Nuclear Waste
Services

ENGINEERING DESIGN

2026 Environmental Safety Case for the LLWR

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Preface

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

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

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

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

The 2026 ESC consists of documents at two levels:

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

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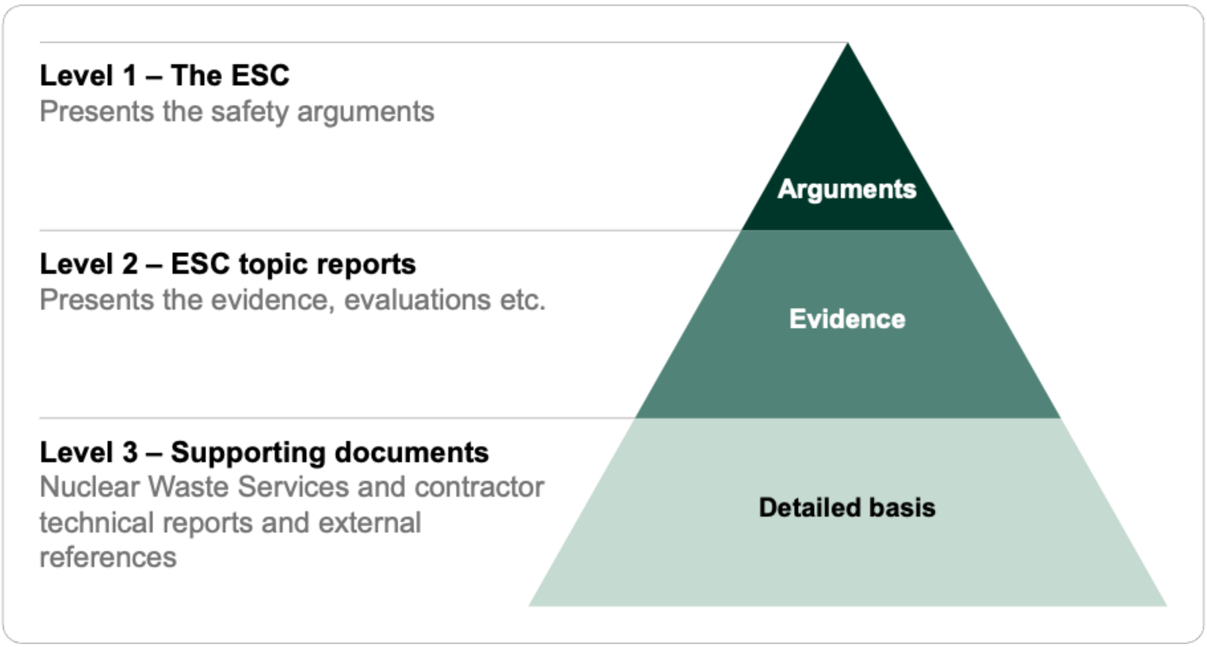
[1] In government policy, LLW is defined as radioactive waste having a radioactive content not exceeding four gigabecquerels per tonne (GBq t^{-1}) of alpha or 12 GBq t^{-1} of beta/gamma activity.

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



Level 1	
Main Report [1]	
Level 2	
Management and dialogue	
Management and Dialogue [2]	Describes our environmental management systems and interactions with regulators and stakeholders
System characterisation and understanding	
Site History and Description [3]	Provides a history and description of the site
Disposal Facility Inventory [4]	Describes the wastes already disposed and wastes that may be disposed at the facility

Engineering Design (this report)	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

Scope

This report describes the engineering features of the Low Level Waste Repository (LLWR), both as currently implemented and as set out in the reference plan for future development. It provides information on proposed facility design and development in sufficient detail to demonstrate their relevance to the Environmental Safety Case (ESC). The design descriptions are intended to underpin and support understanding of the ESC and its assessments, with a specific focus on the engineering of the repository during its development and closure.

The focus is on the description of the engineering design. The report also references wider processes and controls that ensure the design reflects objectives, providing confidence in the design, construction quality, and subsequent performance.

Design Overview

Existing Engineering

The existing system is shown in Figure E1. It includes seven trenches, used from the 1950s to the mid-1990s for the tumble-tipping of loose LLW. The trenches were excavated into clay layers, with Bentonite Enhanced Sand (BES) added to the bases where clay was found to be absent. The trenches are protected by an interim cap to reduce infiltration into the wastes, which is being upgraded at the time of writing. End-of-trench drains are used to collect and monitor leachate. A cement-bentonite cut-off wall works with the cap to reduce lateral releases from the trenches, in particular to the drain associated with the railway running alongside the eastern side of the trenches.

Vault 8 and Vault 9 are concrete-lined vaults housing, predominately, grouted LLW disposals in mild steel containers. Natural clay and BES are present under the Vault 8 base slab. The clay and BES work with the concrete slab to contain leachate within the vault during the operational period and to ensure it accesses the drainage system. The Vault 9 base is more complex and has a double set of composite (geomembrane and BES) layers underlying the vault base slab.

An operational leachate management system collects leachate from the trenches and from the vaults. Vault leachate is currently routed to the system via active pumping. A move to a gravity-based system for the vaults is planned, integrated with the construction of future vaults. Leachate is routed to the Marine Holding Tank before discharge to the marine environment via the marine pipeline. Gas release is monitored, with the main releases originating from the trenches being monitored via gas probes installed through the cap.

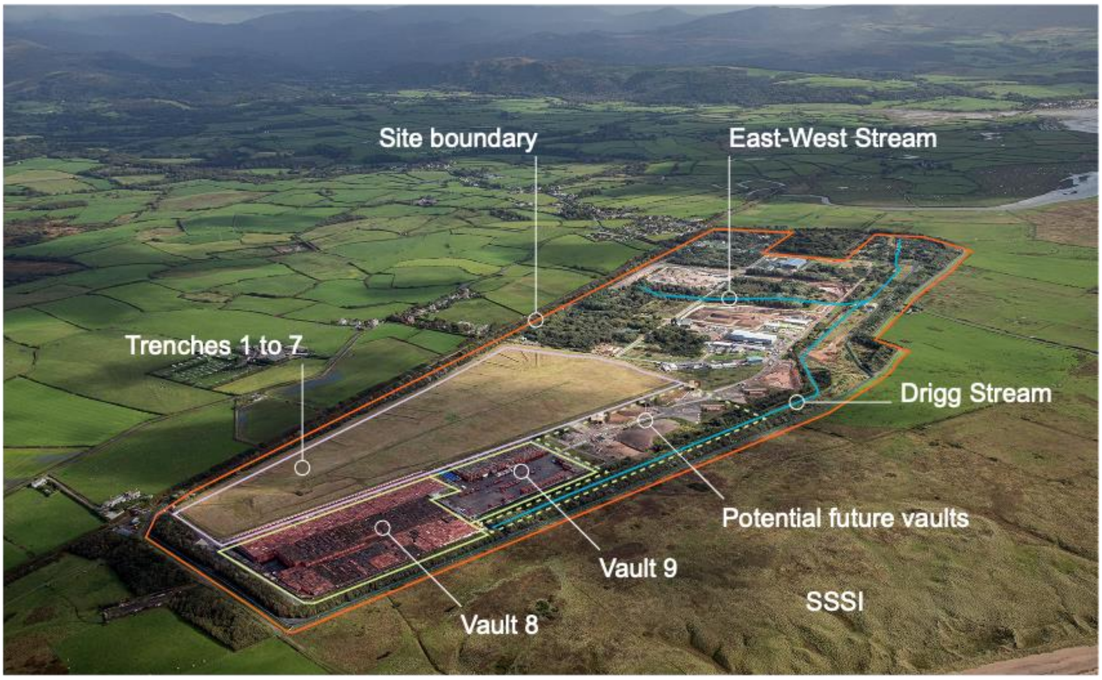


Figure E1: **Key features of the LLWR.**

Future Engineering

Future vault modules will be created to add additional disposal capacity and to achieve progressive closure of the facility. The combination of engineered features including the vaults and closure engineering is termed the ‘pre- and post-closure engineering’ and is a key focus of ongoing design and optimisation.

Disposal capacity will be created via the construction of new concrete-lined vaults, on a similar basis to the existing vaults, but employing a single composite BES and geomembrane system underneath the concrete slab.

The LLWR will be progressively closed via the installation of closure engineering measures. The closure concept is illustrated in Figure E2. The basis of the closure concept is to minimise water contact with wastes, and thus aqueous releases, for as long as practicable, by means of:

- the use of a thick, multi-layered final cap of appropriate profile, to minimise infiltration;
- minimising saturation within the vaults by placing drainage features in walls at the 1 m level above the base slabs – these will then direct overtopping waters to laterally extensive under-vault drainage blankets and thence to the underlying geology; and
- preferentially directing any leachate that does arise, for example as the cap begins to degrade, to deeper, rather than shallower systems. This is achieved by the use of a

cement-bentonite cut-off wall, integrated with the final cap, together with the under-vault drainage blankets.

The cut-off wall will also minimise the risk of lateral flows into the wastes and the drainage blankets.

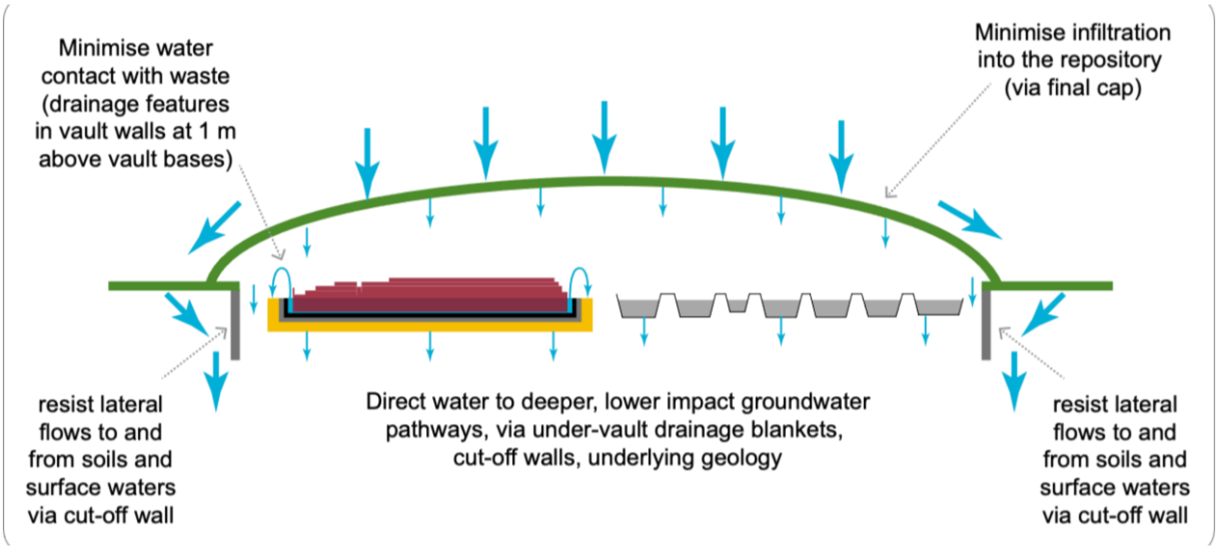


Figure E2: **Schematic illustration of the optimised closure concept. Focuses on water flows. Reflects evolution of the cap to a point where infiltration increases sufficient for the vaults to saturate to the 1 m level with resulting flows to passive drainage features and the underlying vault drainage blankets.**

In addition, the final cap will isolate the wastes from humans and the environment, reduce direct doses and, with the profile fill, reduce the likelihood of human intrusion into the wastes. It will also provide for management of bulk and trace gases.

The profile fill underlying the cap will provide the cap with the required geometry and protect the cap from strains that might otherwise occur due to differential settlements of the wastes. Pre-loading (‘surcharge’) of the trench wastes will also assist in ensuring cap resilience to settlements. The existing vault wastes will also be pre-loaded, together with disposals that are committed to the existing container type. This is required to drive out container deformations that might otherwise occur during cap placement.

Future Wastes and Containers

Future LLW (i.e. LLW which is not committed to be disposed in containers with the current design) will be disposed in strengthened containers. The design of these strengthened containers will resist loading from the overlying containers, the profile fill and engineered cap. Designs will consider interactions with the vault bases to ensure load distributions are consistent with base performance. Removable temporary warehouses will be used, separate from final disposal positions, to protect wastes prior to placement in final disposal positions ahead of relevant strips of the final cap. This is to ensure wastes are not exposed to precipitation and wind-blown chlorides after receipt at the LLWR for longer than a total of a 10-year target period.

If a decision is made to dispose ILW at the LLWR then ILW that can be managed as LLW (i.e. it largely meets the existing LLWR Waste Acceptance Criteria including dose rates) may be disposed in Vault 9 and the future vaults alongside LLW disposals. For ILW that needs additional measures (e.g. for dose management reasons), reinforced concrete shielded modules will be constructed. In both cases, we assume that ILW would be disposed of in mild steel containers which will fit inside Standard Waste Transport Containers if these are required for transport of the wastes to the LLWR. The Standard Waste Transport Containers would not be disposed.

Modular approach

The use of different approaches for the disposal of future wastes to the vaults will lead to a modular approach. The modular approach also offers flexibility to respond to changes in future waste arising projections with time by varying the rate and size of construction of modules. An illustration of the approach is provided in Figure E3.[2]

Basis and maturity of design

The trenches and vaults have been in operation for many years. In addition to existing engineering, the design for the remainder of the pre- and post-closure engineering is robust and provides a firm basis for the ESC.

The first strip of the final cap will be installed by 2037. This will include supporting profile fill, and the relevant sections of the cut-off wall. Designs have been approved for construction. Many years of design and optimisation have led to the current approved approach, informed by learning from other waste facilities and industries, as well as from the performance of existing engineered components. The existing designs for these components will also provide a basis for future strips, as the system is progressively closed.

