLWR. Changes to the engineering designs that would be required, depending on the types of ILW to be disposed of, have been considered. We have also considered the safety controls that would be required. The inclusion of less-hazardous ILW within the scope of the ESC is intended to support the NDA's and Nuclear Waste Services' engagement with stakeholders on the most appropriate use of the site by providing understanding of the types and quantities of less-hazardous ILW that might be disposed of and the engineering and operational changes at the site that would be needed. It does not imply that any decisions have yet been made on the disposal of ILW at the LLWR. Were the option to be pursued, any necessary regulatory and planning permissions would need to be obtained before any disposals could take place. Consignors would need to demonstrate that it was BAT to dispose of individual waste streams at the LLWR.

5 Progress in Developing the ESC Since 2011

Progress in developing the ESC since the last major review and revision in 2011 is summarised in this section.

Following submission, the Environment Agency reviewed the 2011 ESC. The LLWR applied for and received a revised Permit, based on the 2011 ESC and some subsequent work [57], allowing disposal of waste in Vault 9 and subsequent vaults and initiation of progressive final capping of the repository. The necessary planning permission was also obtained. The LLWR implemented the 2011 ESC and initiated a further development programme that led to interim improvements and the 2026 ESC.

There have been a range of inputs to the development programme and the resulting improvements, including:

- the outcomes of the Environment Agency's review of the 2011 ESC, including its Forward Issues and Recommendations [22, 23, 24, 25, 26, 27] and the Process by Agreement (see argument M3);
- comments and reports by the ESC Peer Review Group (see argument M5);
- international research and development and understanding of best practice;
- improved understanding of the waste inventory;
- new information on site characterisation and evolution;
- evolution of the optimised engineering design of the disposal facility and its implications for performance;
- the need for a SWESC and WMP;
- changes in government policy.

The resulting improvements are summarised in the rest of this section. More detail can be found in the relevant Level 2 reports.

Response to feedback

The outputs of work undertaken to address the outcomes of the Environment Agency's review of the 2011 ESC [21], including the Forward Issues [22] and Recommendations [23, 24, 25, 26, 27], the Process by Agreement with the Environment Agency (see argument M3), and comments received from the ESC Peer Review Group (see argument M5) have been incorporated into the 2026 ESC.

Implementation of the 2011 ESC

Processes were developed to implement the 2011 ESC and subsequent work supporting the application for a revised Permit. A new repository site procedure, RSP 2.25 (now

NWSSOP 40.07.01) [38], was created for managing the development and implementation of the ESC as a live safety case. A new clearance certificate, the Environmental Clearance Certificate, was also created to implement the ESC on site. This approach followed that of the clearance certificates used to implement the Nuclear Safety Case, with which the site staff were familiar. The WAC for disposal were amended. New WAC included those controlling levels on heterogeneity of activity in Discrete Items and particles. Other new WAC addressed non-radiological materials, including asbestos. Waste emplacement strategies were developed to optimise the emplacement of waste containers in the vaults. Processes were developed to allocate and control the total radiological, non-radiological and volumetric capacities of the LLWR.

Inventory

We have improved our understanding of the disposed inventory in Vault 8. We have also supported enhancements in submissions by waste consignors to the UKRWI [48] and the processing of inventory forecasts. These activities have led to an improved understanding of both the inventory of wastes already disposed of at the LLWR and of wastes that might be disposed to the facility.

Site characterisation and evolution

We have updated our projections of the timing and form of coastal erosion, supported by the latest scientific consensus on climate change and sea-level rise, new modelling approaches, increased use of analogues and a coastal monitoring programme that we have implemented since 2011.

New boreholes have been drilled to collect data on deeper geological layers beneath the site. These data have been used in the revision of both the geological and hydrogeological models used for the ESC.

The geological interpretation for the site has been updated, incorporating new geomorphological data. This has been used to derive a new 3-D regional geological model.

The environmental monitoring programme has continued to be used to support and validate the ESC.

Optimised engineering design

Work has been undertaken to further optimise and develop the engineering design assumed for the 2011 ESC.

Work on the engineering design has led to an improved understanding of the performance of the final cap. We now believe that the final cap will lead to infiltration rates lower than was assumed previously.

Work on the engineering design has also led to an improved understanding of waste stack response in Vault 8 and in Vault 9 where ISO waste containers of the current design will be emplaced in their final disposal positions. The proposal now is not to 'higher stack' further in Vault 8 or to stack higher than the equivalent of five half-height ISO containers for the current

ISO container design in Vault 9 without further substantiation. Waste stacks in these areas will be surcharged to express settlement prior to installation of the final cap.

Warehouses to provide interim protection of waste containers prior to final emplacement and a 'strip-capping' approach for final capping are proposed, to ensure the time that waste containers are exposed to the local environment is minimised.

A strengthened half-height ISO container is also proposed, capable of supporting the final cap without immediate settlement.

Modelling and assessments

Our improved understanding of the performance of the final cap, derived from our new '*Engineering Performance Assessment*' [12], has been applied in all relevant modelling and assessment for the 2026 ESC.

Our hydrogeological model has been updated, based on the revised geological model. We have considered several hydrogeological uncertainties and quantified their impact.

A new conceptual model of the vault near field has been developed, based on the improved understanding of performance of the final cap and of the cementitious grout, including new experimental data for initial pH and leaching of non-radiological contaminants. The new model has been implemented through PFLOTRAN. We now expect the pH to be higher and to remain elevated for longer. We have an improved understanding of the effects of heterogeneity on the near field. The implications of this new information for sorption, solubility limitation and the generation of ISA have been addressed in our revised assessment of the groundwater pathway.

All assessments for the 2026 ESC have been undertaken applying a consistent philosophy, set out in our '*Assessments Manual*' [42], which advocates a consistent use of bias audits, Features Events and Processes audits and uncertainty management.

We have revised our approach to exposed groups and representative persons, including developing a method for combining impacts of multiple pathways during the Period of Authorisation [13].

Other improvements to the assessment for the Period of Authorisation include: an improved approach to modelling external doses; a combined groundwater assessment model covering both the Period of Authorisation and afterwards; an updated approach to modelling tritium release to the atmosphere to make it specific to the site; and strip capping is now represented.

The assessment of the groundwater pathway has included a new calculation of radiological capacity using Probabilistic Risk Analysis.

A Hydrogeological Risk Assessment has been developed [15].

SWESC and WMP

The scope of the ESC has been extended to address the requirements stated in the GRR for a SWESC and WMP for the LLWR. Our procedure for managing the development and implementation of the ESC as a live safety case [38] has been updated to embed the GRR requirements in our management arrangements.

Implementation of the 2026 ESC

Further improvements to the control of LLW disposals are being proposed in the 2026 ESC. These will be refined and implemented, with the agreement of the Environment Agency where appropriate. These improvements include:

- revised capacities;
- proposed updates to Radionuclide Groups for Discrete Items and Low-activity Sources;
- updates to our approach to managing Hazardous Waste, Hazardous Substances and Non-Hazardous Pollutants;
- revision to the waste emplacement strategy;
- updates to the Approved Disposal Containers (for example, to add the strengthened half-height ISO once the design has progressed and remove container types that are no longer available for use by consignors).

In addition, we will consult with waste consignors and the Environment Agency, and do further work to improve the WAC controls on sub-container-scale heterogeneity of activity. This would aim to move (or support) the current subjective WAC clause on '*a reasonable reflection of activity*' to a safety-based, numerical control.

ILW disposal

Following the recent changes in government policy on the management and disposal of radioactive waste, the 2026 ESC has examined the potential for the LLWR to accept for disposal some less-hazardous ILW.

Any necessary changes to the optimised engineering design have been considered. New container designs, receipt facilities and shielded modules in the disposal vaults might be required, depending on the nature of the ILW. For example, new shielded modules would enable the safe disposal of more active but shorter-lived ILW.

Necessary revisions to waste acceptance controls and management of wastes on site if ILW were to be accepted for disposal have been considered.

6 Future Programme

In this section, we provide an overview of a planned future programme of work that will be undertaken to ensure effective maintenance and application of the ESC and to further reduce uncertainties. For the safety assessment of the disposal facility, we will focus on those uncertainties amenable to reduction and where the calculated impacts are greatest. More detail can be found in the relevant Level 2 reports. The programme may be adapted to take account of the outcomes of the Environment Agency's review of the 2026 ESC and any future changes to the LLWR's Permit and regulatory guidance. The programme will be adapted as necessary to take account of new information arising or external factors, such as changes in radioactive waste management in the UK.

Dissemination

The 2026 ESC will be disseminated to a wider audience. A web-based presentation of the ESC will be implemented and made publicly available. Local stakeholders will be briefed on the outcomes of the ESC. The outcomes will also be presented in appropriate national and international technical fora.

Management

The ESC will continue to be developed as a live safety case using the processes and procedures developed previously, updated as necessary.

The development of the 2026 ESC will be reviewed for learning to be applied in planning further development.

A response will be made to outstanding comments from the ESC Peer Review Group.

We will consider the outcomes of the Environment Agency's review of the 2026 ESC and respond appropriately.

We will consider any new regulatory guidance, assessing implications and taking them into account in our plans.

A detailed further development plan will be produced to ensure the ESC continues to represent the latest state of site and scientific understanding.

The geological and hydrogeological models used for the 2026 ESC have been developed on our behalf by a contractor. Although we will continue to collect geological and hydrogeological data that may allow further refinement, we do not expect further significant development of the models will be required. We will ensure that hydrogeological information is retained and maintained within the corporate body.

The Disposal System Specification, setting out the requirements on the disposal facility, will be updated to take account of the 2026 ESC. We will also further populate the Requirements Management System with verification and validation plans for the components soon to be installed.

We will maintain a watching brief on various aspects of the ESC. Subjects of particular interest include C-14, colloids, and climate change over extended timescales. We will review updates to UKRWI [48] for their implications for the ESC. We will make use of the wider Nuclear Waste Services research and development programme and participate in national and international collaborative groups where helpful.

Implementation

Changes will be made to the implementation of the ESC necessitated by developments in the 2026 ESC. Various changes to the WAC (for LLW) will be required and these will be made with the approval where necessary of the Environment Agency and after consultation with waste consignors. Proposed implementation changes include:

- improved clarity of the WAC;
- updates to capacities, limits and our emplacement strategy;
- updates to radionuclide groupings for Discrete Items and Low-activity Sources;
- updates to our approach to managing Hazardous Waste, Hazardous Substances and Non-Hazardous Pollutants;
- updates to the list of Approved Disposal Containers;
- following further work, the introduction of a new sub-container-scale control on heterogeneity of activity.