Optimised designs have also been identified for other aspects of the system that are not due to be constructed in the next few years. Where beneficial, flexibility has been retained for relevant aspects of the design. For example, final choices on gas venting designs and decisions on gas vent closure will be made on the basis of monitoring of gas evolution from the first strip of the cap, and ongoing modelling and analysis work. All options will remain

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[2] In Figure E3, the numbers of containers for different waste categories are related to a specific set of inventory assumptions developed for the illustration during the optimisation work, and are not applicable to the current inventory cases. The distribution of different wastes and containers is also illustrative only. They are sensitive to inventory assumptions, in particular for those associated with shielded modules. Shielded modules are only shown in Vault 10 in the schematic, but in practice, disposals would be split across modules, to be implemented in the areas designated for Vault 10 and for future vaults. The ends of the shielded modules, and of the warehouses, would be closed whenever not in active operation.

consistent with the overall ESC concept and the related envelope of accepted engineering approaches set out in this document.

Construction Quality Management and Assurance

We recognise that confidence in engineering component performance when installed, and projections of future evolution into the future, require demonstration that engineering components have been built to specification. Construction quality is therefore prioritised through high standards of management and assurance, with independent oversight, real-time testing, and robust documentation. Lessons from current projects (for example, the interim cap upgrades) are being incorporated into the cap construction programme.

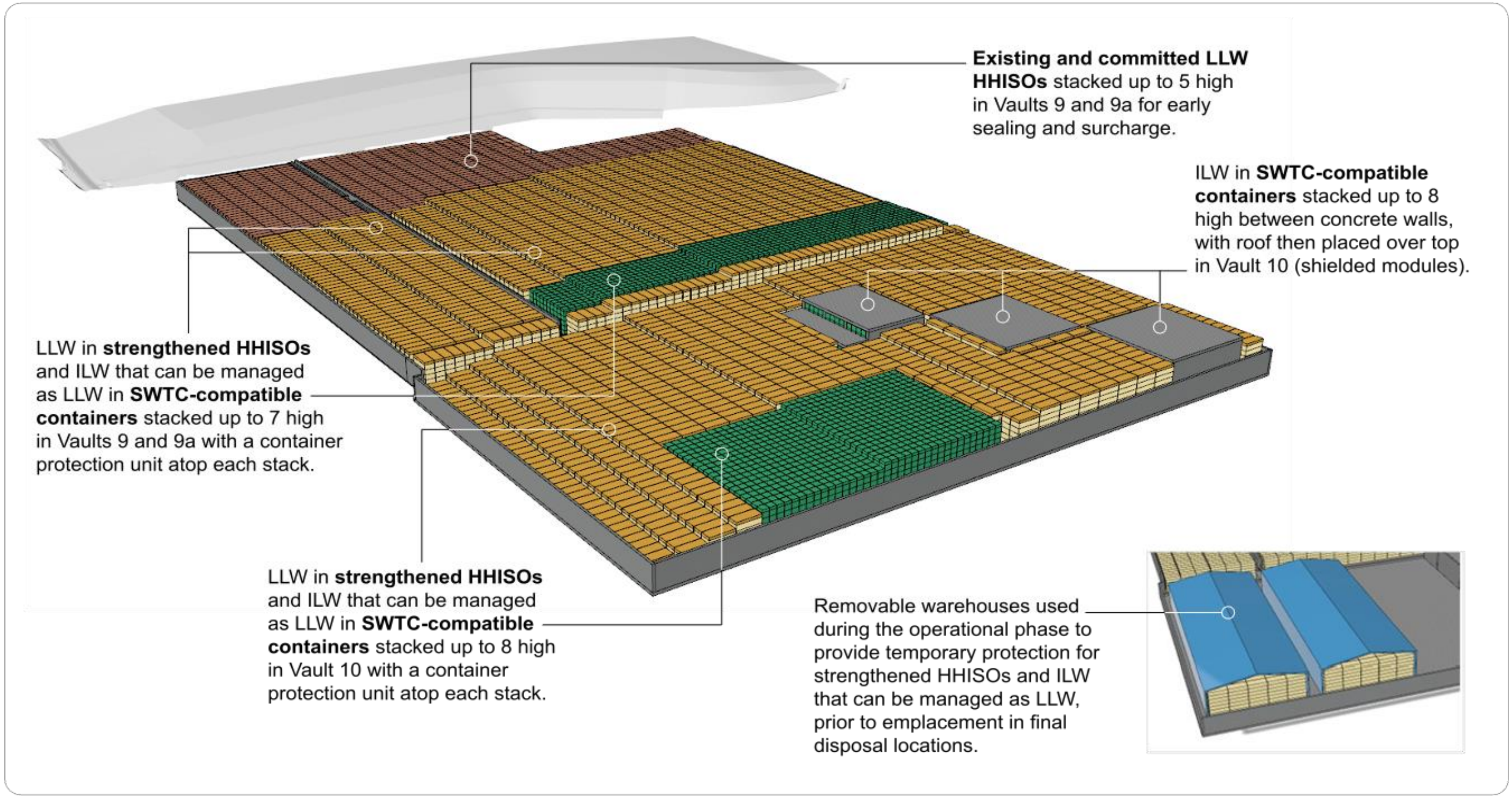

Figure E3: **Illustration of the optimised disposal model for the vaults.**

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1 Introduction

1.1 Objectives

This document presents the engineering features of the LLWR, both as they are currently and as envisioned in our reference plan for future development. It describes the assumed engineering design, construction and associated matters that form the basis of the 2026 Environmental Safety Case (ESC) [1].

This report addresses paragraph 6.2.27 in the regulatory Guidance on Requirements for Authorisation (the GRA) [19], which requires that *‘all work that supports the environmental safety case needs to follow good engineering practice’* and particularly addresses Requirement 12 of the regulatory guidance (the GRA [19]) as it relates to the engineering design.

Box 1.1: GRA Requirements most relevant to this report

Requirement R12: Use of site and facility design, construction, operation and closure

6.4.16: The developer/operator of a disposal facility for solid radioactive waste should make sure that the site is used and the facility is designed, constructed, operated and capable of closure so as to avoid unacceptable effects on the performance of the disposal system.

This report, together with the *Management and Dialogue* [2], *Optimisation and Site Development Plan* [9], and *Implementation* reports [17], seeks to ensure that information on proposals for facility design and development is presented in such a way that their *‘relevance to the safety case is clear’* (paragraph 6.2.34 of the GRA [19]). This, in turn, relates to the expectation that the ESC should *‘describe all aspects that may affect environmental safety’* (paragraph 7.2.6 of the GRA [19]), including the design of the facility and the techniques used to construct, operate and close it.

It is recognised that *‘all engineered measures will degrade with time’* (paragraph 6.2.31 of the GRA [19]). The engineering design incorporates measures to maximise the longevity of engineered component performance, including associated barriers, where relevant. We have considered in our *Engineering Performance Assessment* [12] the evolution of the barriers, including identification of parameters and consideration of associated uncertainties required for input to safety assessment calculations.

In the 2011 ESC [20], the engineering design assumed all disposals would be of low-level radioactive waste (LLW). In May 2024, the UK government and devolved administrations published a new policy framework for managing radioactive substances and nuclear decommissioning [21]. 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)[3] might be disposed 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[4]. On that basis, the current report also presents potential designs for any ILW that may be disposed.

1.2 Scope

This document presents and discusses the details of the reference engineering design for the LLWR, including existing and planned engineering.

The *'Main Report'* [1] describes the Environmental Safety Strategy (ESS) under which it was developed. The ESS leads to an optimised Site Development Plan (SDP) that sets out how we will manage the site (see references [9] and [17]). This report describes the engineering design of the disposal systems, current and future wasteforms, and the closure engineering and implementation plan, reflecting existing disposals and engineering as well as future developments as part of the SDP.

Relationships between key reports are summarised below (illustrated in Figure 1.1).

- The *'Optimisation and Site Development Plan'* report [9] sets out our approach to optimisation of the repository, including the resulting optimised disposal model and closure concept. The SDP then describes how the optimised approaches identified will be implemented. The report provides the primary justification of the design strategy.
- This '*Engineering Design'* report follows from that report and summarises the design of existing and future engineering components. It presents the main design assumptions underpinning the ESC.

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[3] Nuclear Waste Services use the term 'less-hazardous ILW', reflecting Government policy, to describe ILW that can be safely disposed at the LLWR, in-line with regulatory protection criteria – specifically risk and dose guidance levels.

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

- The '*Engineering Performance Assessment*' report [12] describes the expected evolution and performance of the key engineered components of the design including related parameters that support the assessments of repository performance reported elsewhere in the ESC (e.g. in references [13, 14, 16]).

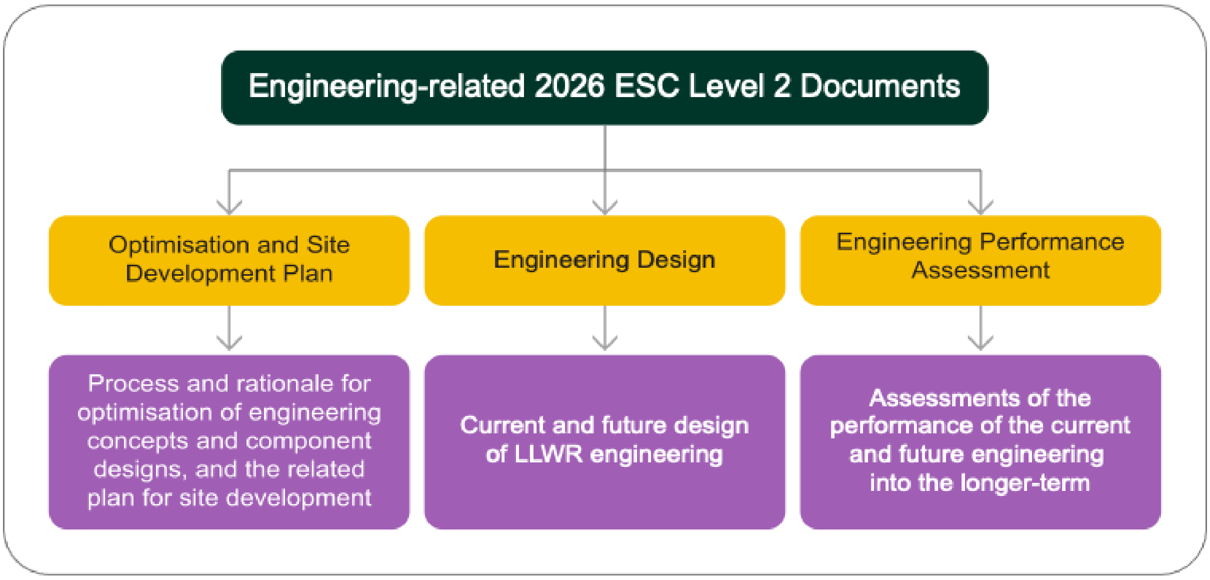

Figure 1.1: Relationship between key engineering-related 2026 ESC Level 2 documents. This diagram focusses on the presentation of information and is not indicative of the interactions of the processes involved in optimisation, design and performance assessment.

In addition:

- The '*Monitoring*' report [8] further describes the approach to monitoring of the implementation of the engineering and its evolution into the longer term. This document should also be read alongside the '*Implementation*' report [17] which describes the approach to ESC implementation more generally, complementing the engineering-specific discussions which are presented in this report.
- The '*Safety Functions*' report [11] describes how long-term safety is ensured by the engineering and other controls. This document describes the engineering functions that contribute to delivery of the safety functions described in that report.

The relationships between this report and other aspects of the ESC are described in more detail in Subsection 2.7.

A full list of Level 1 and Level 2 ESC reports is presented in the table in the Preface to this report.

1.3 Structure

The remainder of this report is structured as follows.

- Section 2 provides an overview of the engineering design and the concept it implements, together with a discussion on approaches to construction and associated quality management and assurance.
- Section 3 summarises aspects of the design associated with the closure engineering.
- Section 4 summarises the design of the trenches.
- Section 5 summarises the design of the vaults.
- Section 6 summarises design developments since the 2011 ESC.
- Section 7 provides an overview of leachate management arrangements.
- Section 8 describes details of arrangements for the practical implementation of the engineering and associated concept.

2 Engineering Design Overview

2.1 Background and Design Basis

2.1.1 Approach Overview

This report describes and discusses the reference engineering design. This recognises existing facilities, and the pre- and post-closure design concept derived through successive optimisation studies. The design takes into account our current best understanding of the role and performance of the existing and future engineering. It has been developed using the documented optimisation strategy [9] and is consistent with, and part of, our Environmental Safety Strategy. It is therefore based on the following [1].

- 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 wastwe hierarchy for site wastes;
- According people and the environment in the future the same level of environmental protection as now.
- A preference for passive over active controls during the Period of Authorisation (PoA) and reliance only on passive engineering controls after the PoA.
- 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.

We focus in this report on presenting the engineering design of the repository. Other elements of site engineering, required for site operation but not significant to the ESC, are not presented in detail.

The planned engineering relies on well-established technologies, many of them already used successfully at the LLWR. There are no significant novel technologies planned. Lessons learnt from existing engineering features, processes and practices are continually reviewed and incorporated in detailed design and construction as and where appropriate. We also take into account learning from experience (LfE).[5]

The design seeks to make best use of the LLWR as a national asset within the existing constraints, most notably the planning desire to make the profiles of the final cap as visually unobtrusive as possible, while ensuring minimum and maximum gradients are commensurate with meeting engineering safety objectives.

The design maintains flexibility to review and incorporate technological advances in future iterations of the detailed design. It also maintains flexibility for the development of additional vaults to the south.

During the operational period, the engineering design needs to safely support disposal and leachate management arrangements. Post-closure, the key functions of the engineering controls are:

- to protect against disturbance so far as is practicable (i.e. to isolate wastes from humans and the environment);
- to minimise water contact with waste for as long as is practicable;
- to control gases and leachate that may be produced within the facility;
- to direct leachate releases that may occur, as the cap begins to degrade, preferentially to deeper rather than shallower systems, to minimise their impact.

These functions will be delivered within a multi-barrier approach that ensures passive safety.

The *Optimisation and Site Development Plan* report [9] describes how these have been optimised.

2.1.2 Site Setting and History Summary

The site setting and history have been described fully in the '*Site History and Description'* report [3]. The following provides summary information useful to understand the current report in terms of the design model and design evolution.

2.1.2.1 Site History

Figure 2.1 gives a summary timeline diagram of the site history. The site was originally agricultural land. It was owned and developed as a Royal Ordnance Factory (ROF) for the manufacture of TNT in 1940. TNT manufacture ceased in 1945. The trenches area was subsequently developed for disposal of radioactive waste under a planning permission for an area termed ‘the consented area’ of 88 acres.

The design of the disposal areas has developed and evolved considerably over the lengthy history of the site. The evolution of the site design is discussed in Subsection 2.4.

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[5] Subsection 2.5 provides additional details from the perspective of engineering design. The *'Management and Dialogue*' report [2] describe the broader approach that applies across the ESC.

The first trench, Trench 1, was opened in 1959. It was dug into clay in a railway cutting made for the ROF and the waste was placed by tumble tipping. The practice of daily covering of the disposed materials was introduced, and vertical fire breaks installed at intervals, as shown on records drawings. Trenches 2 to 7 were developed in sequence. Trench 7 continued in operation until 1995. The current interim cap was placed over Trenches 1 to 6 in 1989 to 1990 and over Trench 7 in 1995. Further details of the trenches are discussed in Section 4.

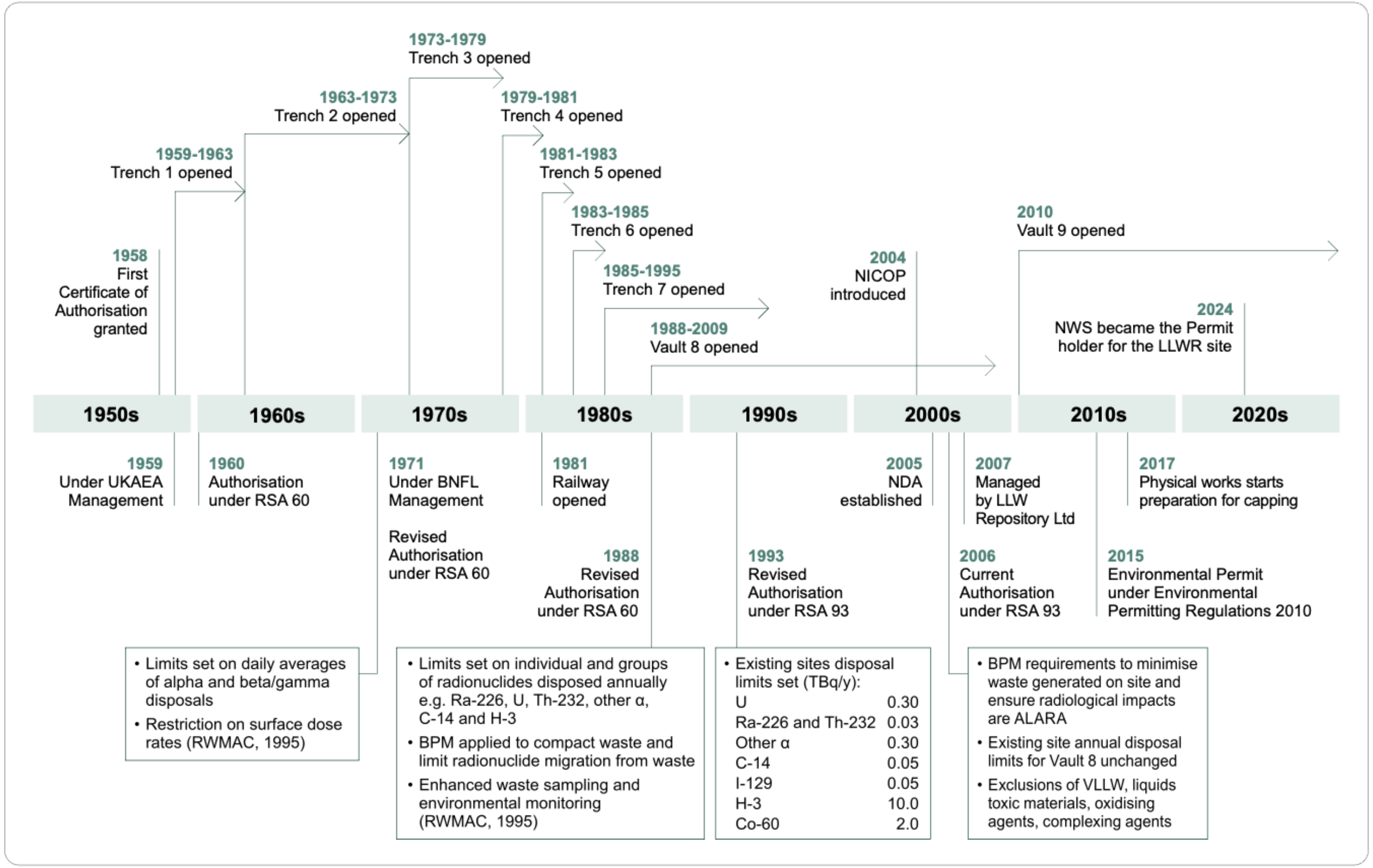

Figure 2.1: Timeline of radioactive waste management operations at the LLWR and related developments

Vault 8 began operation in 1988. Vault 9 was constructed in 2008 to 2010. Details of Vaults 8 and 9 are discussed in Section 5.

Works are currently being undertaken, under the relevant Planning Application and Environmental statement [22], to replace the interim cap for the southern trenches (the Southern Trenches Interim Membrane or STIM project). This work will be followed by construction of the first strip of the final cap, and the associated leading edge, vault and trench seal (see Subsection 5.5). This involves a programme of materials movement and stockpile management, landscaping, habitat management, associated contractors' compound construction and management, and construction of associated access roads, hard-standings and construction mitigation works.

The application includes an Environmental Impact Assessment and assessment of construction and other impacts and full details of landscaping, including a three-dimensional virtual model and views.

2.1.2.2 Topography and Landform

The LLWR is located on the coastal plain of West Cumbria near the village of Drigg. It is approximately 3 km north of the Ravenglass Estuary where the Rivers Irt, Mite and Esk converge. The Rivers Irt and Mite flow roughly south-west from the inland Lakeland fells. The River Esk is separated from the other rivers by the prominent ridge of Muncaster Fell.

The site occupies an area of approximately 100 ha, of which approximately 40 ha form the existing waste disposal area, see Figure 2.2. The topography surrounding the site varies from 25 m OD (above Ordnance Datum) to the north-east, and at Barn Scar Hill to the west of the site, to less than 5 m 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. Inland of the LLWR the topography rises, initially gradually but then steeply, to be dominated by the Lakeland fells.

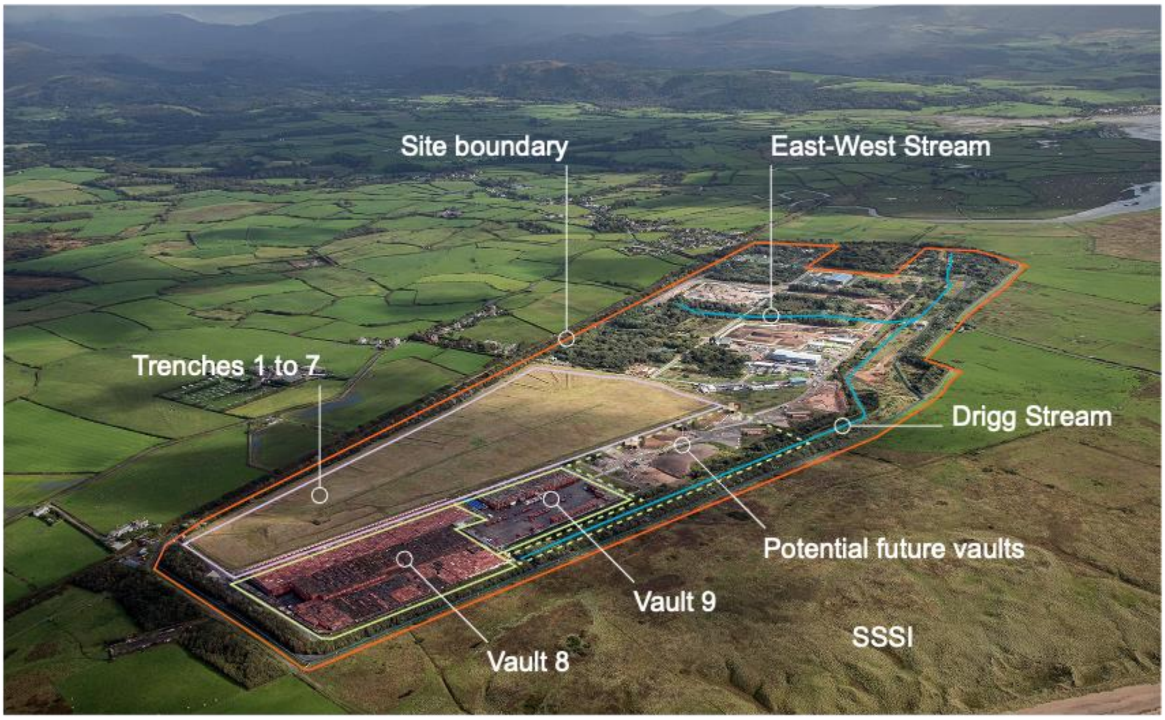

Figure 2.2: Key features of the LLWR

The broader coastline is characterised by a beach and inter-tidal zone with sand dunes and low cliffs inland. Most of the coastal plain consists of grassy fields with only a small amount of land dedicated to woodland and the growing of crops. Roads and minor tracks allow access to the coastal plain and to settlements that are located there.

Currently, the closest point of the LLWR vaults lies approximately 350 m inland from the present-day coastline and studies [7] have indicated that the site may be disrupted by coastal erosion or inundated as a result of sea-level rise in the future. The most likely outcome is considered to be disruption of the LLWR site by undercutting of the engineered structures within a timeframe of several hundreds to a few thousand years. The '*Site Evolution*' report [7] provides details of the expected evolution of the site and the underpinning studies that have been conducted.

A railway line runs along the entire length of the north-eastern boundary of the site. Along the western boundary the site borders a Site of Special Scientific Interest (SSSI). The site is principally surrounded by grazing land.

2.1.2.3 Habitats and Landscaping

Environmental aspects (including habitat management) for present works are addressed in reference [22]. Subsequent developments will build on and update this approach.

Landscaping compatible with the local landform and ecology will be undertaken. Care will be taken during construction not to disturb flora and fauna associated with the adjacent SSSI. If required, there will be appropriate relocation of species within the construction site. Suitable locations are available on site.

The course of the existing Drigg Stream will be diverted in connection with the planned cut-off wall and cap construction (see Section 3). This will provide an environmental improvement on the current ditch-like profile and help to preserve and improve flows in the stream.

2.1.2.4 Geology and Ground Conditions

The LLWR site and its surrounding area have been the subject of extensive surface and sub-surface investigation for decades (particularly since the 1990s). The sub-surface in the region consists of thick (up to 70m) Quaternary age (last 2.6 million years) deposits overlying bedrock. The Quaternary deposits are particularly important for the hydrogeology because the LLWR is a near-surface facility. A detailed review of the geology of the area and the development of the geological conceptual model is provided in the *Hydrogeology* report [6]. The conceptual model is summarised in Figure 2.3 and Figure 2.4.

The LLWR site has been subject to glacial processes during the Quaternary period, which have given rise to a complex sequence of sedimentary deposits. The deposits consist, for the most part, of interbedded deposits of clayey diamicton, sandy diamicton, glacio-fluvial sands and gravels and glacio-lacustrine silts and clays. At the LLWR, the Quaternary deposits overlie Triassic sandstone of the Ormskirk Formation (around 240 million years old). The complexity of the Quaternary sediments has been revealed through the extensive investigations that have been undertaken at the LLWR site.

Made ground occurs across the majority of the LLWR as a result of site development. The thickness of the made ground is variable across the site. Made ground typically comprises a mixture of sand and clay with some gravel, representing reworked natural materials originating from within the LLWR, with occasional construction waste such as brick and concrete fragments.

The various engineering components have been designed to suit the ground conditions.

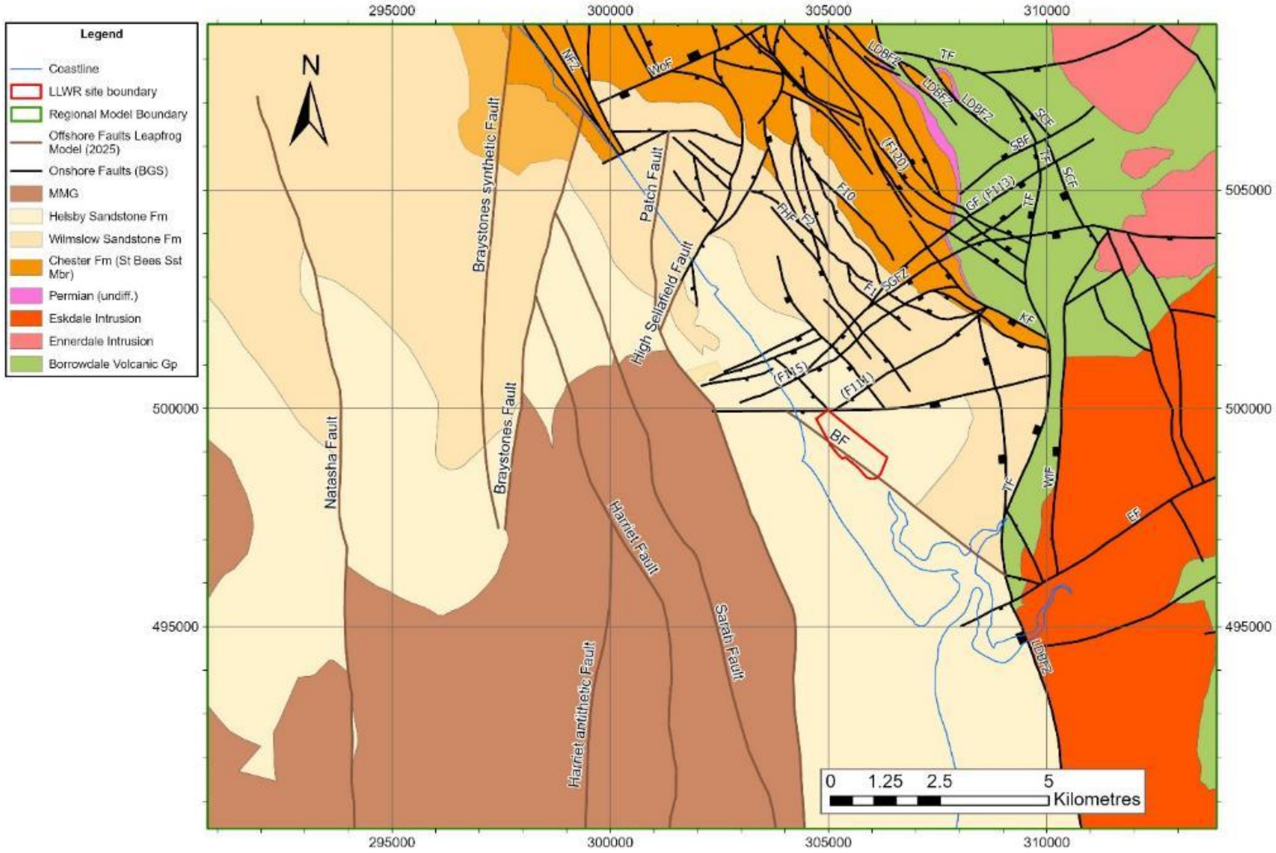

Figure 2.3: Bedrock Geological Map for west Cumbria and the adjacent offshore, for the area covered by the regional bedrock Leapfrog model. Map combines various data sources: Onshore geology and faults simplified from BGS bedrock geology 1:50,000 scale map data; offshore geology and faults from regional bedrock Leapfrog model. Contains British Geological Survey materials copyright NERC [2025] [23].