Our approach to managing external dose prior to final capping from the wastes disposed in the vaults will be kept under review.

Site Development Plan

The revised Site Development Plan will be implemented. Over the next few years, this is expected to include developing and substantiating the engineering design of the following:

- Vaults 9a and 10;
- interim storage warehouses;
- changes to the leachate management system as capping proceeds;
- strengthened ISO waste containers;
- container protection units.

Final capping of Vault 8 and the adjacent area of the trenches will continue.

Monitoring of the finally capped areas of the facility is required to build confidence in our modelling of gas generation, enabling decisions to be made on whether venting of the disposal facility is required.

Near field

We will continue to develop our near-field experimental programme to examine long-term processes in the unsaturated vault environment, alongside our work on improving new models of the near field in PFLOTRAN. This work will focus on reducing uncertainties in the impacts of heterogeneous saturation and chemical conditions in the vaults. We also anticipate future work to develop a chemical model for the new grout formulation that is under development. In addition, we will continue to develop our models for gas generation and transport to support future optimisation of gas management.

Coastal erosion

A review will be undertaken of capabilities and research relating to the modelling of coastal erosion. One aspect the review will focus on is the relationship between sea-level rise and coastal erosion. Based on this review, a strategy for the future modelling of coastal erosion in the LLWR's locality will be implemented.

Monitoring

We will continue our general environmental monitoring programme, reviewed at appropriate intervals to validate the assumptions and outcomes of the ESC. It is expected that the monitoring programme will need to change over time to adapt to changes on site or to investigate specific questions or trends.

Cap performance monitoring is identified as a key long-term interest in the ESC to assess the long-term performance and evolution of the final cap, including:

- monitoring of the trial surcharge area to assess container deformation;
- settlement monitoring of capped areas beyond construction;
- measurement of infiltration and drainage behaviour, to confirm predicted reductions in recharge;
- assessment of the physical condition and degradation of cap materials over time, including pre-installation testing of the membrane to improve the baseline assumptions on performance and help identify deviations from the expected evolution.

These options will be considered further as part of the capping project.

In addition, it is recognised that the external dose models developed for the Period of Authorisation currently overestimate dose compared with measurements. It is proposed that additional targeted monitoring is carried out to better understand the discrepancy, including:

- gamma spectrometry to distinguish Cs-137 and Co-60;
- measurements that separate direct and scattered radiation.

This should provide improved data to enable a more direct comparison between modelled and measured dose components.

SWESC and WMP

We will continue to characterise the site, to improve understanding of contamination and potential future waste arisings of site wastes and to develop the SWESC and WMP aspects of the ESC to support decision-making on appropriate timescales. As more knowledge is gained about potential future waste arisings or contamination, this will be added to the WMP to keep it live. This will support optimised management of waste and contamination across the site's lifecycle to work towards the regulatory criteria defined for release from regulation.

The main outstanding decisions are on the management of the contamination of the site by its use as a Royal Ordnance Factory prior to that as a radioactive waste storage and disposal facility, and on the leachate management system for the disposal facility, including the contamination in Drigg Stream.

ILW

We will continue to support the NDA in its consideration of the option to dispose of some less-hazardous ILW at the LLWR, including in its interactions with stakeholders, consistent with government policy. Were the decision be made to pursue this option, we would seek any necessary revisions to our Permit to dispose of waste at the site and planning permission. The necessary changes to the Site Development Plan and management of the receipt of waste would be implemented.

7 Addressing the Regulatory Guidance

The GRA sets out a fundamental protection objective (see Subsection 2.2), five principles for solid radioactive waste disposal and fourteen requirements – see Figure 7.1. The GRR takes the same approach of stating principles and requirements – see Table 7.2. The ESC must demonstrate compliance with all the relevant requirements of the GRA and GRR and show consistency with the supporting guidance therein. We do not have to separately show adherence to the principles, although we observe that all the principles set out in the GRA and GRR have, effectively, been incorporated in our Environmental Safety Strategy, as discussed in Subsection 3.1.

The ESC is structured around the presentation of our safety arguments and the evidence that supports them. In this section, we show how the arguments and evidence correspond to the regulatory requirements and hence demonstrate the requirements are satisfied. Table 7.1 lists the GRA requirements and shows how our safety case arguments, as set out in Section 4, correspond to each of the requirements. There is not a one-to-one correspondence, rather, many of our safety case arguments are building blocks that underpin our claim to have met a given requirement. Table 7.2 does the same for the GRR requirements.

To verify fully that we have met a given requirement, it is necessary to consider not just the arguments as articulated in Section 4, but also the supporting evidence presented in the Level 2 documents, as referred beneath each argument. Nevertheless, Table 7.1 and Table 7.2 provide maps by which the Environment Agency may begin to examine our approach to complying with each of the requirements.

A more detailed analysis covering the all requirements, and the much larger number of guidance paragraphs of the GRA and GRR that can be interpreted as essential conditions, is set out in the '*Addressing Regulatory Requirements and Feedback'* report [18]. That report systematically sets out our high-level response to each of the guidance paragraphs and identifies where in the ESC documentation more detail can be found to show how the guidance has been interpreted and addressed in the ESC.

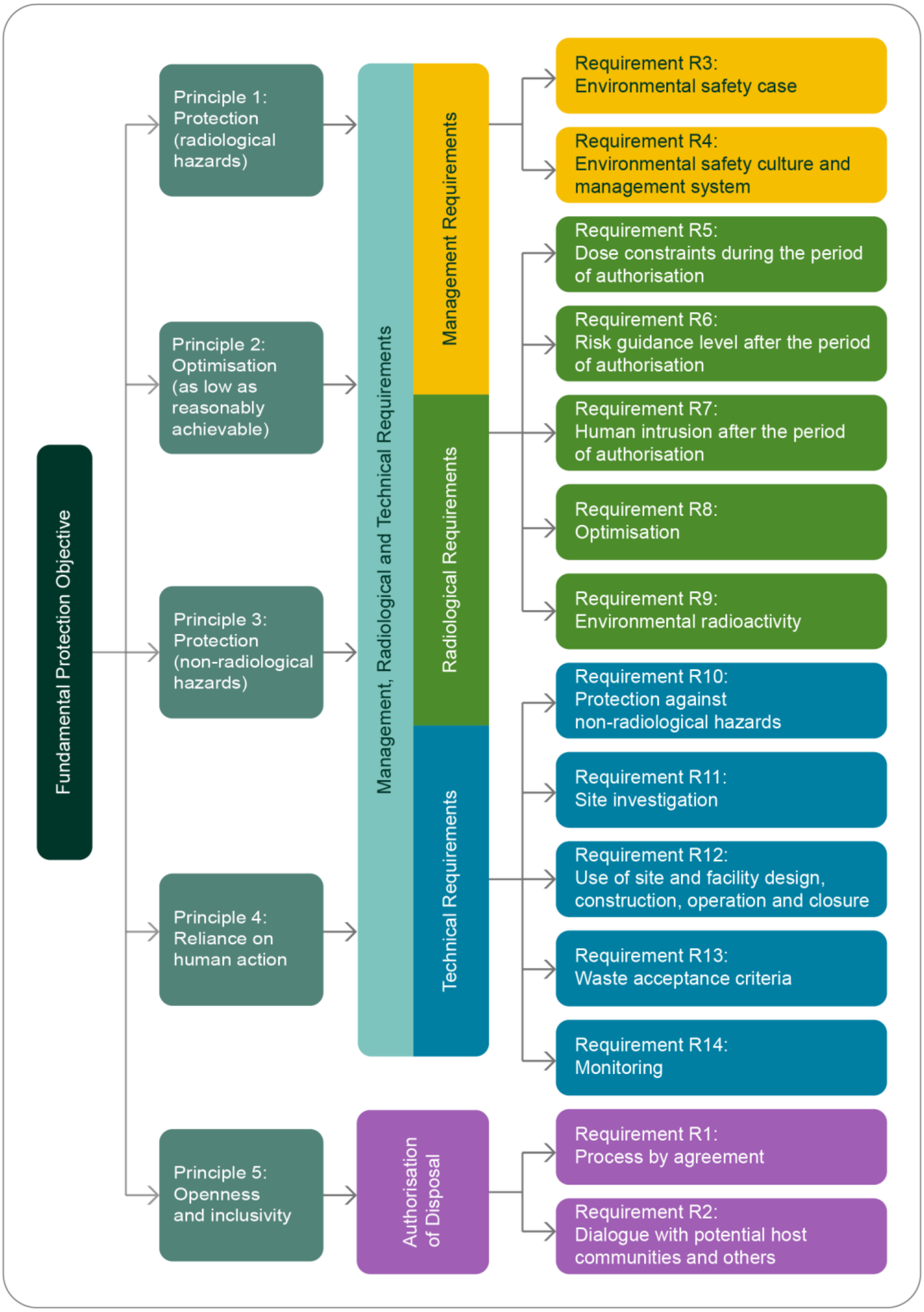

Figure 7.1: Relationship between the fundamental safety objective, principles and requirements in the GRA [29]

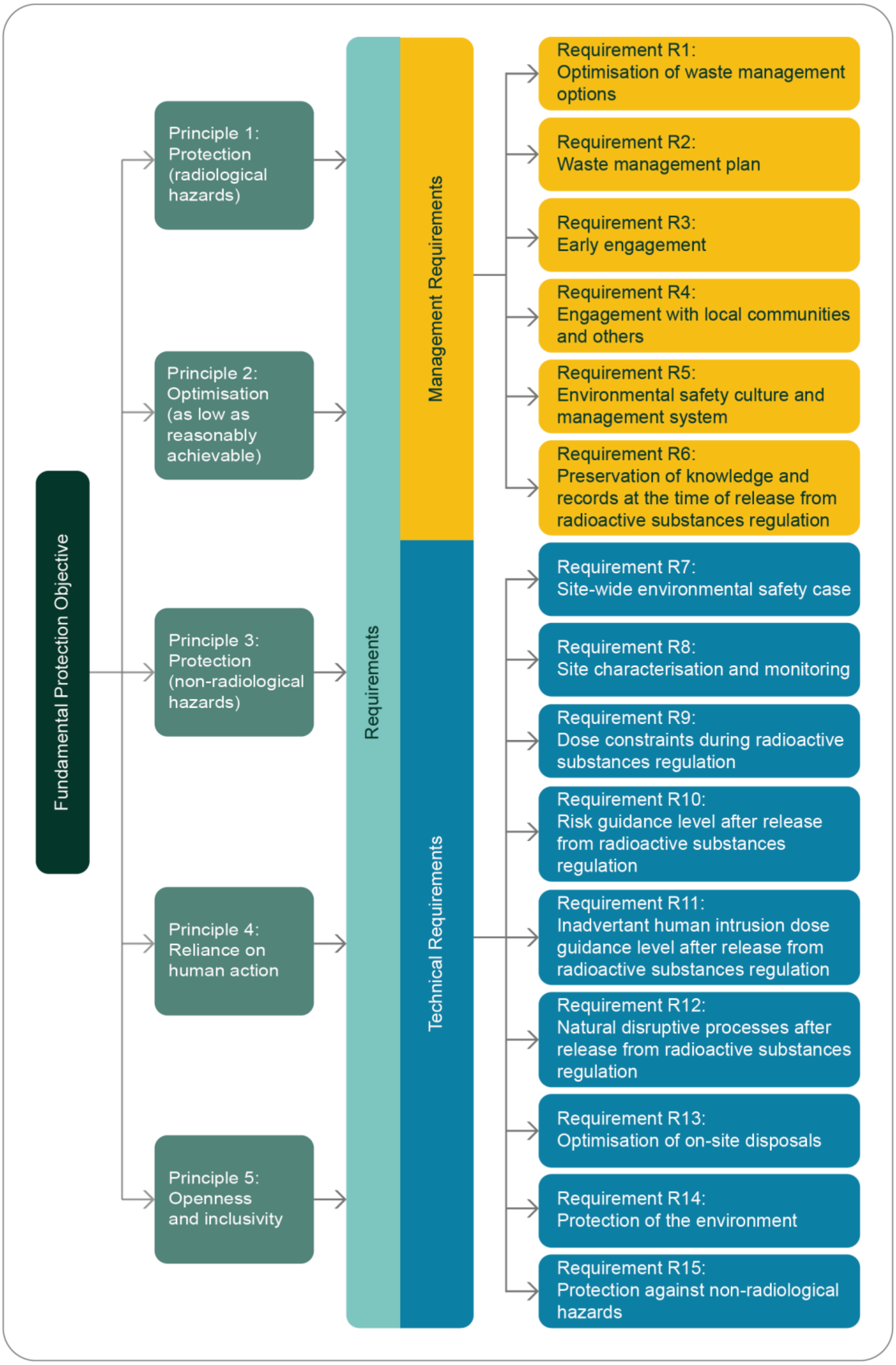

Figure 7.2: Relationship between the fundamental safety objective, principles and requirements in the GRR [30]

Table 7.1: The GRA requirements and corresponding ESC arguments

GRA Requirement	Main related safety case arguments (and comments)
R1: Process by agreement	This requirement is mainly directed at the early stage of repository development, whereas the LLWR is an operating facility. It is mostly not directly applicable to the ESC. Relevant points are developed under 'M3'.
R2: Dialogue with local communities and others	*'M3: Dialogue with our environmental regulator'* *'M4: Dialogue with our stakeholders'*
R3: Environmental safety case	All our safety arguments, apart from '*O6: Wastes associated with the use of the site*', relating to our WMP, contribute to satisfying the requirements for an ESC set out in the GRA.
R4: Environmental safety culture and management system	*'M1: Management system and safety culture'* *'M2: Management and development of the ESC'* *'M3: Dialogue with our environmental regulator'* *'M4: Dialogue with our stakeholders'* *'M5: Peer review'*
R5: Dose constraints during the period of authorisation	*'A4: Radiation doses during the Period of Authorisation'* (Underpinned by *'S1', 'S2', 'S3', 'S4', 'S5', 'S6', 'O5', 'A1', 'A2', 'A3'*)
R6: Risk guidance level after the period of authorisation	*'A5: Radiation doses and risks in the long term'* (Underpinned *by 'S1', 'S2', 'S3', 'S4', 'S5', 'A1', 'A2', 'A3'*)
R7: Human intrusion after the period of authorisation	*'A5: Radiation doses and risks in the long term'* (Underpinned by 'S1', 'S2', 'S3', 'S4', 'S5', 'A1', 'A2', 'A3')
R8: Optimisation	*'O1: Remediation of past waste disposals'* *'O2: Optimisation of future waste disposals'* *'O3: Site engineering'*

GRA Requirement	Main related safety case arguments (and comments)
	'O4: Waste emplacement strategies' *'O5: Management of run-off and leachate'* *'O7: Management during closure'* *'I4: Optimising the use of the LLWR'* (Underpinned by *'S1', 'S2', 'S3', 'S4', 'S5', 'S6', 'A1', 'A2', 'A3'*)
R9: Environmental radioactivity	*'A7: Impacts on non-human biota'* (Underpinned by *'S1', 'S2', 'S3', 'S4', 'S5', 'S6', 'A1', 'A2', 'A3'*)
R10: Protection against non-radiological hazards	*'A6: Non-radiological impacts'* (Underpinned by *'S1', 'S2', 'S3', 'S4', 'S5', 'S6', 'A1', 'A2', 'A3'*)
R11: Site investigation	*'S3: Characterising and understanding the geology and hydrogeology'* *'S4: Characterising and understanding the coastal environment'* *'S5: Characterising and understanding the surface environment'* (Underpinned and guided by *'A1'*)
R12: Use of site and facility design, construction, operation and closure	*'O3: Site engineering'* *'O4: Waste emplacement strategies'* *'O5: Management of run-off and leachate'*
R13: Waste acceptance criteria	*'I1: Waste Acceptance Criteria'* *'I2: Radiological and non-radiological capacity'* *'I3: Implementing the ESC'* *'I4: Optimising the use of the LLWR'*
R14: Monitoring	*'S6: Monitoring'*

Table 7.2: The GRR requirements and corresponding ESC arguments

GRR Requirement	Main related safety case arguments (and comments)
R1: Optimisation of waste management options	*'O6: Wastes associated with the use of the site'* *(Underpinned by 'O5', 'I4')*
R2: Waste management plan	*'O6: Wastes associated with the use of the site'* *(Underpinned by 'S3', 'S4', 'S5', 'S6')*
R3: Early engagement	*'M3: Dialogue with our environmental regulator'*
R4: Engagement with local communities and others	*'M4: Dialogue with our stakeholders'*
R5: Environmental safety culture and management system	*'M1: Management system and safety culture'* *'M2: Management and development of the ESC'* *'M3: Dialogue with our environmental regulator'* *'M4: Dialogue with our stakeholders'* *'M5: Peer review'*
R6: Preservation of knowledge and records at the time of release from radioactive substances regulation	*'M1: Management system and safety culture'*
R7: Site-wide environmental safety case	The arguments listed in this table contribute to satisfying the requirements for a site-wide environmental safety case set out in the GRR.
R8: Site characterisation and monitoring	*'S3: Characterising and understanding the geology and hydrogeology'* *'S4: Characterising and understanding the coastal environment'* *'S5: Characterising and understanding the surface environment'* *'S6: Monitoring'*

GRR Requirement	Main related safety case arguments (and comments)
R9: Dose constraints during radioactive substances regulation	*'O6: Wastes associated with the use of the site'* *(Underpinned by ‘S3’, ‘S4’, ‘S5, 'S6’, 'A4')*
R10: Risk guidance level after release from radioactive substances regulation	*'O6: Wastes associated with the use of the site'* *(Underpinned by ‘S3’, ‘S4’, ‘S5, 'S6, 'A5’)*
R11: Inadvertent human intrusion dose guidance level after release from radioactive substances regulation	*'O6: Wastes associated with the use of the site'* *(Underpinned by ‘S3’, ‘S4’, ‘S5, 'S6’, 'A5')*
R12: Natural disruptive processes after release from radioactive substances regulation	*'O6: Wastes associated with the use of the site'* *(Underpinned by ‘S3’, ‘S4’, ‘S5, 'S6’, 'A5')*
R13: Optimisation of on-site disposals	No proposal for on-site disposal (of 'site' wastes) is being made at this time
R14: Protection of the environment	*'O6: Wastes associated with the use of the site'* *(Underpinned by ‘S3’, ‘S4’, ‘S5, 'S6’, 'A7')*
R15: Protection against non-radiological hazards	*'O6: Wastes associated with the use of the site'* *(Underpinned by ‘S3’, ‘S4’, ‘S5, 'S6’, 'A6')*

8 Concluding Statements

We have set out the factors that frame and provide the context for the development of the ESC:

- UK national policy and NDA strategy for the management of radioactive waste, which sets the objective of the LLWR;
- the history, current conditions and environmental context of the facility and site.

The ESC has been developed according to our Environmental Safety Strategy, which lays out our approach to achieving the continuing environmental safety of the LLWR.

The ESC sets out our environmental safety arguments and supporting evidence that we believe justify the use of the LLWR to dispose of radioactive waste.

At a high level, our case is that:

- we work within a sound management framework and firm safety culture, while engaging in dialogue with stakeholders;
- we characterise and establish a sufficient understanding of the LLWR site and facility, and their evolution, relevant to its environmental safety;
- on which basis, we carry out comprehensive evaluation of options to arrive at an optimised Site Development Plan for the LLWR;
- we assess the environmental safety of the Site Development Plan, to show that impacts are consistent with regulatory guidance;
- we implement our Site Development Plan and ESC to ensure safe and optimal use of the LLWR.

We have extended the scope of the ESC to cover the regulatory requirements set out in the GRR.

Our aim has been to be realistic in our modelling and assessment. Unnecessary conservatism might lead to sub-optimum management of wastes. We have been, however, cautious where appropriate because of, for example, uncertainties.

We have identified, considered and treated uncertainty within the ESC sufficiently to meet its objectives. Our intended future work programme to further reduce key uncertainties has been described.

The 2026 ESC addresses feedback received from the Environment Agency on the 2011 ESC and subsequently on the evolution of the ESC. Learning from operation of the facility and studies performed since the last ESC has been applied.

We have shown how the ESC has addressed the requirements set out in the regulatory guidance.

The 2026 ESC demonstrates the safety of the LLWR now and during the rest of its lifetime. This includes the period of continuing disposal operations, at the time the final closure engineering is installed, during the period of active institutional control, and after, including during and after coastal erosion of the facility.