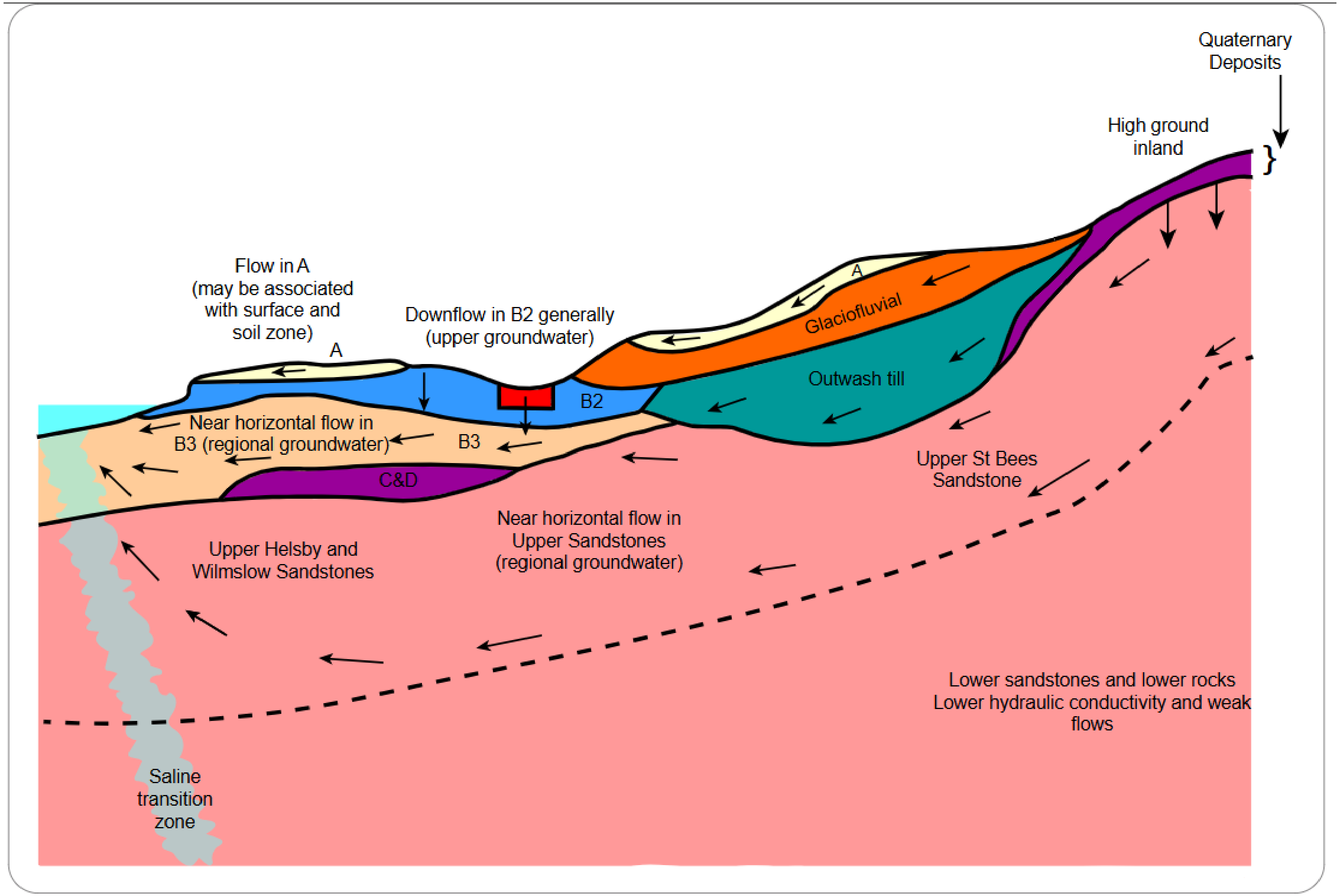

Figure 2.4: **Hydrogeological conceptual model**

2.1.2.5 Hydrogeology and Groundwater

A detailed summary of the hydrogeology of the LLWR site is provided in the '*Hydrogeology'* report [6].

In the vicinity of the LLWR, groundwater generally flows sub-horizontally from the Lakeland fells towards the coast. Groundwater flow occurs within the Quaternary drift deposits and in the underlying Ormskirk Sandstone.

The Regional Groundwater occurs within the deeper Quaternary deposits and the underlying bedrock. It is distinguished from the Upper Groundwater by differences in the characteristics of the groundwater head. In the Regional Groundwater, there is not a significant vertical head 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 Regional Groundwater is made up of hydrogeological unit B3 (and lower units in the Quaternary deposits) and bedrock.

Although the data suggest that it is possible to distinguish between the Upper Groundwater and the Regional Groundwater, they are not separate systems. Groundwater flows between them.

The flow is generally downwards in the Upper Groundwater, 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.

There are localised discharges from the groundwater to the streams near the LLWR: the Drigg Stream and the East-west Stream. A component of the Regional Groundwater passing under the south-eastern part of the site discharges to the River Irt and the Ravenglass Estuary.

Several engineered structures - including the northern section of the modified Drigg Stream, a railway line and associated drain (running in a cutting along the north-eastern site boundary), trench and vault engineering and a historical surface and sub surface drainage system - all affect groundwater flow to a greater or lesser extent.

2.1.2.6 Hydrology and Surface Waters

The hydrology of the site is also described in the '*Hydrogeology'* report [6]. The various surface water courses are shown on Figure 2.5 and are subject to extensive environmental monitoring, as discussed in the '*Monitoring'* report [8].

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, as shown in Figure 2.5. Across the LLWR site, these streams are fed by numerous drains, for example, the railway drain, which is located parallel to the north-eastern edge of the trenches. The Drigg Stream discharges into the tidal section of the River Irt. The River Irt is located about 500 m to the south-east of the south-eastern boundary of the LLWR site and flows to the south-east for about 2.5 km before entering the Ravenglass Estuary. This estuary includes the confluence of the Irt, Mite and Esk Rivers. The confluence with the Drigg stream is about 500 m downstream of the railway viaduct across the River Irt. Waters within the Ravenglass Estuary interact with the Irish Sea.

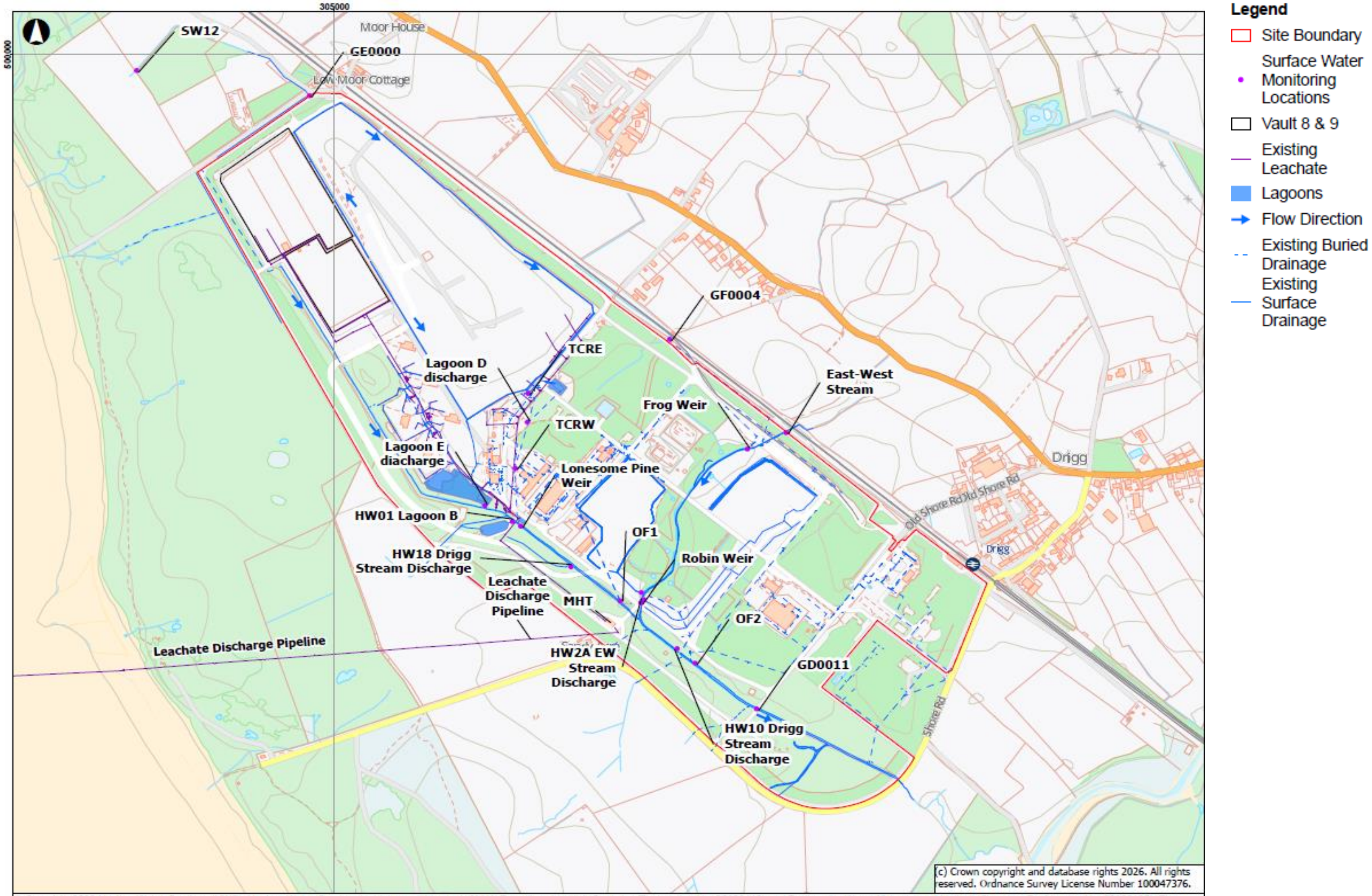

Figure 2.5: Streams, surface water drains and leachate drains near the LLWR

As part of the cap construction work a new sustainable urban drainage system for surface waters (SuDS), including multiple lagoons to aid sediment removal, has been installed across the site to support surface water management relating to this work [24]. The SuDS system has been designed to be able to accommodate a 1 in 200 year flood event, with contingency[6]. The proposed arrangement of the lagoons after the completion of the capping of Vault 8 is shown in Figure 2.6. It is anticipated that once the final cap is completed there will be only one lagoon collecting run-off from the cap as shown in Figure 2.7.

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[6] Defined as a 1 in 200 year event "+20%".

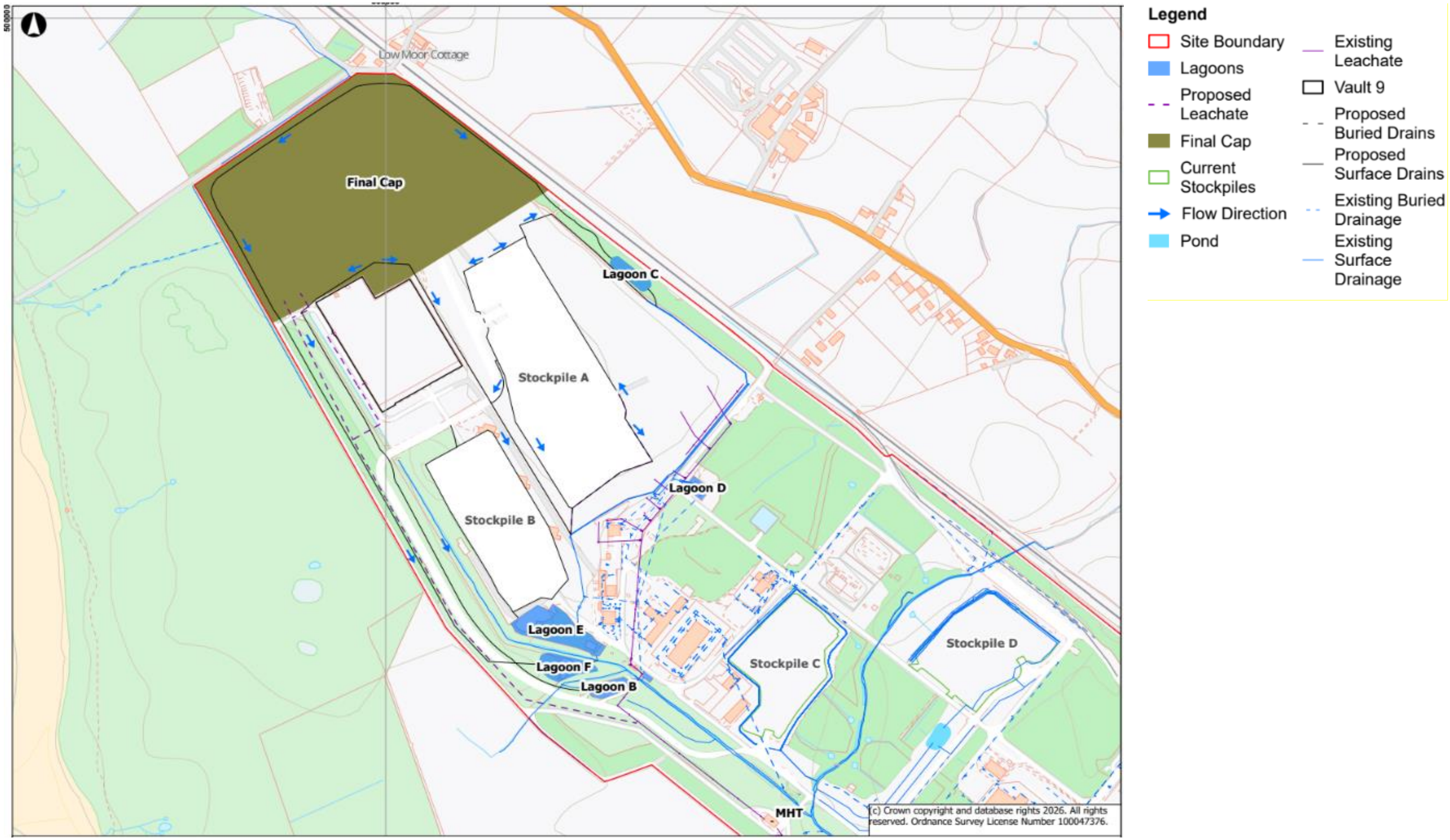

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Figure 2.6: **Drainage arrangements after Vault 8 and northern part of the trenches are capped**