Changes to the implementation of the ESC for the disposal of LLW, required by this revision, will be implemented, in dialogue with the Environment Agency.

Based on the safety analyses reported in the 2026 ESC, and our Site Development Plan, there would be significant excess capacity to dispose of a wider range of radioactive wastes than LLW. Proposals may be made to seek the necessary permissions to further optimise the use of the facility to dispose of a wider range of wastes. No decision has been made yet to seek these permissions and the decision would only be taken by the NDA after appropriate consultation with stakeholders.

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Appendix A: List of Abbreviations

ALARA	As low as reasonably achievable
ALARP	As Low As Reasonably Practicable
BAT	Best Available Technique
BNFL	British Nuclear Fuels Limited
ESC	Environmental safety case
GRA	Guidance on Requirements for Authorisation for Near-Surface Disposal Facilities on Land for Solid Radioactive Wastes
GRR	Guidance on Requirements for Release from Radioactive Substances Regulation
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
IMS	Integrated Management System
ISO	International Organization for Standardization
LiDAR	Light detection and Ranging
LLW	Low Level Waste
LLWR	Low Level Waste Repository
NDA	Nuclear Decommissioning Authority
NWSSOP	Nuclear Waste Services Standard Operating Procedure
OD	Ordnance Datum
ONR	Office for Nuclear Regulation
RSA	Radioactive Substances Act
RSP	Repository Site Procedure
SSSI	Site of Special Scientific Interest
SWESC	Site-wide environmental safety case
TNT	Trinitrotoluene
UKRWI	United Kingdom Radioactive Waste Inventory
VLLW	Very-low-level Waste
WAC	Waste Acceptance Criteria
WAGR	Windscale Advanced Gas-cooled Reactor
WCSSG	West Cumbria Sites Stakeholder Group

WMP	Waste Management Plan

Appendix B: ESC Glossary

This is a glossary of important and general terms that are used across several ESC documents. It does not provide a comprehensive glossary of technical terms. Terms are ordered by logical connection, then alphabetically. Further specialist technical definitions may be found in:

- the International Atomic Energy Agency '*Safety Glossary*' [67];
- documents available on the Environment Agency website, especially the glossary in '*Near-surface Disposal Facilities on Land for Solid Radioactive Wastes. Guidance on Requirements for* Authorisation' [29].

Organisations

Environment Agency

The Environment Agency is a non-departmental public body operating in England. Its principal sponsoring department is the Department for Environment, Food and Rural Affairs. In the context of the LLWR, the Environment Agency regulates the disposal of radioactive waste through an *environmental permit*.

Nuclear Decommissioning Authority

The Nuclear Decommissioning Authority (NDA) is a non-departmental public body created under the Energy Act 2004. It owns the 19 civil nuclear sites and associated nuclear liabilities and assets that were previously under the control of the United Kingdom Atomic Energy Authority and British Nuclear Fuels Ltd. The role of the NDA is expanding to include the decommissioning of the UK's Advanced Gas-cooled Reactors. The NDA owns the LLWR site and Nuclear Waste Services Ltd.

Nuclear Waste Services

Nuclear Waste Services is the *Site Licence Company* that manages and operates the LLWR on behalf of the NDA. Nuclear Waste Services is a wholly owned subsidiary division of the NDA.

Office for Nuclear Regulation

The Office for Nuclear Regulation is a statutory corporation established under the Energy Act 2013. It regulates safety, security and nuclear safeguards at nuclear sites and the transport of radioactive substances by road, rail and inland waterways. It issues a *nuclear site licence* for each *nuclear licensed site*, including the LLWR, and regulates operations at each site through the site licence conditions.

Terms related to legislation and regulation

Environmental permit

An environmental permit is required under the *Environmental Permitting (England and Wales) Regulations 2016* in order to lawfully conduct a radioactive substances activity on the LLWR site. We currently hold an environmental permit for, amongst other things, disposal of radioactive waste. A variation was issued in 2015 on the basis of the 2011 ESC, most recently amended in 2025. The 2026 ESC will be the basis for any application for a revised environmental permit for our continued authorised disposal of radioactive waste under determined conditions.

Environmental Permitting (England and Wales) Regulations 2016

The Environmental Permitting (England and Wales) Regulations 2016 were introduced on 1st January 2017, replacing the 2010 Regulations. The 2016 Regulations were a consolidation and rationalisation of the 2010 Regulations and all their subsequent amendments. They did not introduce any new policy regime or make any major changes.

Management of Radioactive Waste from Decommissioning of Nuclear Sites: Guidance on Requirements for Release from Radioactive Substances Regulation (GRR)

The GRR was issued by the UK environment agencies, including the Environment Agency, in July 2018. The guidance describes what operators of nuclear sites need to do when they are planning and carrying out their work to decommission and clean up their sites. In line with this guidance and related environmental permit conditions, operators are required to develop and maintain a suitable *Waste Management Plan* and *Site-wide Environmental Safety Case*. These requirements will ensure the condition of the site meets regulatory standards for protection of people and the environment, now and into the future.

Near-surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation (GRA)

The GRA was issued by the UK environment agencies, including the Environment Agency, in February 2009. The guidance sets out the framework within which the Environment Agency regulates near-surface disposal facilities, and the intended regulatory approach. It is written mainly for the developers and operators of these facilities. The guidance sets out five principles for solid radioactive waste disposal and fourteen specific requirements, which, if fulfilled proportionately to the hazard presented by the waste, should ensure that the principles are properly applied. We have been advised that the Environment Agency is planning to issue a revised version of the GRA. The 2026 ESC has been prepared against the existing version.

Nuclear licensed site

The nuclear licensed site is the area of ground covered by the nuclear site licence. Most of the LLWR nuclear licensed site is contained within a security fence. An area of the south of the site containing administrative buildings and unused land is part of the nuclear licensed site but not within the secure perimeter.

Nuclear site licence

Where appropriate, sites where activities are conducted involving nuclear matter, such as the LLWR, are issued with a nuclear site licence before any activities of nuclear safety significance commence on the site. The nuclear site licence requires the licensee (the *Site Licence Company*, Nuclear Waste Services in the case of the LLWR) to make and implement adequate arrangements for work at the site. The nuclear site licence contains 36 licence conditions, which cover aspects such as: documentation; training; emergency arrangements; safety documentation; quality assurance; radiological protection; control and supervision of operations; disposal of radioactive waste; and control of radioactive material and radioactive waste. The nuclear site licence is issued by the Office for Nuclear Regulation.

Site Licence Company

A Site Licence Company (SLC) is a company that holds a *nuclear site licence* under the Nuclear Installations Act 1965 in the UK. The Site Licence Company is responsible for the financial management and operation of the nuclear site. Nuclear Waste Services is the Site Licence Company for the LLWR site. Nuclear Waste Services operates and is accountable for ensuring compliance with safety regulations and conditions attached to the nuclear site licence.

Terms related to radioactive waste management

Consignment

A consignment is a container or item of waste sent by a consignor to a disposal facility (such as the LLWR).

Consignor

A consignor is an organisation or person that sends waste to a facility for disposal.

Intermediate Level Waste

In government policy, Intermediate Level Waste (ILW) is defined as radioactive waste that exceeds the upper boundaries for Low Level Waste but does not generate sufficient heat to be considered High Level Waste.

Less-hazardous Intermediate Level Waste

The term ‘less-hazardous Intermediate Level Waste’ is not formally defined in national or international guidance, but we use it to describe Intermediate Level Waste that can be safely disposed of at the LLWR, in line with regulatory protection criteria – specifically the *risk guidance level* and *dose guidance level*.

Low Level Waste

In government policy, Low Level Waste (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.

United Kingdom Radioactive Waste Inventory

The United Kingdom Radioactive Waste Inventory (UKRWI) is produced by Nuclear Waste Services on behalf of the NDA and the Department for Energy, Security and Net Zero (DESNZ). It is routinely updated and published in the public domain, currently on a three-yearly cycle. It describes the sources, quantities and properties of radioactive waste that exists and is forecast to arise in the future.

Waste hierarchy

The waste hierarchy sets out the priority order for managing waste materials based on their environmental impacts. It gives top priority to preventing waste from being generated in the first place. When waste is created, it gives priority to preparing it for re-use, then recycling, then recovery, and last of all disposal (e.g. landfill). It is one factor used in making decisions on waste management options, alongside safety and other factors.

The waste hierarchy was first introduced in 1975 in EU waste policy in the Waste Framework Directive for non-radioactive waste. Application of the waste hierarchy is central to the UK government policy [28].

Waste stream

Radioactive waste is divided into waste streams to enable effective characterisation, and to allow the most appropriate disposal and treatment routes to be applied to a group of wastes. These waste streams form the basis of the forward inventory. A waste stream includes waste or a collection of waste items at a particular site, usually from a particular facility or process.

Terms related to the Low Level Waste Repository

Completion of closure engineering

Completion of closure engineering denotes the time that final capping and cut-off wall installation is complete. At this time, active leachate management will be ongoing. Upon completion of closure engineering, the site will enter the period of active institutional control.

Vault closure

Vault closure for an individual vault denotes the time when the capping over the vault is complete. At this time, active leachate management will be ongoing.

Disposal

The permanent removal, deposit, destruction, discharge or burial of radioactive waste, without intent to retrieve it. Retrieval may be possible but, if intended, the appropriate term is storage.

Disposal system

The disposal system is the *waste*, the *wasteform* and *waste containers*, the *engineered structures* of the LLWR, and the environment within which it sits and which may be impacted.

Emplacement

Emplacement is the placement of a waste package in a designated location for disposal, with no intent to reposition or retrieve it subsequently.

Emplacement strategy

An emplacement strategy is a strategy to control the locations in which certain waste streams and waste consignments are emplaced, for example, not placing certain wastes in the upper stacks in the vaults. This would have the effect of reducing the probability of inadvertent human intrusion into such wastes. An emplacement strategy may be necessary in order that *dose constraints* and *dose guidance levels* are met or might be an optimisation measure to minimise the environmental impact of disposals to the LLWR.

ISO containers

A steel container built to standard dimensions certified by the International Organization for Standardization (ISO). ISO containers can be loaded and unloaded, stacked and transported efficiently over long distances without being opened. Currently, wastes for disposal in the vaults at the LLWR are mostly placed in half-height ISO containers.

Low Level Waste Repository

The Low Level Waste Repository is the UK's principal facility for the disposal of LLW. It is situated near the village of Drigg in Cumbria. Operated since 1959, the LLWR site is now owned by the NDA and currently operated on its behalf by the *Site Licence Company*: Nuclear Waste Services.

The LLWR consists of the engineering for the disposal of solid radioactive wastes. It includes the trenches (Trenches 1 to 7) and existing vaults (Vaults 8 and 9), in which LLW has been or is emplaced. There are also plans for future vaults and post-closure engineering. The LLWR also includes plant such as the Drigg Grouting Facility and the leachate management system.

Low Level Waste Repository site

The Low Level Waste Repository site is the nuclear licensed site on which the LLWR is constructed and operated. The site is designated under the Nuclear Installations Act 1965 (as amended).

Monitoring

Monitoring consists of taking measurements so as to be aware of the state of the disposal system and any changes to that state. This may include measuring levels of radioactivity in samples taken from the environment, and geological, physical and chemical parameters relevant to environmental safety and which may change as a result of construction of the disposal facility, waste emplacement and closure. A comprehensive monitoring programme has been established at the LLWR. An important objective of this programme is to provide data to underpin and increase confidence in the conceptual and numerical models of the LLWR system that are used in the ESC, particularly relating to models of groundwater flow and contaminant transport. An annual review of the monitoring programme is undertaken.

Royal Ordnance Factory

The LLWR site was first developed in 1940 as a Royal Ordnance Factory (ROF) for the production of TNT. The first TNT was produced in March 1941. Ownership of the site later passed to the United Kingdom Atomic Energy Authority, which was granted planning consent in 1957 for the disposal of LLW in the northern 40 ha of the site.

Standard Waste Transport Container

The Standard Waste Transport Container (SWTC) is a design for a Type B transport container for transporting ILW to a geological disposal facility. The design is suitable for unshielded waste packages that exceed the activity limits for IP-2 containers (such as *ISO containers*) and require greater protection in the case of fire and accidents.

SWTC-compatible strong box

Some of the low-hazard ILW inventory considered in the 2026 ESC may require transport in a *SWTC* because it exceeds the activity limits for IP-2 containers (such as *ISO containers*). Therefore, we have assumed the use of a smaller container which would fit inside a SWTC: the SWTC-compatible strong box. The concept design assumes a similar construction to an ISO container, i.e. it will be made of mild steel with the strength provided by the container framework and in particular corner elements.

Storage

Storage is the placing of waste in a suitable facility with the intent to retrieve it.

Validation monitoring

Validation monitoring seeks to confirm that the condition and behaviour of the site, and where relevant the surrounding area, is in accordance with the assumptions of the ESC. Validation monitoring will be conducted by the environmental permit holder and may continue for a period after the *completion of closure engineering*. Results and conclusions from the validation monitoring programme will be used by the operator to demonstrate that the *Site Reference State* has been reached, supporting an application for environmental permit surrender.

Waste Acceptance Criteria

Waste Acceptance Criteria are the quantitative and qualitative criteria, specified by the operator of a disposal facility, for solid radioactive waste to be accepted for disposal. Waste Acceptance Criteria form part of the set of waste acceptance arrangements that ensure the safety of waste disposal at the site.

Waste Acceptance Procedure

The Waste Acceptance Procedure governs the full lifecycle of a waste consignment − from enquiry, characterisation, and allocation of capacity through to verification and emplacement. The Waste Acceptance Procedure ensures that only waste is accepted and emplaced consistent with the ESC and that consignors provide sufficient evidence to support disposability, compliance, and ESC development.

Waste variation

A case-by-case assessment whether to accept and dispose of a waste consignment that does not fully meet the standard *Waste Acceptance Criteria*, subject to additional justification, assessment (including ESC implications), and any specified extra controls/conditions (e.g. on packaging, conditioning, or emplacement).

Terms related to the Environmental Safety Case

Annual Review of the ESC

Collates and checks the previous year's disposal and monitoring information against the ESC assumptions and safety envelope. The Annual Review considers aspects such as radiological and non-radiological capacity usage, disposal of bulk materials affecting performance, significant monitoring results and new information, changes to the ESC and processes, significant site changes, and review of the ESC uncertainty register.

Argument

The reasoning that links evidence to a claim, explaining why the evidence is sufficient. The key safety arguments for the ESC are presented in Section 4 of the '*Main Report*'.

Best Available Techniques

In the context of radioactive waste management, Best Available Techniques (BAT) refers to the process used to identify and assess options for managing wastes (including discharges) across the waste management lifecycle. BAT is closely related to *optimisation*, and the terms are often used interchangeably. For our purposes, BAT studies and the use of BAT demonstrate that our disposal model is optimised, with the aim of ensuring that the level of exposure to the public is as low as reasonably achievable. BAT is a key principle in the regulatory framework for managing radioactive waste and is applied throughout the lifetime of a facility, from design to decommissioning. The application of BAT involves a balanced judgment of the benefits and costs associated with implementing measures to reduce environmental impacts.

Claim

A statement about performance or compliance that the ESC seeks to justify. At a high level, our claims are that:

- we work within a sound management framework and firm safety culture, while engaging in dialogue with stakeholders;

- we characterise and establish a sufficient understanding of the LLWR site and facility, and their evolution, relevant to its environmental safety;
- on which basis, we carry out comprehensive evaluation of options to arrive at an optimised Site Development Plan for the LLWR;
- we assess the environmental safety of the Site Development Plan, to show that impacts are consistent with regulatory guidance;
- we implement our Site Development Plan and ESC to ensure safe and optimal use of the LLWR.

Environmental safety case

An environmental safety case (ESC) is a set of claims concerning the environmental safety of disposals of solid radioactive waste, substantiated by a structured collection of arguments and evidence. It should demonstrate that the health of members of the public and the integrity of the environment are adequately protected. It will be provided by the developer or operator of the disposal facility and should be designed to demonstrate consistency with the principles set out in the UK environment agencies' GRA. It is important to recognise that an environmental safety case is broader than the safety assessment calculations. It will also include a range of more qualitative arguments to demonstrate safety, and description of the measures that we take to implement the ESC, including limits, controls and conditions, such as those implemented in our *Waste Acceptance Criteria* and *Waste Acceptance Process*.

Environmental Safety Strategy

The Environmental Safety Strategy lays out our approach to achieving the continuing environmental safety of the LLWR. The Environmental Safety Strategy is the process and means by which we achieve this primary objective in a demonstrably environmentally safe way. Our Environmental Safety Strategy leads to an optimised *Site Development Plan*; our plan for developing the site consistent with our Environmental Safety Strategy.

Evidence

Information that supports arguments (e.g. monitoring data, design information, assessments, operating experience). Together, the Level 2 documents form the evidence that support the arguments.

Limit

A principal component of *Waste Acceptance Criteria* is the setting of limits relating to the quantities and concentrations of material (principally radionuclides) that can be disposed of in a facility to ensure regulatory criteria are met. The results of the various *assessment cases* that have been developed for the ESC are used to develop these limits. This includes:

- limits on total activity and non-radiological materials in the repository (referred to as '*radiological and non-radiological capacities*');
- limits on activity in individual consignments;

- limits on average activity concentration in a consignment (referred to as 'activity concentration limits');
- limits we use to determine *emplacement* locations of certain consignments to support the emplacement *strategy* (referred to as 'emplacement limits');
- activity limits at a sub-container scale including controls on *discrete items* (including sealed sources) and *active particles*; and
- limits for fissile radionuclides.

We often have to consider several radionuclides. If, for each radionuclide, we were to dispose of an activity equal to the calculated limit, the assessed impacts could exceed relevant regulatory criteria. In such cases, our limits are applied using a sum-of-fractions approach.

Live ESC

The change-controlled, authoritative baseline set of documents that together comprise the Environmental Safety Case for the LLWR at a point in time, maintained and updated through formal governance. It does not mean each document is 'live' or frequently updated; rather, new or revised documents are added to the baseline as they are issued, with implications assessed and recorded. The live ESC is tracked via *Annual*, *Periodic* and *Major reviews*. At the point of submission, the 2026 ESC represents the ‘live’ ESC, but may be further updated prior to the next Major Review under change control and as new information arises.

Major Review of the ESC

A Major Review is the process by which the ESC is comprehensively reassessed and consolidated, producing a single, internally consistent re-baselined document set that brings together all updates since the previous Major Review. A Major Review is normally undertaken to fulfil a condition in the site's Permit. Such Major Reviews are normally undertaken on a ten-yearly cycle.

A Major Review may also be initiated, for example, by significant cumulative changes to the ESC, by a new phase of construction requiring review of the planning permission, by a proposed major change to the function of the repository, or by the regulator requiring submission of a revised ESC by a specified date. These changes are preceded by a Major Review of the ESC. A Major Review takes account of any construction that has taken place and the outcomes of the development programme of the ESC since the last Major Review.

A Major Review includes a detailed analysis of all aspects of the ESC, and relevant aspects of the LLWR’s activities and future plans and programmes. It has the objective of ensuring that the LLWR is safely operated and developed, performs safely during the *period of active institutional control*, and evolves safely after *completion of final closure engineering*.

Consideration of whether further optimisation of the facility and its operation is required is also included in a Major Review.

Optimisation

Optimisation is the principle of ensuring that radiation exposures are as low as reasonably achievable under the circumstances prevailing at the time of disposal, taking into account economic and societal factors and the need to manage radiological risks to other living organisms and any non-radiological hazards. Optimisation is closely related to *Best Available Techniques* (BAT), and the terms are often used interchangeably. For our purposes, BAT studies and the use of the BAT process are used to demonstrate optimisation of our disposal model. This in turn underpins our Site Development Plan.

Optimisation is a key principle of radiation protection recommended by the International Commission on Radiological Protection (ICRP) and incorporated into UK legislation and the GRA. Although reducing radiological risk is important, it should not be given a weight out of proportion to other considerations. The best way forward is not necessarily the one that offers the lowest radiological risk.

For a full definition of Optimisation, see the GRA [29].

Peer Review Group

We appoint a Peer Review Group (PRG) to provide independent challenge of the ESC and constructive feedback. The PRG consists of experts of longstanding experience and strong reputation, with a balance of expertise reflecting the multidisciplinary nature of the ESC. It is formed of individuals who are independent of the development of the ESC for the LLWR. The scope of the PRG's work focuses on issues that are important to: environmental risks; development and evaluation of options; and clear presentation of evidence and arguments. The PRG works in such a way that it can be demonstrated to stakeholders that an effective and proportionate process of independent technical review and scrutiny is operating.