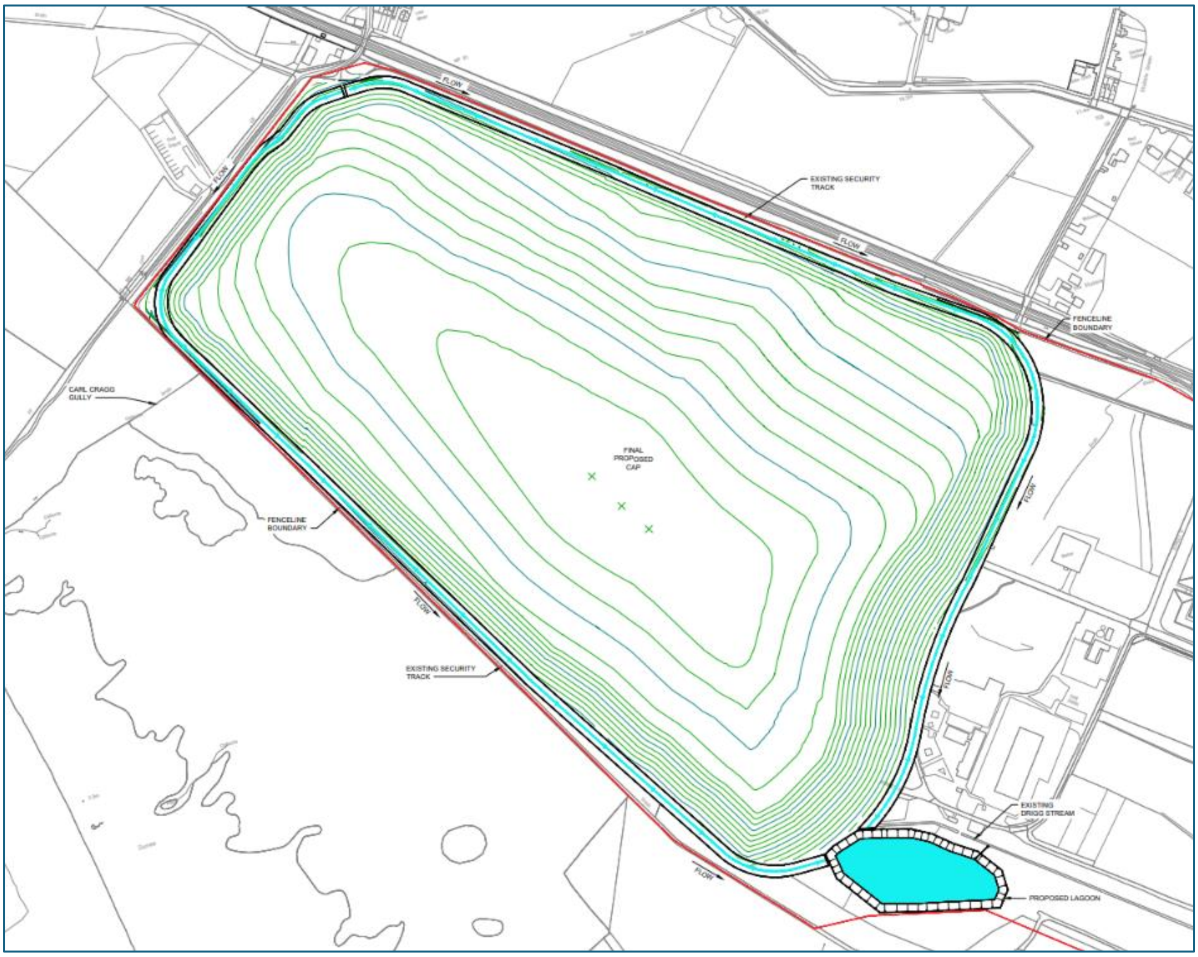

Figure 2.7: Final cap drainage

2.1.3 Disposal Approaches

Details of the disposal facilities, wastes, and containers, including photographs and diagrams, are provided in Sections 4 and 5. A brief summary follows.

Disposals to date have predominantly included:

- tumble-tipped disposals of loose LLW to the trenches;
- disposals of LLW grouted within half-height ISO freight containers (HHISOs) to the engineered vaults.

Vault 8 has also received other types of container including, for example, third- and full-height ISO containers. Vault 8 also includes several large items (e.g. used fuel flasks) and other items that have been directly grouted into the vault.

Infiltration into the trench wastes is reduced by the interim trench cap, which is currently being upgraded. The existing trench cut-off wall works with the interim cap to minimise releases of leachate to the north of the trenches.

The vault bases provide a running surface and safe platform for disposal of the wastes in container stacks. Together with the underlying clay and Bentonite-enhanced Sand (BES; Vault 8) and composite geomembrane and BES liners (Vault 9), waters are drained from the vault bases to the Marine Holding Tank (MHT). Active pumping is currently used for the vaults, with a planned future change to a gravity system. The end-of-trench drains also pass leachate to the same system.

The grout was primarily designed to fill voids within the containers and assists in minimising settlements; it does not necessarily provide a spanning encapsulated waste matrix, especially for older disposals. The grout provides further functions recognised in the ESC, including contributing to the conditioning of vault waters to high pH. This inhibits releases of key contaminants through solubility limitation and helps control microbial activity. The grout also provides a sorption substrate for key radionuclides.

Future disposals are anticipated to include:

- continued use of the current approach in the near term, where disposals are committed to the current container design ('existing and committed LLW');
- grouted LLW in strengthened HHISOs in coming years ('future LLW' disposals), referring to planned future updates to containers;
- the potential for ILW to be disposed to the vaults in appropriate containers. This will include ILW that can be managed as for LLW, and 'shielded modules' for wastes that require additional measures, e.g. shielding.

The adoption of modified disposal models for different waste categories naturally leads to a modular approach. Disposal within Vault 9 will be disaggregated according to disposal type. Future vaults will be constructed in modular fashion reflecting the disposal categories and arising profiles.

2.2 Optimisation Framework for the Engineering Design

The use of optimisation in engineering design is an essential part of good practice as well as a core component of regulatory guidance. Optimisation of the engineering needs to address:

- engineering used to manage legacy facilities designed to past standards;
- engineering planned for future disposal facilities;
- closure engineering; and
- other supporting aspects of engineering, e.g. leachate management.

For an integrated system such as the LLWR, these aspects need to be optimised as a system, recognising interactions. The resulting combination was therefore framed as 'pre- and post-closure engineering optimisation' in the 2011 ESC.

Optimisation of the design and operation of the LLWR has been ongoing for many years, although ahead of the 2011 ESC, the use of formal optimisation processes was limited and sporadic. A major review of the pre- and post-closure engineering design of the facility was implemented for the 2011 ESC, using a systematic optimisation process. The 2011 ESC process has since been used for successor studies, with appropriate modifications to reflect the context and aims of each study.

Similarly, the LLWR engineering concept identified for the 2011 ESC has been used to frame and inform the development and assessment of engineering options since then.

The optimisation process is described in detail in reference [9]. A key point is that ‘confidence’ in human or environmental safety performance is a primary consideration in optimisation, and in the ESC more broadly. From an engineering perspective, this confidence comes from:

- understanding the relevant benefits of engineering approaches in terms of confidence in providing the required functions if constructed;
- ensuring confidence that the construction approach will successfully, and demonstrably, achieve the provision of those functions over required timescales.

The designs for the future engineering reflect an optimised approach recognising these priorities.

Studies since the 2011 ESC were framed by the approach and concept defined for the 2011 ESC, as described in reference [9]. These studies have in turn provided a means for checking and reviewing the 2011 ESC outcomes. No changes to the overall pre- and post-closure engineering concept have been identified as a result, providing additional confidence that the concept is robust. However, several updates have been made to the optimisation of individual system components as a result of new information.[7]

2.3 Engineering and Concept Summary

This section presents a summary of the over-arching environmental safety concept, and how engineering components deliver the required functions. The overview provides context for the closure-relevant aspects descriptions of the individual engineering components. Further details of the component engineering designs are provided in Sections 3 to 7.

To aid this summary, the figures that follow (Figure 2.2 to Figure 2.10) provide an overview of the site arrangements associated with the final cap, the vaults and the trenches.

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[7] Examples include the status of the interim trench cap (Subsection 4.3.3); studies considering container performance under load (Subsection 4.4); and the updated approach to options for the final cap membrane made as a result of developments in the EPA (Subsection 3.2.4.8).