Periodic Review of the ESC

A scheduled review (typically about every four years) that focuses on cumulative changes since the last *Major Review*, assessing whether the ESC remains adequate for the next review cycle, including consideration of longer-term trends of aspects addressed in the *Annual Reviews*.

Radiological and non-radiological capacities

Radiological and non-radiological capacities for a disposal facility are defined as an inventory of material that the facility is capable of safely accepting according to its ESC. We use several capacities, each derived from a distinct *assessment case*. For a given assessment case, the limit for each species specifies the maximum amount of that species that could be disposed of and, for radionuclides, result in peak radiological impacts consistent with appropriate regulations or guidance, or, for non-radiological contaminants, give rise to concentrations in the groundwater at *compliance points* that are consistent with landfill guidance.

In general, we have to consider several radionuclides. If, for each radionuclide, we were to dispose of an activity equal to the calculated limit, the assessed impacts could exceed relevant regulatory criteria. To prevent this occurring, our capacities are applied using a *sum-of-fractions* approach.

Site Development Plan

The Site Development Plan is developed from the *Environmental Safety Strategy.* An optimised Site Development Plan forms the basis of our assessments of repository performance, an important part of our demonstration of environmental safety. The Site Development Plan set out our proposals and assumptions on operations, remedial activities, vault design, capacity and future waste disposal practice, closure design and management up to the end of the *Period of Authorisation*. The plan is flexible, however, and will be amended as necessary in the light of UK radioactive waste management needs, operating experience, results of monitoring, regulatory and planning decisions and stakeholder views.

Site-wide Environmental Safety Case

A Site-wide Environmental Safety Case (SWESC) is a documented set of claims, made by the operator of a nuclear site, to demonstrate achievement by the site as a whole of the required standard of environmental safety. Where relevant, the SWESC includes the ESC for any on-site disposal facility.

For the LLWR site, the 2026 ESC is a SWESC, but the term ‘ESC’ has been retained because the great majority of the content relates to the on-site disposal facility. This is because of the nature of the site and facility, which is a disposal facility with some temporary waste storage. The wastes in the disposal facility form the main environmental hazard. Retaining the name 'ESC' is also helpful because the organisation is familiar with the term and its importance.

The 2011 ESC

The Major Review of the ESC submitted in May 2011.

The 2026 ESC

The Major Review of the ESC submitted in May 2026.

Terms related to radiological safety

Dose constraint

The dose constraint is a prospective restriction on the individual dose delivered by a source and serves as an upper bound on the dose in optimisation of protection and safety for the source. The concept of dose constraint is applicable to the *Period of Authorisation* of a disposal facility. In this period, the effective dose to a representative member of the critical group should not exceed a source-related dose constraint of 0.3 mSv per year and a site-related dose constraint of 0.5 mSv per year.

Dose guidance level

In the context of near-surface disposal facilities, the dose guidance level is the dose standard against which the radiological consequences of human intrusion are assessed. It indicates the standard of environmental safety expected, but does not suggest that there is an absolute requirement for this level to be met. The assessed effective dose to any person during and after the assumed intrusion should not exceed a dose guidance level in the range of around 3 mSv per year to around 20 mSv per year. Values towards the lower end of this range are applicable to assessed exposures continuing over a period of years (prolonged exposures), while values towards the upper end of the range are applicable to assessed exposures that are only short term (transitory exposures).

Effective radiation dose

Effective radiation dose is a measure of the health risk to the human body from the effects of ionising radiation. For the purposes of the ESC, 'dose' is used as shorthand for 'effective dose' and the targets are humans. 'Annual dose' is calculated as the sum of effective doses received from external sources in a year, plus the sum of committed effective doses incurred from intakes (ingestion and inhalation) during the same year. Annual dose is expressed in units of Sv.

In some cases we calculate 'dose from the event', by which we mean the sum of effective doses from external sources during the event, plus the sum of committed effective doses from intakes arising from the event.

Dose rates to non-human biota are estimated as absorbed dose rate at a point in time or integrated over a period. Unlike in assessments of radiological impact to people, there is no concept of committed nor effective doses for biota. Dose rates to biota are calculated from the internal (biota tissue) and external (environmental media) activity concentrations using dose coefficients.

Passive safety

Passive safety is safety that is achieved without relying on active safety systems (i.e. systems whose functioning depends on an external input such as actuation, mechanical movement or supply of power) and human intervention.

Radiological risk

Radiological risk is the probability that an individual will suffer a serious radiation-induced health effect as a result of the presence of a radiation source, for example, a disposal facility. In this context, a serious radiation-induced health effect is a fatal cancer or a severe hereditary defect. The risk associated with a potential exposure situation corresponds to the product of the estimated effective dose that could be received, the estimated probability that this dose will be received and the estimated probability that detriment would occur as a consequence to the person exposed. Radiological risk should be consistent with a risk guidance level of 10^{-6} per year. This is the standard of environmental safety expected, although there is not an absolute requirement for this level to be met.

Representative person

The individual receiving a dose representative of the members of the population who are subject to higher exposures. In defining our representative persons, we adopt an approach that is cautiously realistic at early times, with increasing caution applied at later times to reflect increasing uncertainty in human behaviours.

A candidate representative person (CRP) is a hypothetical individual defined for assessments of retrospective dose and prospective dose over the near term (over the next ten years), whose habits and occupancy are based primarily on local habits survey data and site-specific local knowledge. Multiple CRPs may be identified to represent different plausible local behaviours, locations, or age groups. The CRP receiving the highest calculated dose is designated as the representative person for the assessment period.

For prospective assessments of dose from ten years hence to the end of the Period of Authorisation, potential representative person (PRPs) are defined using a more cautious approach that reflects increasing uncertainty in future human behaviour. PRPs are defined using a combination of local and generic habits data, with higher-rate assumptions applied to key exposure pathways and supplemented by local knowledge of possible future activities and occupancies. The PRP receiving the highest calculated dose is designated as the representative person for this assessment period.

For long-term assessments of times beyond the end of the Period of Authorisation, we define what we judge to be cautiously realistic exposure group based on a narrative description of potential future human behaviours. The representative member of that group is termed the PRP. The PRP receiving the highest calculated dose is designated as the representative person for the assessment period.

Risk guidance level

The level of radiological risk from a disposal facility that provides a numerical standard for assessing the environmental safety of the facility after the *Period of Authorisation*. For a disposal facility, the risk guidance level is a risk of detriment of 10^{-6} per year. The risk guidance level is applicable to a person representative of those at greatest risk. The risk guidance level limits the rate of accumulation of lifetime risk in increments of years, hence, we express radiological risk in terms of annual individual risk. Annual individual risk can only be assessed and not measured.

Sum of fractions

A method used to check that the combined radiological impact from multiple radionuclides remains within the relevant regulatory criterion by adding the fractions of each radionuclide's disposed activity (or activity concentration) relative to its corresponding radiological capacity (i.e. the activity or concentration that alone would meet the criterion). Compliance is demonstrated when the sum of these fractions is less than one for the applicable assessment case(s).

Terms related to LLWR site management

Period of active institutional control

The period of active institutional control is the time during which we will take active measures to control the disposal site following completion of closure engineering. During this time, access and land use will be controlled. The current position is that the LLWR site will remain under active institutional control for a period of around 100 years. Active leachate collection and management will continue until monitoring demonstrates that the leachate management system may be decommissioned. Monitoring to meet regulatory requirements and to provide reassurance that the facility is performing safely and as expected will continue during the period of active institutional control (see *Validation monitoring*).

Period of Authorisation

The period over which the site is being regulated under an environmental permit. The Period of Authorisation ends when the Environment Agency accepts surrender of the environmental permit. To apply for permit surrender, we will need to demonstrate that the *Site Reference State* has been reached. Sufficient *validation monitoring*, carried out during the *period of active institutional control*, will be required to make this demonstration. Once the permit has been surrendered, the site will enter *passive institutional control*.

Period of passive institutional control

During the *Period of Authorisation*, measures will be put in place to encourage sustainable and appropriate uses of the site in the longer term. Hence, longer-term controls may remain over the site in the form of covenants, planning controls and record keeping, in order to deter, or prevent, inappropriate site uses. These measures do not require the presence of a dedicated organisation or ongoing actions to be taken by the operator. We term such measures passive institutional control.

Site End State

The condition of the site (or part thereof) following all physical decommissioning and clean-up activities required to conclude the NDA's mission for the site. The Site End State of the LLWR site will make it suitable for its next planned use.

Site Reference State

The condition of a nuclear site when it is fully compliant with the requirements for release of the site from Radioactive Substances Regulation. This condition may be achieved after all planned work involving radioactive substances has been completed or after a subsequent period of control for the purpose of radiological protection.

Site release

The presumed release of the site from regulatory control, including surrender of the environmental permit. This marks the end of the *Period of Authorisation* and the *period of* *active institutional control*. For the Environment Agency to accept a surrender application, the *Site Reference State* needs to be demonstrated via appropriate *validation monitoring*.

Waste Management Plan

A documented plan, prepared by the operator of a nuclear site, that provides a comprehensive description of the current intent for dealing with all radioactive substances on or adjacent to the site and demonstrates how waste management has been optimised.

Terms related to LLWR engineering

Cut-off wall

A low-permeability vertical barrier around the LLWR trenches and vaults. The main functions of the cut-off wall are to minimise lateral infiltration of groundwater (including water shed by the cap) into the waste and to direct any leachate preferentially downwards. A cut-off wall along the northern and eastern sides of the trenches was constructed between 1988 and 1995; it is a bentonite-cement structure, designed to be keyed into underlying clay (cut-off wall depth is between 7.3 m and 9.4 m). The existing cut-off wall will be extended around the whole facility.

Container protection unit

The top-most container of stacks of new *strengthened containers* and *SWTC-compatible strong boxes* will be fitted with a concrete container protection unit designed to protect the vulnerable container lid from the loads that will be imposed during and after cap installation.

Drigg Grouting Facility

On arrival at the LLWR site, containers are currently stored within Vault 9. Once there is a sufficient quantity, the containers are grouted in campaigns; the containers are transferred to the Drigg Grouting Facility, where any residual voidage within the containers is filled with grout. This facility can handle up to four containers at one time. During grouting, the containers are tilted to help ensure that residual air is able to escape and are returned to the horizontal for the final filling.

Engineered Barrier System

The Engineered Barrier System is a combination of engineered (man-made) barriers to contaminant release. These may be:

- physical e.g. container or vault walls;
- hydraulic e.g. bentonite layer to prevent water flow;
- chemical e.g. substrate providing sorption capacity.

Engineered structures

The physical structures built to create, and close, the disposal volume.

Engineered structures include the *Engineered Barrier System*, but the Engineered Barrier System does not include all engineered structures.

Final engineered cap

A passive, multi-layered barrier to be built over the top of the vaults and trenches that will:

- restrict infiltration;
- isolate the waste;
- control release of landfill and radioactive gases;
- resist damage due to movement, settlement and erosion;
- address the visual impact of the site.

The final engineered cap will have a single dome profile and will provide a suitable long-term landform, physical cover and low permeability surface barrier. It will be installed in sections over the relevant areas of the trenches and vaults after waste emplacement is complete.

Future vaults

Planned future concrete-lined vault modules intended to provide additional disposal capacity and enable progressive closure of the LLWR. The future vaults will incorporate a single composite bentonite enhanced sand and geomembrane system beneath the concrete slab. Long-term passive drainage features include laterally extensive drains installed in side-walls at the 1 m level above the base slab. These will limit saturation above this level, and route overtopping waters to laterally extensive drainage blankets underlying the future vault bases, maximising access to the drainage capacity provided by the underlying geology.

Vault 9a: The first of the future vaults, to be installed on the coastal side of Vault 9. This will also provide an important component of the passive drainage arrangements for the existing vaults, as part of the strategy to route leachate generated in Vaults 8 and 9 in the longer term to the drainage blankets underlying the future vaults.

Vaults 10 and beyond: Planned additional future vault modules intended to provide additional disposal and passive drainage capacity, and to enable progressive closure of the LLWR.

Grout

Voidage in containers in the vaults are filled with a low-viscosity cementitious grout prior to disposal. The grouted containers provide an essentially monolithic *wasteform*. The grout fulfils several safety functions, which include:

- minimising voidage, and thus, differential settlement, which could lead to damage to the final engineered cap;
- promoting preferential chemical conditions and providing a substrate for sorption;
- promoting a more even distribution of container loads across the vault base.

The grout currently used to fill residual voidage in ISO containers comprises a 3:1 mix of Pulverised Fuel Ash and Ordinary Portland Cement with a super-plasticiser and an initial water/solids ratio of about 0.4. The mix was selected to ensure that the grout exhibited suitable viscosity, flow, setting, bleed and strength characteristics.

Higher stacking

Higher stacking refers to stacks of more than the equivalent of four half-height ISO containers.

Interim storage warehouses

Interim storage warehouses will be used to protect waste containers in the vaults from local environmental conditions prior to emplacement of the containers in their final disposal positions and construction of the final cap over them. The design of the warehouses will be similar to that of standard industrial warehouses. The warehouses will initially be constructed in the Vault 10 area to provide interim storage of containers prior to being moved to their final disposal positions in Vaults 9 and 9a, shortly before the implementation of relevant strips of the cap.

Interim trench cap

The interim trench cap covers the LLWR trenches and is designed to limit infiltration and reduce leachate production. It was placed over Trenches 1 to 6 in 1989 to 1990 and over Trench 7 in 1995. It comprises a soil mound with 1:25 gradient and is typically around 1 m thick (excluding profiling material), with an integral geomembrane. The interim cap will eventually be covered by the final engineered cap.

A new interim cap is being constructed over the southern end of the trenches. A geosynthetic clay liner and geotextile composite drainage layer will be installed to form a continuous low permeability layer, which will be laid on top of a new layer of profile fill that will have appropriate gradients to direct surface run-off towards the existing drainage.

Marine Holding Tanks

Leachate from the LLWR trenches and run-off from the open vaults is directed to the Marine Holding Tanks, where it is monitored prior to discharge under consent via the *Marine Pipeline* to the sea. The Marine Holding Tanks system currently has a consent to discharge 6,500 m^3 per day.

Marine Pipeline

The Marine Pipeline is used to discharge leachate from the LLWR to the sea via the *Marine Holding Tanks*. The Marine Pipeline discharges to sea through three diffusers about 1.2 km offshore.

Passive drainage

The features of design that promote the drainage of any infiltration (either from precipitation or by lateral percolation) without an active system or human intervention.

During the *Period of Authorisation*, it is intended that active leachate management will cease, the system will operate without further intervention and drainage will be passive. It is part of our *passive safety* measures.

For the vaults, infiltration will be directed down between the waste packages to the floor of the vault, from where it can be released over the low side-walls into the underlying geosphere by structures incorporated within the vault design (e.g. an under-vault drainage layer).

Profile fill

Material placed above the waste packages to define the profile of the final cap.

Requirements Management System

A structured framework that clearly defines all of the requirements on the disposal system and its components and shows how these are interlinked and affect each other. We have developed a Requirements Management System for the engineering design.

Shielded Module

Shielded modules are reinforced concrete structures that could be installed in vaults to provide the required degree of shielding for disposal of the higher dose rate portion of the inventory of *less-hazardous ILW* that is considered within the 2026 ESC. The shielded modules would only be constructed in Vault 10 onwards.

Strengthened container

A new stronger ISO container design for wastes not yet committed to a disposal container. Stronger ISO containers will be *higher stacked* and will be disposed to the southern parts of Vaults 9 and 9a and we expect will comprise the majority of disposals in Vaults 10, 11 and 12. Stacks of strengthened containers will be fitted with a *container protection unit*.

Strip capping

The requirement to close vaults and cover emplaced wastes in a timely fashion means that the repository will be capped progressively from the north (Vault 8) to south (Vaults 10 onwards) as vaults are filled (or potentially also for sections of vaults if the emplacement rate remains low). The final cap will be emplaced in east-west strips that cover each particular vault and the adjacent section of the trenches.

Surcharge

The intent of surcharge in the vaults is to express container deformation and associated accessible voidage prior to final engineered cap placement by applying a load. The area to be surcharged will be loaded by material up to an equivalent height of the final cap. The intent of surcharging of the trenches is to remove any remaining voidage in the tipped wastes. Surcharging will ensure that available settlement has been expressed before cap installation, which will provide confidence in the long-term performance of the cap by ensuring that there is a stable foundation for the low permeability layers of the cap. We have identified the need for surcharge of the trenches, and of LLW disposals already received at the LLWR or committed to the current container design. We have also identified options for future waste containers that will be strengthened to support the cap without the need for surcharge.

Trench

Trench disposals commenced at the LLWR in July 1959. The first trench (Trench 1) was filled by the end of 1963. In the years that followed, a further six trenches (Trenches 2 to 7) were constructed by excavation into the glacial sequence beneath the site. Each trench was founded predominantly within an underlying natural clay layer, which was intended to form a low hydraulic conductivity base. Bentonite was rotovated into the base of trenches in less clayey areas, at least in the case of the later trenches. The trenches were designed with drainage systems and the run-off water originally entered a ditch, which discharged into the *Drigg Stream*. An enhanced active effluent management system is now in operation: leachates are directed to the *Marine Holding Tanks* and then discharged to sea via the *Marine Pipeline*. During operation, the trenches were progressively filled by tipping loose wastes from the top of the previously filled area into the excavated trench. Trench disposal began to be phased out in 1988 when Vault 8 commenced operation. Disposals to Trench 7 were completed in 1995 and the trench was then capped. An interim cap now covers all of Trenches 1 to 7 to limit infiltration and leachate production.

Vault

The first disposal vault (*Vault 8*) at the LLWR commenced operations in May 1988. *Vault 9* is currently being filled. The bulk of wastes emplaced in the vaults are grouted into ISO containers and stacked in the vaults. Large items that will not fit into a container will be placed or grouted in place, uncontainerised, in the vaults. The *future vaults* will also include drainage materials, which are designed to delay the onset of saturated conditions in the vaults after closure and to promote drainage into underlying Quaternary strata. Active leachate management systems are in place in each vault.

Vault 8

An existing concrete-lined disposal vault housing predominantly grouted LLW disposals in *ISO containers*, in which natural clay and bentonite enhanced sand beneath the base slab work with the concrete slab and walls to contain leachate within the vault during the operational period and direct it to the operational drainage system. In the post-closure concept, Vault 8 drainage is connected to the long-term passive vault drainage system via measures backfitted at around the 1 m level and via drainage arrangements provided by future vaults including *Vault 9a*.

Vault 9

An existing concrete-lined disposal vault housing predominantly grouted LLW disposals in ISO containers, with a more complex base than Vault 8, incorporating a double set of composite layers (geomembrane and bentonite-enhanced sand) beneath the base slab, to contain leachate within the vault during the operational period and direct it to the operational drainage system. In the post-closure concept, Vault 9 drainage is connected to the long-term passive vault drainage system via measures backfitted at around the 1 m level and via drainage arrangements provided by future vaults.

Void Fill

The placement of materials into void spaces within a disposal facility. In *Vault 8*, void fill refers to the emplacement of granular, free-draining, inert, low-fines material within voids between waste container stacks where those voids are sufficiently wide to be effectively filled.

Terms related to environmental assessments

Assessment case

A specified combination of events, circumstances, conditions and their evolution, including specification of model boundary conditions and data, which represents a particular realisation of the disposal system, its evolutions and radionuclide or contaminant release, migration and exposures. A large number of cases may require consideration to adequately explore aspects of, or uncertainties within, a scenario. Where the meaning is clear, the abbreviated term, 'case', is used.

Biosphere

The accessible environment and relevant processes therein, including human practices for use of that environment, for example, farming, fishing and recreational uses, that do not disturb the facility.

Deterministic analysis

An analysis in which parameters are assigned single numerical values, leading to a single value for the result. Typically, deterministic analysis is used with either ‘realistic’ or ‘cautious’ values, based on expert judgment and knowledge of the phenomena being modelled. Deterministic analyses may also be used to understand the behaviour of the system. Many of the calculation cases that we present in the ESC are based on deterministic analysis.

Discrete Item

A distinct item of waste that, by its characteristics, is recognisable as unusual or not of natural origin and could be a focus of interest, out of curiosity or potential for recovery and recycling/re-use of materials, should the waste item be exposed after repository closure.

Geosphere

The strata and bedrock around the LLWR facility, and relevant processes therein. The geosphere provides a groundwater pathway for the migration of contaminants.