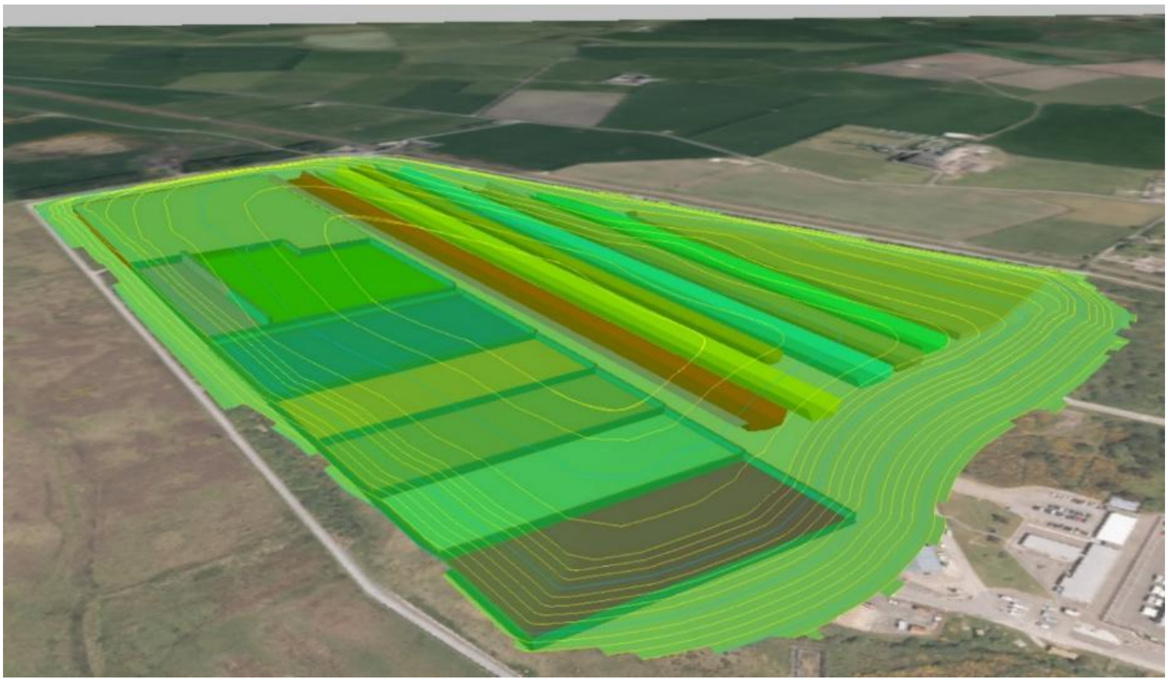

Figure 2.8: Overview of trench and vault locations with illustrative cap contour

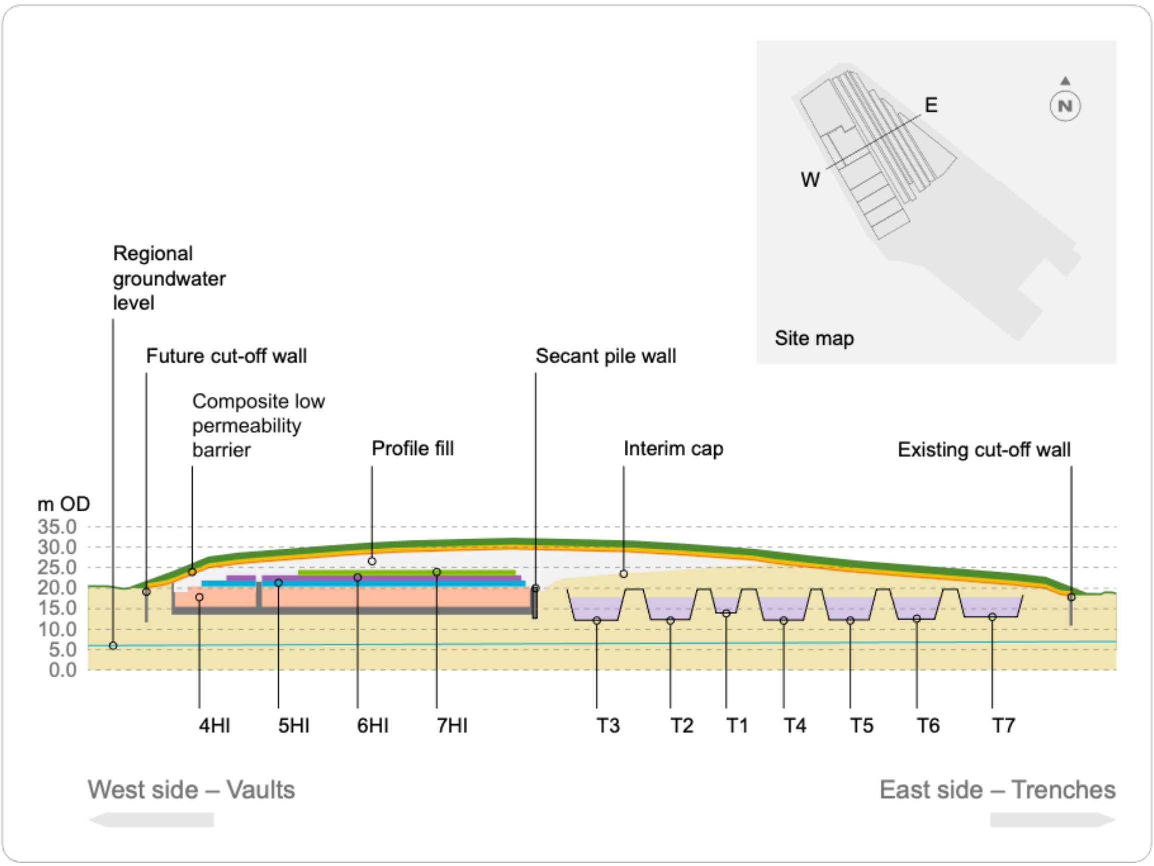

Figure 2.9: Typical cross section illustration

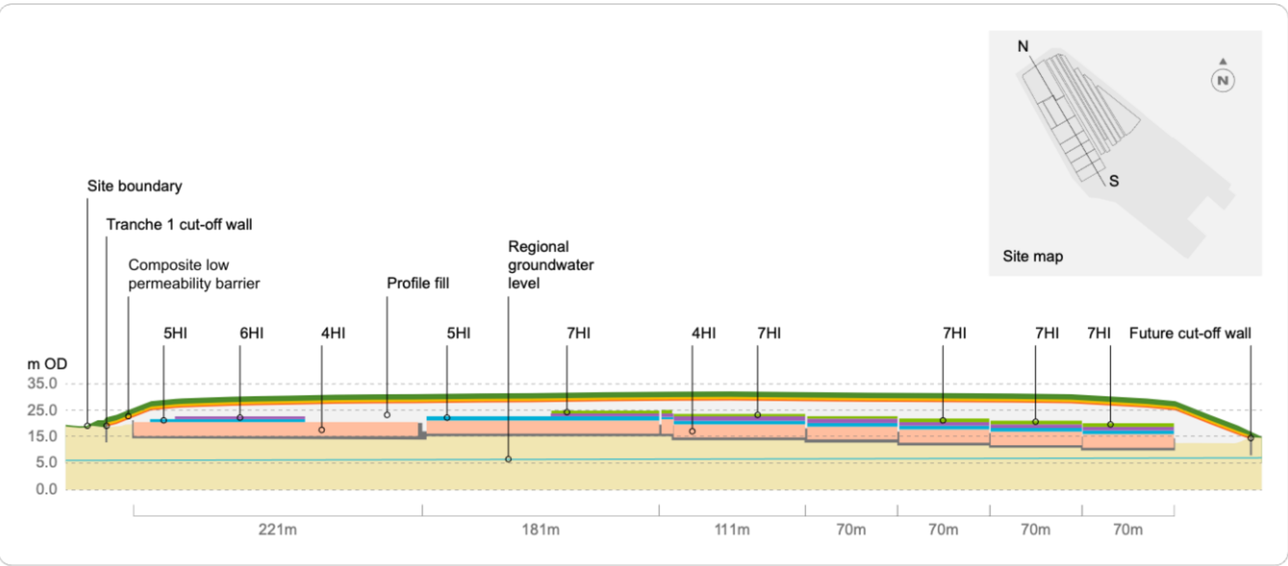

Figure 2.10: Long section (north-south) through the vaults

The overall closure concept for the LLWR reflects controls provided in response to potential impacts that could arise from different exposure pathways.

During the optimisation process for the 2011 ESC ([25, 26]), control of waters and reduction of releases to groundwater was recognised as a key priority. The concept therefore includes measures to minimise water contact with wastes, primarily by the use of a thick engineered cap to reduce infiltration into both trench and vault wastes. [25, 26]

For the vaults, the cap will be complemented by the use of long-term vault passive drainage systems, connected to the drainage capacity provided by the underlying geology via under-slab drainage blankets. These will be accessed by drainage arrangements at the 1 m level in the eastern and western walls for future vaults. They will prevent the vaults from saturating above this level once the cap begins to degrade. The drainage blankets will be laterally extensive, granular drainage layers that will maximise the interface of the drainage system with the drainage capacity provided by the underlying geology. Drainage for the existing vaults will be connected to the drainage capacity underlying future vaults by measures back-fitted to relevant vault walls at around the 1 m level.

The cut-off wall will be integrated with the final cap to promote the direction of leachate from both the trenches and vaults to deeper, rather than near-surface systems. The cut-off wall will also help mitigate the risk of lateral inflows into the drainage blankets underlying the vaults, as well as the trench and vault wastes (see Subsection 3.3).

The cap and profile fill will also isolate the wastes from the environment. This will reduce external irradiation, and the probability of, and impacts arising from, human intrusion. The cap also provides a means of managing bulk (and therefore trace) gases, including gas venting (see Subsection 3.2.6).

The profile fill will act to ensure the correct geometry of the cap, together with providing a stable formation for cap implementation. It will also reduce any general or differential settlements arising from waste and container degradation. Surcharge (that is, pre-loading to express any available settlements) will be utilised for the trenches, and relevant vault wastes.[8] Future disposals in the vault will transition to disposals in containers or engineered modules[9] that will withstand closure loads. These disposals may also include ILW appropriate for vault disposal.

The cap will be constructed incrementally with the first strip of the cap due to be installed over Vault 8 and the adjacent trenches by 2037. As part of the implementation of each strip, a 'seal' will extend from the open face of the cap to stabilise the cap and the profile fill below it, and to provide interim levels of protection of the wastes below similar to that afforded by the full cap. Each implementation of the seal will be temporary and will be removed as part of the installation of the next strip of the cap. The seal will be fully engineered and will include geomembranes, to reduce infiltration, gas venting and drainage measures.

The concept, reflecting the position after closure, is summarised in Figure 2.11.

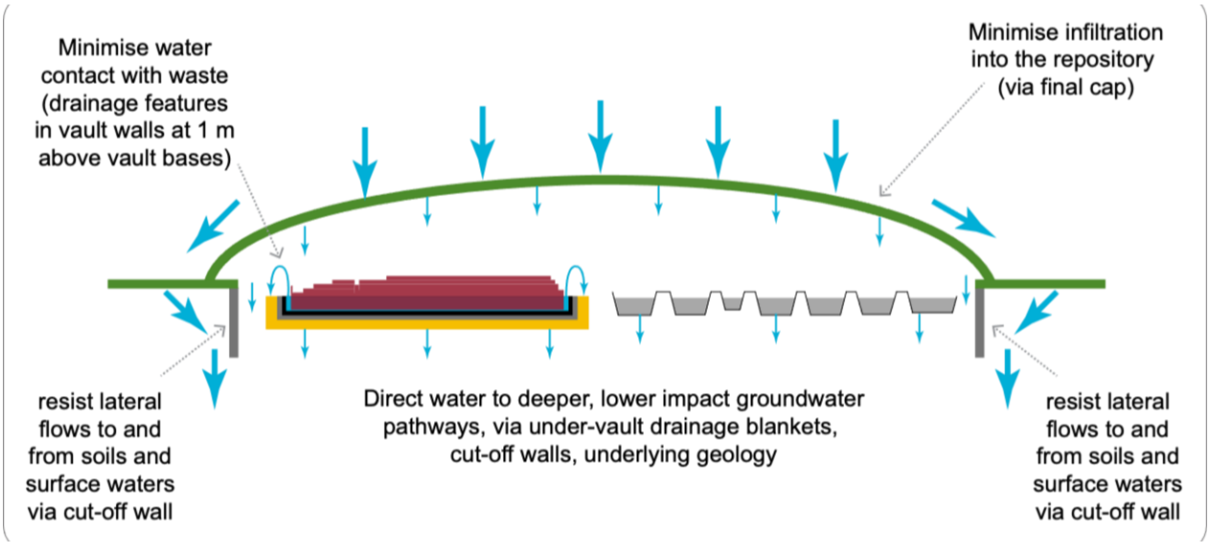

Figure 2.11: Schematic illustration of the optimised closure concept. The schematic focuses on water flows. It reflects evolution of the cap to a point where infiltration has increased sufficient for the vaults to saturate to the 1 m level, resulting in flows to passive drainage arrangements including the underlying vault drainage blankets.

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[8] See also Subsections 3.2, 4.4 and 5.2.2 for details.

[9] See Subsections 5.3 and 5.4.

2.4 Evolution and Maturity of Design

The design presented in this document represents an optimised and robust disposal model for the LLWR and is the basis for the 2026 ESC. Nevertheless, design and optimisation are continuous processes. Within this framework therefore, allowance needs to be made for future developments. This is necessary to:

- accommodate any future changes in waste arisings or other priorities;
- enable improvements to understanding, the reduction of uncertainties, and the outcomes of future assessments to be fed in to future iterations of design;
- ensure future developments in technologies can be fed in to the approach where beneficial; and to
- ensure continuing optimisation of the LLWR.

Fixing all design details now could unnecessarily foreclose options and prevent continuing optimisation.

The ESC assessments are therefore based on reference assumptions for engineering but they also consider uncertainties including potential variations to design and performance. The approach aims to bracket and prioritise the remaining uncertainties in design and inventory to provide a robust set of outcomes, which will in turn be used to inform future design developments and wider acceptance controls on disposals.

Aspects not yet approved for construction will therefore continue to be subject to design development and optimisation.

Within that wider picture, Table 2.1 provides a summary of the design status of the different components. The definitions are intentionally restricted to their use in this ESC to communicate the level of maturity of designs.[10] Further details are provided in the component-specific descriptions in Sections 3 to 7.

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[10] That is, they are not drawn from other sources of good practice or guidance, noting that definitions can vary and can have a different intent and usage to the approach used here.

Table 2.1: Maturity of design of the main existing and planned engineering components of the LLWR

Design maturity category	Components	Discussion
Already constructed	Trenches and the existing cut-off wall. Vaults 8 and 9 and associated engineering. Leachate management arrangements for the above.	This category comprises both legacy and operational facilities.
In construction	Updated interim (STIM) cap over the southern trenches.	In construction at the time of writing.
Approved for construction	Final cap and profile fill over Vault 8 and the northern trenches. Associated sections of the extended cut-off wall.	Includes the approach to surcharge and closure of Vault 8 and the adjacent tranches, and the approach to the final cap leading edge and vault seal.
Mature design	Future strips of the final cap including profile fill and surcharge, and the leading edge and vault seal. Future sections of the extended cut-off wall. Future vault walls and bases. Existing vault operational drainage arrangements.	Includes the approach to surcharge, and the leading edge and vault seal. Future strips of the cap and profile fill will follow the design for the first strip, with appropriate modifications e.g. to geometry, and the approach to gas venting. Future sections of the cut-off wall will follow the design for the existing extension section, with appropriate modifications, e.g. depth).

Design maturity category	Components	Discussion
		Future vault walls and bases will be optimised developments based on the existing vaults for which performance has been demonstrated. Future vault drainage arrangements will be comparatively simple approaches and have been part of the design since the 2011 ESC.
Robust concept design	Strengthened containers for LLW. Container for ILW disposal if taken forward. Shielded modules for relevant categories of ILW if taken forward. Future development of the leachate management system.	Strengthened containers for LLW will be a logical development of the current HHISO approach. Containers for ILW will be a logical development of the current container categories, modified to address specific requirements for ILW, including transport and shielded overpack requirements. Shielded modules for ILW will be based on comparatively simple approaches consistent with the existing vault design and materials. Future vaults and modules will be drained via a gravity-based leachate management that will be developed alongside the designs for the above waste categories.

2.5 Basis of Design and Good Engineering Practice

2.5.1 Standards and Processes

The design, construction, operations and future management of the facility are kept as simple as possible within the design constraints. This is to help minimise uncertainty in the long-term system performance.

The proposed engineering takes into account international good practice e.g. IAEA SSR-5, SSG-23 and SSG-29, and all appropriate Standards and Guidance, Eurocodes, British Standards and Codes of Practice.

A key current example is the programme for final capping of Vault 8 and the adjacent trenches, and the associated work to upgrade the interim cap over the trenches (See Subsections 3.2 and 4.3.3 respectively). The approach has been developed in alignment with a hierarchy of regulatory, technical, and good practice documents.

- The starting point is the requirements stated in the Requirements Management system (RMS) which are identified on the basis of the ESC and including the over-arching optimised concept [9]. These provide the key functional requirements for the repository's long-term safety and performance (see Subsection 2.7.1).
- Whilst the WAC [17] are focussed on disposals, the information and assessments associated with them have also been used to inform materials choices for the wider engineering.
- Within that framework, the technical design follows the relevant British Standards (BS) and Eurocodes, particularly BS EN 1997-1 (Eurocode 7) for geotechnical design and BS 3882:2015 for topsoil specification. These standards ensure that the engineering design meets recognised safety, durability, and environmental performance criteria.
- In addition, the design addresses Codes of Practice and sector-specific guidance, such as those developed by the Landfill Engineering Working Groups.

Throughout the design process, BAT assessments and Design Justification Documents (see, for example, references [27, 28, 29], and underpinning documents) have been used to justify material choices, construction methods, and resilience strategies. These documents flow directly into the construction quality management requirements and associated Construction Quality Assurance (CQA) plans, which govern the verification and inspection of materials and workmanship during construction.

2.5.2 Engineering Good Practice

The design and construction cycle ensures the use of engineering good practice (consistent with paragraph 6.2.27 of the GRA [19]) by:

- identification of skilled competent resource;

- application of relevant sections of the management system;
- review of good practice and LfE at other radiological and conventional waste disposal sites in the UK and overseas (see the specific discussion in Subsection 2.5.3);
- basing major decisions on a process of optimisation, using appropriate information and experts; and
- ensuring key principles from good practice resources and guidance are used to frame our design, such as the multi-barrier concept and the focus on passive safety measures.