Human intrusion

Human actions taken after withdrawal of active institutional control that penetrate into or expose the disposed waste, or significantly damage the barriers that are intended to isolate and contain the waste. The regulatory guidance requires that we assess inadvertent human intrusion; that is, actions taken without full knowledge of the facility or potential hazards that the waste therein may present. Actions taken with full knowledge of the facility and associated hazard are taken to be reasoned actions that are the responsibility of those that undertake the action.

Model

The assembly of features, events, processes and interactions that are treated in a given case or set of assessment cases. We distinguish three types of model:

- conceptual model – the scientific understanding and descriptive presentation of the underlying system;
- mathematical model – a model of the system capturing the key processes, as represented by mathematical equations;
- computer model – the model as implemented in software.

Near field

The engineered features of the repository, all of the materials contained within the repository including the wastes and any associated soils and sediments within the envelope of the facility.

Pathway

Different routes or mechanisms by which radioactive waste or contamination may adversely affect humans or non-human biota. The pathways for the LLWR 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.

Probabilistic analysis

An analysis in which the uncertainties in key parameters are described using probability density functions. In such an analysis, multiple calculations are undertaken, with parameter values sampled from the probability density functions. The result of the analysis is a probabilistic distribution of risk or assessed dose. This allows the robustness of the disposal system with respect to parametric uncertainty to be analysed. The 2026 ESC considers a probabilistic calculation case for the groundwater pathway. Probability distribution functions of key flow and transport parameters were derived through expert data review and expert data elicitations.

Reference case

An assessment case used within a safety assessment that represents the system and against which alternative cases, sensitivity studies and different scenarios can be compared. The reference case may best represent our expectations for the evolution of the system.

Reference Inventory

The Reference Inventory consists of the known disposed inventories of the trenches and Vault 8, the waste currently accepted for disposal in Vault 9, and a forward vault inventory developed from the UKRWI. The Reference Inventory is intended to provide a best estimate on the volume of LLW and, if a decision is taken to accept ILW, an estimate of the volume of ILW that might be suitable for disposal at the LLWR within the site constraints. The actual site inventory will depend on assessments against the *Waste Acceptance Criteria* during the *Waste Acceptance Process*.

Safety argument

A safety argument provides a link between the safety evidence and a safety *claim*, showing that the safety evidence is sufficient to support the claim. For the 2026 ESC, they include descriptions of our management framework, system understanding, design and management choices, assessments and implementation of the ESC.

Safety function

A way in which a component of the disposal system may contribute towards environmental safety, e.g. the vaults are designed so that any water in the vaults is released downwards rather than to any near-surface receptor. The more historical features of the disposal facility also provide an important function and some are the consequence of actions taken to apply other controls. 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.

Scenario

The broad alternative future events, circumstances, conditions or their evolution that are characteristically different and provide a framework for analysis that is useful in providing an understanding of the environmental safety of the disposal system. We have defined three scenarios for the 2026 ESC, which represent high, low and a reference case for global greenhouse gas emissions. Future greenhouse gas emissions will affect the climate, the rate of sea-level rise and, for example, the rate and characteristics of coastal erosion of the LLWR.

Uncertainty

Lack of complete knowledge, which precludes an exact or complete description of past, present or future. We recognise three types of uncertainty:

- scenario uncertainty, which is uncertainty in the broad future evolution of the disposal facility and its environment;
- conceptual model uncertainty, where scientific understanding of the process being represented is uncertain;
- parameter uncertainty, where the quantitative value of a parameter is uncertain.

'What-if' case

An assessment case put forward to explore the consequences of a defined set of assumptions. 'What-if' cases are usually not grounded in scientific understanding and should not be interpreted as a realistic interpretation of the system.

Terms related to the near field

Disposal volume

A general term for the space within the repository in which waste will be emplaced. It can be used qualitatively, to describe the location of this volume (e.g. the vaults or trenches), and quantitatively, to describe the magnitude of the emplacement volume.

Engineering performance assessment

An assessment of the processes affecting barriers or components of the engineered system over time, and a quantification of any evolution in the properties of those barriers and components.

Multi-barrier system

A combination of man-made (engineered) and natural barriers that work together to provide isolation and containment of radioactive waste.

It is a regulatory requirement that the disposal concept involves several barriers to prevent or restrict contaminant release. One barrier is usually the geology or host rock (see *geosphere*) while others are engineered (see *Engineered Barrier System*). It is normally expected that different barriers provide safety in different ways, potentially over different timescales, and fail in different ways (avoiding common mode failure).

Overpack

A secondary waste container that provides additional benefits, e.g. reducing handling operations by consolidating small primary waste packages or providing mechanical strength for thin-walled primary containers. They are sometimes required for off-site transport.

Ullage

The unfilled space between the top of the *wasteform* and the inside of the container. A specific form of *voidage*.

Voidage

Unfilled volume in a waste package. Total Potential Voidage in a waste package is the sum of:

- inaccessible voidage – enclosed voids e.g. within pipework, not able to be filled by grout;
- compression voidage – settlement within a container as a result of compaction of waste materials (may be expressed only once the container is grouted);
- biodegradation voidage – voidage generated by degradation of, typically, cellulosic wastes.

Waste

The radioactive or radiologically contaminated materials within a disposal container.

Waste container

The container that encloses the *wasteform* for disposal. This may or may not be a transport container in its own right.

Wasteform

Term for the combination of waste material and grout within a container.

Waste mass

Term covering the combined waste packages and any surrounding void fill within the engineered structure.

Waste package

The combination of a waste container and its contents.

Terms related to the groundwater pathway

Compliance point

The point in the groundwater system at which concentrations of pollutants are assessed against defined target concentrations to determine whether remediation or control measures are required. The location and definition of compliance points depend on whether the contaminants are classified as *hazardous substances* or *non-hazardous pollutants*.

Drigg Stream

The LLWR site is located in a small surface water catchment area. The catchment is drained by the Drigg Stream, which rises immediately to the south of Vault 8, and the East-West Stream, which rises to the north-east of the site in farmland and is a tributary to the Drigg

Stream on the site. These streams are fed by the railway drain, which is located along the railway line adjacent to the site and parallel to the north-eastern edge of the trenches, and numerous drains on site. The Drigg Stream discharges into the tidal section of the River Irt. We carry out regular monitoring of stream flows and surface water quality.

East-West Stream

The East-West Stream rises to the north-east of the LLWR site in farmland and is a tributary to the Drigg Stream on the site.

Hazardous substance

A hazardous substance is any substance or group of substances that are toxic, persistent and liable to bioaccumulate, or that give rise to an equivalent level of concern. For the purposes of groundwater protection under the Environmental Permitting (England and Wales) Regulations 2016, all radioactive substances are treated as hazardous substances, where radioactive substances are defined as substances containing one or more radionuclides whose activity cannot be disregarded for the purposes of radiation protection. Radionuclides present in disposed solid waste that are within scope of the radioactive substances regulatory framework are therefore treated as hazardous substances.

Leachate

Potentially contaminated water that may have been in contact with wastes in the vaults and trenches.

Lithofacies unit

In developing the geological conceptual model, it is assumed that strata with similar material characteristics and lithological associations can be grouped together in ‘lithofacies units’. Each unit is associated with particular hydrogeological properties. Knowledge of the locations and geometry of the lithofacies units allows the development of a regional 3-D geological model. The improved level of confidence in the interpretation of the Late Quaternary site- and regional-scale glacigenic deposits has allowed a single, integrated lithofacies framework (with units A, B2, B3, B4, C and D) to be set out.

LLWR Assessment Standard

An assessment standard used to evaluate monitoring results for radiological and non-radiological contaminants in groundwater, river water and surface water.

Radiological LLWRAS are derived by applying Environment Agency guidance on protection of groundwater from radioactive contamination. They are set such that the dose to members of the public from the groundwater pathway during the Period of Authorisation is consistent with an annual dose of 20 µSv, and are used to demonstrate compliance with regulatory requirements for protection of groundwater, surface waters and associated receptors.

Non-radiological LLWRAS are defined using relevant chemical and environmental standards. For *hazardous substances*, the LLWRAS is taken as the most restrictive of Environmental Quality Standards, Drinking Water Directive standards, Minimum Reporting Values (where available), and limits of detection. For *non-hazardous pollutants*, LLWRAS are generally based on the most restrictive applicable Environmental Quality Standard or, where unavailable, Drinking Water Directive standards.

LLWRAS do not take account of background concentrations and exceedance does not, in itself, indicate pollution attributable to the site.

Monitoring Assessment Level

Monitoring Assessment Levels (MALs) are a threshold used to interpret measured concentrations of radiological and non-radiological contaminants in groundwater and surface water that takes account of background concentrations.

For non-radiological substances, MALs are defined as the higher of the applicable *LLWR Assessment Standard* and the concentration discernible above background, typically determined using the 95th percentile of the background or baseline dataset.

MALs are used within the monitoring programme to reduce false positives and to distinguish concentrations that are above those normally expected from natural variability. An exceedance of a MAL indicates a result higher than the typical background range but does not, on its own, demonstrate pollution from the site.

Non-hazardous pollutant

A non-hazardous pollutant is any pollutant other than a hazardous substance. Substances that are out of scope of the radioactive substances regulatory framework are classified as hazardous substances or non-hazardous pollutants for groundwater protection purposes on the basis of their chemotoxic properties rather than their radioactive properties.

Regional Groundwater

Regional Groundwater occurs within the deeper Quaternary deposits and the underlying bedrock. It is distinguished from the *Upper Groundwater* by the lack of a significant vertical gradient in the measured heads. The transition from Upper Groundwater to Regional Groundwater occurs roughly at 4 m above OD and is generally coincident with the interface between *lithofacies unit* B2, which has low vertical hydraulic conductivity, and lithofacies unit B3, which has a relatively high hydraulic conductivity.

Unsaturated

A volume of material is unsaturated when some or all of the pore space is filled with air. At the LLWR, unsaturated rock or soil occurs above the *Upper Groundwater* (the ‘surface and soil’ zone) and in some areas of site between *Regional Groundwater* and Upper Groundwater. The intention of the design at the LLWR is to keep the waste as unsaturated as possible.

Upper Groundwater

Upper Groundwater lies in the upper part of the Quaternary deposits between the *Regional Groundwater* and the surface and soil zone. It is distinguished from Regional Groundwater by a significant downwards-directed vertical gradient in the measured heads.

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