2.5.3 Learning from Experience and Benchmarking

We engage with good practice and LfE associated with national and international facilities, for hazardous waste facilities as well as for radioactive waste disposal. Our engineering, ESC and Nuclear Safety Case (NSC) teams all actively maintain LfE processes and resources, and these are brought together for optimisation and design programmes to ensure their value is maximised.

Aspects of LfE activities that are particularly relevant to engineering design include, but are not limited to, the following examples.

- Reviews of developments for engineering and disposal technologies in the literature.
- Information exchange processes within the NDA estate, including liaison and co-working between LLWR and deep disposal NWS teams.
- Surveillance of non-NDA disposal facility practices, including sites that accept very low-level radioactive waste (VLLW), and hazardous waste facilities, e.g. via the IWMP and NWP programmes.
- Active participation in international programmes involving information exchange and site visits. We have applied learning from other relevant operators and international good practice throughout the ESC. We are members of the IAEA International Low Level Waste Disposal Network (DISPONET), and have visited peer facilities in Canada, France and Slovenia amongst others. We have a technical co-operation agreement with Andra/ENRESA/ONDRAF on engineered caps for near-surface facilities. Learning from other facilities relating to cap performance and longevity has been a particular focus, with learning drawn from Canadian, French, and Spanish peers, amongst others. We have contributed to an IAEA guidance document on closure engineering of near-surface disposal facilities, which is currently under publication [30].
- Integrating opportunities for international review and liaison into our ongoing projects, including interacting with international industry experts wherever appropriate. Recent examples include ensuring world-leading North American experts were consulted on detailed aspects of cap geomembrane design and performance, supplementing

detailed reviews of the literature by UK experts and also including discussion with UK and European suppliers (see references [12] and [9]).

We have processes in place to ensure effective knowledge capture, management and control. These processes for retention of critical knowledge and for the allocation of retention of documents. Examples of project-specific approaches include specific extensions to work scope in the EPA to ensure capture of details of the design history and developments from relevant experts.

2.5.4 Extreme or Disruptive Events

Consistent with meeting standards and requirements such as those described in Subsection 2.5.1, the design is secure against extreme events. This includes those that might occur during operations and the PoA, and for as long as practicable thereafter, noting the eventual degradation of the engineered features.[11] Specific examples are as follows.

- **Rainfall and surface water drainage.** The site is secure against flooding and extreme rainfall events, including surface erosion risks, both during operations and once the cap has been installed. The proposed capped system is designed to entrain a 1-in-200-year rainfall event plus 20% allowance for climate change. This is considered a proportionate approach ensuring the resilience of the surface water management system. The approach accepts the possibility, with climate change, that if the system reaches capacity, the site could be susceptible to surface water flooding during a more extreme event; it is unsustainable to design a system that could cope with every eventuality. However, this is a longer-term risk primarily associated with clean waters above and around a capped system. The drainage system and the capping geometry would together minimise run-off into any open vaults even for an extreme event. The location of the site means there will be little detriment caused by surface water flooding as there will be no developments nearby, and any flooding of adjacent land would be infrequent and unlikely to cause notable damage. The Surface Water Management Plan [24] provides further details.
- **Leachate management**. For the vaults, the operational leachate management system provides the required capacity including provision for a wide range of rainfall events. This includes the option, for extreme events of very low frequency, to divert flows to the Drigg Stream to avoid inundation of events. The closure design is also secure against extreme rainfall, drainage and flood events. Cap resilience to erosion is discussed further in Subsection 3.2.7. The final cap infiltration is not significantly affected by extreme rainfall events [12].[12]

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[11] Cap resilience specifically is discussed in Subsection 3.2.7, and in more detail in the '*Engineering Performance Assessment*' report. Moreover, engineering component degradation more generally is discussed in the EPA [12].

[12] Even in the future when cap drainage begins to clog and when the cap is saturated above the low permeability layers, there is confidence that the vegetation layer and cap gradients will persist and serve to attenuate and slow surface runoff in high-rainfall events, but still allow quick drainage from the cap which will help ensure any build of

- **Long-term evolution and coastal erosion**. Our understanding of the site evolution and coastal development are presented in the '*Site Evolution*' report [7]. Within the scope of the ESC, no passive engineering controls or related designs have been identified with the potential to offer significant protection over the long term against disruption of the LLWR by sea-level rise and coastal erosion (as discussed in the '*Optimisation and Site Development Plan*' report [9]). Therefore, from the perspective of the engineering, the primary aspect is that the timeframes for erosion bound the timeframes over which engineering performance is required (as described in the EPA [12]). This in turn informs the nature of design.
- **Seismic events**. The EPA [12] describes how seismic hazards have been considered for the operational and post-closure phases of repository development. In particular, seismic loading in the post-closure period is not considered a significant risk to cap performance, and the current design provides a robust solution.
- **Other disruptive events**. Iterations of assessment (as reported in the EPA [12]) describe how disruptive events such as those associated with meteorite impact and tsunamis are very unlikely to occur, or to present a key risk to the LLWR if they do occur. These aspects are therefore not major factors for the LLWR design.

2.6 Construction Quality Management

2.6.1 Overview

Demonstration of the successful construction of engineered features is essential to subsequent claims of closure system performance. This includes ensuring the constructed components meet requirements identified on the basis of the ESC[13], and therefore will perform and evolve consistent with expectations (for example, as articulated in the EPA [12]). This subsection therefore provides an overview of the construction quality management and assurance arrangements that will be put in place. The focus of the discussion is the final cap, given it is the most complex component, and the first strip is already approved for construction. The principles and approaches described will also apply, appropriately modified, to subsequent components.[14]

2.6.2 Final Cap Construction

2.6.2.1 Overview of CQM Arrangements

The construction of the first tranche of the final cap is the start of a nationally significant infrastructure project, with a design life extending well beyond conventional civil engineering assets. As such, our processes reflect the importance of construction management across the full lifecycle of final cap implementation.

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head or of erosive pressures on the cap is minimised. Average daily infiltration is therefore expected to remain very similar when compared to more normal precipitation conditions.

[13] See also Subsection 2.7.

[14] summarises the main existing and planned engineering works at the LLWR.

Construction quality management is reflected in all stages of design development and construction, including:

- design and constructability review;
- procurement and contracting strategy;
- construction execution and supervision;
- CQA and regulatory compliance; and
- handover and operational integration.

For example, the procurement and contracting strategy step includes appropriate contractual requirements and incentivisation for behaviours aligned with construction quality.

More specifically, constructability, as a key aspect of confidence in quality, has been a key consideration in final cap design throughout its development over several decades. For example, Subsection 3.2 describes how man-made layers have been added to the design to aid construction, and how the design has been simplified by reducing the number of layers through combining the bio-intrusion and drainage layers. Wider considerations needed to support and ensure construction quality and related controls include the following examples.

- Material availability and logistics (e.g. rail and road transport, quarry sourcing).
- Sequencing and access planning.
- The interface with ongoing waste disposal operations at the LLWR site.
- Interactions with other programmes, in particular the STIM cap upgrade for the trenches.
- Environmental requirements such as water management, waste minimisation in construction, and consideration of habitats.

These are all part of the integrated programme for construction, and are needed to ensure an overall approach that ensures the efficient and optimised construction of the cap. It is important, for example, that pinch-points, conflicts and risks are identified and resolved that could otherwise hold up construction.

For example, continuity of supply of materials to the workface consistent with project execution phasing and requirements is essential if work is to progress to plan and ensure quality. This means that logistics, sequencing, contractor access and other related activities need to be carefully aligned. This includes ensuring interactions with disposal processes and other construction work on the site do not impede progress or prevent the desired working methodologies from being fully implemented (and vice-versa). In addition, access to the site needs to be secured not just for the contractor undertaking construction but for supervisors and independent CQA staff verifying activities. Similarly, environmental requirements need to be carefully managed and integrated to ensure the required approaches are implemented appropriately and to programme.

These examples are provided to indicate ways in which all of these aspects are directly or indirectly relevant to confidence in the overall construction programme.

Under UK legislation all construction is subject to the requirements of the Construction Design and Management (CDM) Regulations. The focus of the CDM regulations is on conventional safety; however execution of the key roles identified is also relevant to ensuring construction quality and verification.

For the first tranche of cap construction, the proposed responsibilities under CDM are summarised in Table 2.[15] These are important as construction management requirements need to be understood and flowed down through the organisation and contractual hierarchy, and responsibilities understood; confidence in construction is intrinsically linked to behaviours, reinforced by accountabilities.

Table 2.2: CDM Roles and responsibilities for the Capping Programme

Role	Organisation / Responsibility
Client	NWS (retains overall responsibility for project delivery, construction quality and regulatory compliance)
Designer	Appointed design consultants
Principal Designer	NWS or delegated party (responsible for design risk management under CDM)
Principal Contractor	Appointed contractor (responsible for site safety, coordination, and delivery including construction quality)
Subcontractors	Managed by Principal Contractor, subject to NWS approval

In addition to these roles which are formally required by CDM regulations, a further role for construction quality will be the CQA Consultant[16]. The CQA Consultant is independent and responsible for quality assurance and reporting. This is a key role and the consultant is able to stop work, for example, if concerns are identified.

In practice, the governance arrangements for CQM and CQA implementation and accountability are as follows.

- Designer CQA Plan and Technical Specification. The starting point is the *Designer's CQA Plan* and supporting design specifications (e.g. reference [31] for STIM). These

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[15] These reflect current assumptions. This approach may be updated in discussion with the principal contractor when appointed.

[16] Often also termed the CQA engineer.

documents define the quality objectives, required independence, hold-points, and test frequencies expected for all closure engineering materials and components.

- Contractor development into Inspection and Test Plans (ITPs) and Inspection and Check Lists (ICLs). The Principal Contractor translates these design-level requirements into detailed ITPs and ICLs that define the specific inspection points, verification methods, and acceptance criteria for each construction activity.
    - The ITPs and ICLs are aligned directly with the specification clauses and drawings to ensure that every quality control activity can be traced back to design intent.
    - These working documents are progressively refined through workshops and pre-start reviews before implementation on site.
- CQA review and approval. The CQA Consultant independently reviews and approves all ITPs and ICLs prior to works commencing. This ensures that CQA oversight is embedded within the method of working, specifying where CQA must be present (full-time or part-time), which inspections are hold points, and what evidence is required for sign-off.
- Implementation and daily coordination. During construction, the ITPs and ICLs are live tools used for day-to-day quality control and record-keeping. CQA Consultant attendance is scheduled and confirmed through daily tri-party briefings (NWS, Contractor, CQA Consultant), where the next day’s planned activities and inspection points are reviewed. The CQA Consultant will maintain independent daily records and issue inspection sheets and photographic evidence against each checklist.
- Feedback, stop-works and continuous improvement. Any non-conformances or deviations are captured immediately through non-conformance reports (NCRs) or stop-work processes, ensuring traceability and corrective action. Lessons learned (e.g. from reference [32]) are rolled back into the ITP and ICL suite and CQA procedures.

2.6.2.2 Examples of Actions in Support of Construction Management

For the final cap, a wide range of practical actions will be required to ensure construction quality. These are set out in the relevant design and CQA documentation, and implemented through the arrangements and responsibilities outlined above. Examples are set out below, noting that these are just a subset of requirements.[17]

- Prior to commencement of the final cap placement, the contractor will undertake tests to finalise the mix design for the BES using the proposed selected materials. This will

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[17] Procedures may evolve through discussions with designers, contractors and CQA consultants and so details of the final approaches may differ.

include tests to confirm the mix proportions, placement moisture content and the achieved laboratory hydraulic conductivities.

- During this period the contractor will also finalise equipment selection and develop the first drafts of method statements. These will identify equipment requirements and document the practical approaches to implementation of the design that the contractor will adopt. These method statements will be maintained and updated throughout construction.
- Construction of a trial section of the cap is proposed [33]. This is a routine approach adopted on many capping sites to help finalise designs and methodologies, including for example, equipment selection for BES mixing and cap placement. The trial will be constructed over a small area with the purpose of confirming the contractor's method statements, mix design, equipment selection and capability. It is also intended to demonstrate that critical components of the cap can be constructed as intended. Examples of anticipated outcomes are confirmation the proposed pre-compaction layer thicknesses for the BES mix design, the number of compaction passes required and the adequacy of the compaction process. The construction trial will also be used to confirm the placement of separation membranes, drainage layers, and other aspects of the design.
- The construction trial will also provide an opportunity to review and refine the CQA engineer's method statements for CQA sampling and testing and laboratory testing times.
- Similar trial testing will be undertaken prior to the installation of the geomembrane, to confirm aspects such as the sub-contractor's method statements, the sub-contractor's ability to effectively install the geomembrane, and to complete testing and CQA checks in accordance with the specification.

Construction Quality Assurance (CQA)

For the first tranche of cap construction, the independent CQA Consultant will be responsible for checking construction compliance. This role will be in addition to the supervision roles of NWS, the design consultants and the Principal Contractor, and ensures provision of independent certification of construction quality.

CQA, and in particular post-installation checks, provide evidence that construction has been carried out in accordance with the design and specifications but cannot compensate for poor design or inadequate site management, which is why we follow the lifecycle strategy outlined above.

Key elements of the CQA process include:

- pre-delivery checks for critical components like membranes;
- post-delivery checking and independent testing;
- independent oversight of material placement, compaction, and layer thickness;

- real-time testing of installed components via on-site laboratories;
- sampling testing and certification of materials against specification;
- agreement of layer thicknesses and placement during construction; and
- documentation and reporting to the Environment Agency and other regulators.

The Designer has developed a specification for the first tranche of the final cap [33] and a CQA plan to accompany the specification [34]. The specification, amongst other aspects, outlines the design philosophy and defines the material requirements, characteristics and tolerances expected by the design and the capping layer sequence and thicknesses. The CQA plan summarises the required inspection regime, testing frequency and testing methodologies for each component of the final cap and the reporting requirements.[18]

Learning from the Current Interim Cap Construction

The process for construction of the interim cap upgrade has served as a learning process for NWS, contractors, and stakeholders.[19] Key lessons include the:

- importance of early contractor involvement in design development;
- value of material testing and on-site laboratories;
- need for clearer role definitions and better integration between design and CQA;
- benefits of direct engagement with material suppliers and logistics providers;
- confirmation of the benefits of rail transport to reduce environmental impact and improve efficiency.

Our approach has developed to reinforce further the importance of broader aspects including:

- expectations for clear translation of design QA requirements into field-based controls and traceable documentation;
- demonstration that CQA verification is embedded within sequencing, edge protection, and material handling activities; and
- clarifying the governance structure and the roles and authority of the CQA consultant and interactions with them.

Overall, continuing learning from the STIM process will be used to complement our existing plans for the final cap, to ensure confidence in CQM for the final cap is maximised.

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[18] The current specification and CQA reports are working documents and their provisions will be subject to appropriate review and update as the programme progresses, through the arrangements described above.

[19] As part of this we recognise observations, feedback and discussions, from the Environment Agency on the STIM programme to date and have integrated learning and recommendations from those discussions into our ongoing work.

2.7 Relationship of the Engineering Design Process to Other Aspects of the ESC and Engineering Implementation

2.7.1 Integration with the Requirements Management System

The RMS within the Disposal System Specification (DSS) [35] captures requirements for the engineering design and performance on the basis of the understanding and assessments arising from, and necessary for, the ESC. The RMS is described in detail in the '*Implementation*' report [17]. A very brief overview of its role in informing engineering design is provided here.

The RMS requirements address the key functions, controls and wider performance needs of the engineering. Requirements for future vault design, and trench and vault closure engineering are included.[20]

The RMS therefore provides requirements and information for optimisation and design processes. Execution of these processes, and related projects such as the EPA, can then lead to the identification of additional information or more detailed requirements.

As an example, recent studies considering the potential for disposal of different categories of wastes and containers in the vaults (see Section 5) were framed by relevant requirements from the RMS. The RMS will in turn be updated to take into account process outcomes that further inform on detailed requirements. This iterative approach to the RMS is a key aspect of its development and use.

2.7.2 Relationship to the Engineering Performance Assessment

The EPA [12] provides a systematic analysis of engineering performance, at both component-specific and integrated system levels. This informs the overall conceptual understanding of the system, the key modes for its evolution, and conceptual and parameter uncertainties. The EPA provides direct support to the assessments, including through the development of appropriate conceptual and mathematical models. In turn, there is a feed-back loop from the EPA to optimisation and hence the engineering design process.[21]

2.7.3 Other Relationships with the Engineering Design

The relationship between optimisation processes and engineering design is fundamental to the ESC and to the operation and development of the LLWR as a whole; this is set out in the '*Optimisation and Site Development Plan'* report [9].

Other relationships include those related to engineering implementation and repository controls as a whole. For example, the engineering design, optimisation, and EPA processes

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[20] Requirements for designs that pre-date the RMS, e.g. the trenches and Vaults 8 and 9, are not included. The focus is on future developments (including closure).

[21] An example is the recent geomembrane BAT options study [50], which will inform the process for selection of the geomembrane to be used in the first strip of the final cap, and then for subsequent steps, on the basis of updated understanding from the EPA.

inform monitoring programmes associated with construction processes, repository operations, and monitoring of engineering and wider environmental performance into the longer term.

The understanding developed through these processes also helps identify wider opportunities and priorities. An example is the work on design, optimisation and performance that led to the development of radiological capacities (e.g. as set out in the 2011 ESC [36]). These capacities in turn informed on the potential for risk-based disposal of appropriate categories of ILW at the site.

In general, the understanding developed via the engineering design, optimisation and assessment processes are a key part of enabling the use of the ESC as a tool for site management.

2.7.4 Illustration of Interactions

Processes for optimisation, design and assessment of any site involving legacy disposals, continuing operations, and future developments are necessarily iterative. Future work for the ESC and other LLWR programmes will generate updates to understanding that need to be fed back into the optimisation and design processes.

While it might superficially appear that such relationships should be simple, the reality is more complex. Iteration and feedback loops need to be integrated into any realistic representation of the overall process.

The figures that follow are intended to illustrate the overall process. Figure 2.12 illustrates the main interactions and information flows. Figure 2.13 builds upon this to present an illustration of the evolution of interactions with time, with examples shown (selected for the purposes of the diagram and not intended to be comprehensive).

When viewing these it is important to recognise the following considerations.

- The extent of iteration is a function of the nature of an individual development and so this is reflected in the flexibility inherent in the process.
- It is essential that the outcomes satisfy the requirements for optimisation, and underpin and are reflected by a logical and implementable design, commensurate with the level of maturity of an option.
- The figures are illustrative. Secondary level interactions may be enabled through the use of a common project team rather than being explicitly documented.
- For the example in Figure 2.13 in particular, the schematic is an approximation. It shows how a flexible process can be implemented within the overall constraints of the optimisation methodology. Flexibility in process is essential for a complex facility such as the LLWR, subject to uncertainties including those associated with legacy facilities and inventories, as well as future inventory projections. The approach therefore includes the flexibility to appropriately respond to the significance of findings at each step.

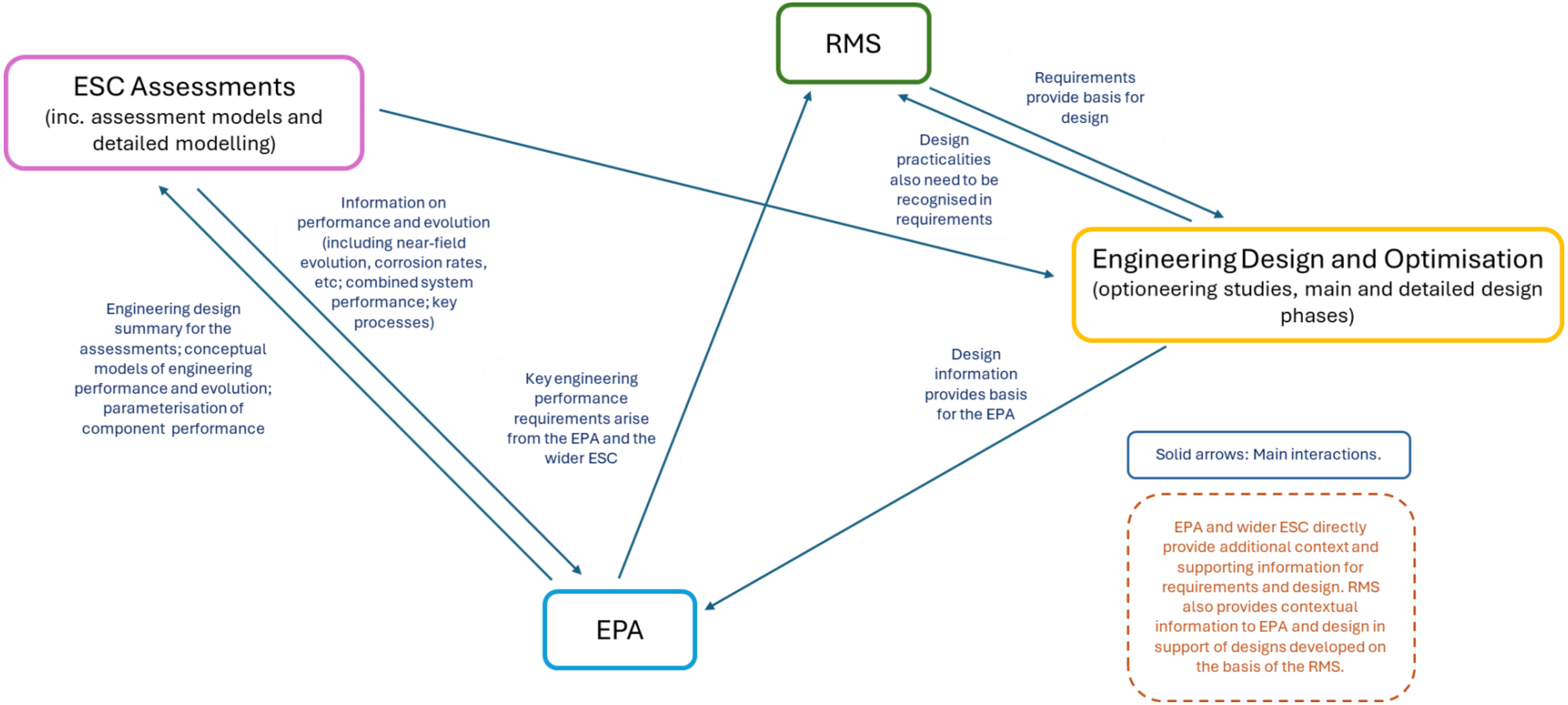

Figure 2.12: **Illustration of interactions between engineering design and optimisation, the RMS, the EPA, and the wider ESC. NB '*Safety Functions*' not shown but are key aspect of communications. They are a subset of the wider engineering functions produced by design and optimisation; inform the RMS, and inform and are informed by the EPA and the assessments.**

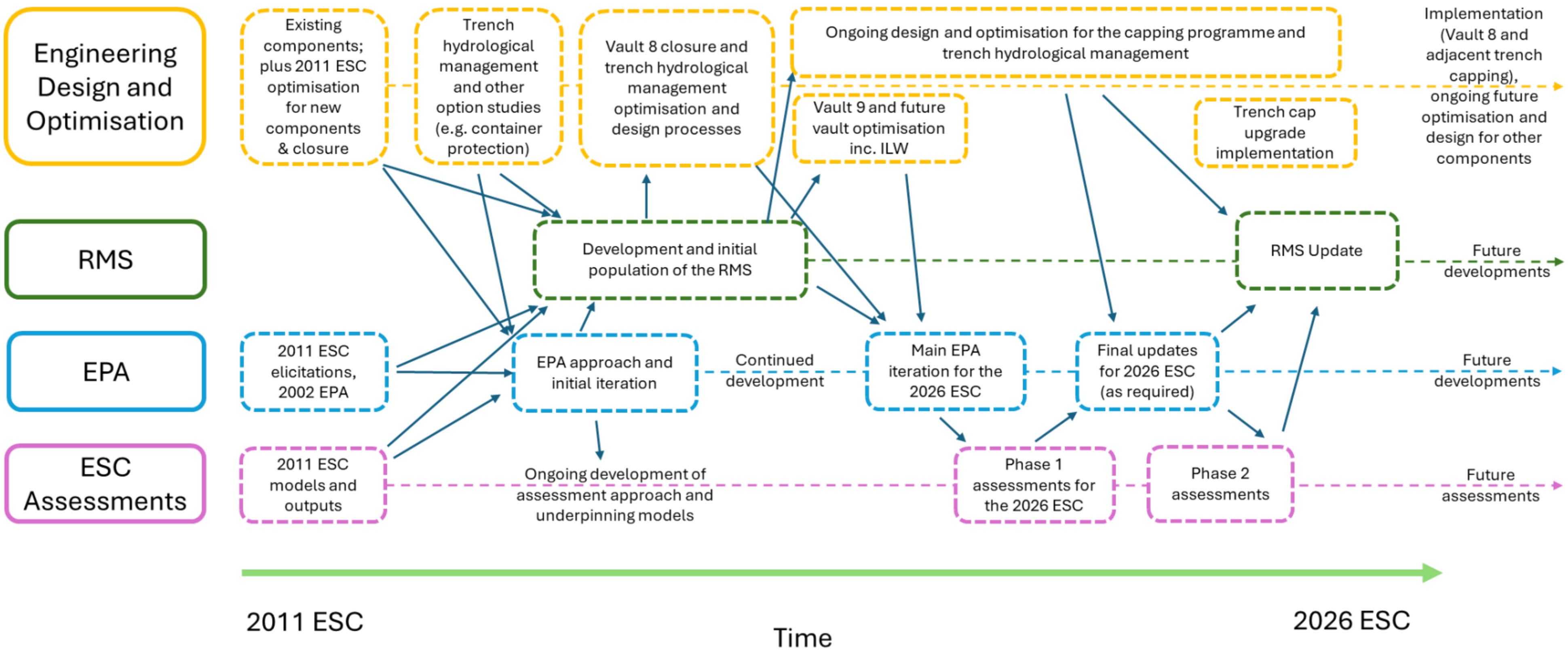

Figure 2.13: **Illustration of interactions with time between engineering design and optimisation, the RMS, the EPA, and the wider ESC, with examples. As for Figure 9, '*safety functions*' are identified and used throughout this process to communicate information on key aspects of the system of relevance to the ESC and its assessments. Note the diagram is illustrative of types of interactions and is not intended to be fully comprehensive nor are timings indicated precise.**

3 Closure Engineering Design

3.1 Introduction

In the subsections that follow, the closure engineering design is described.

- Subsection 3.2 provides an overview of the design of the final cap including profile fill.
- Subsection 3.3 presents the design of the existing and final cut-off wall.

The descriptions are provided on a component-specific basis to maximise clarity. However, it is important to recognise that the components act as an integrated system. Their roles as part of the overall concept, as highlighted in Subsection 2.3, need to be considered in order to understand the overall design rationale in each case.

For each component, a summary table showing the overall status of the design is first provided. The summaries in the tables are then expanded upon as appropriate in the text.[22]

For the final cap only, as the cap is a combined system including a range of layers or sub-components, additional summary tables for each of the layers are also provided in relevant sub-sections.

3.2 Final Cap

3.2.1 Introduction and Requirements

Table 3.1 provides a summary of the design status of the final cap.

The final cap will be a 3 m thick multi-layered structure. It will be installed via strip-capping into a single dome covering both the trenches and the vaults. The gradient will be a minimum of 1:25 with local steepening at the edges up to a maximum gradient of nominally 1:5 (primarily outside the footprint of the wastes) to accommodate boundary-related geometrical constraints. These contours will be ensured by the underlying profile fill (Subsection 3.2.5).

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[22] More detailed discussions of safety functions related to the components are provided in [11] and supporting references.

Table 3.1: Final Cap design summary

Category	Summary
Main functions	Isolate the wastes from humans and the environment; reduce infiltration into the wastes; manage bulk and trace gases.
Design status	The design of the final cap over Vault 8 and the adjacent trenches has been approved for construction. The design of the remainder of the cap will follow the approach set out for the first strip.
Design and optimisation history	Many iterations of design, optimisation and review. Current design has evolved from those first developed in the late 1980s.
Implementation schedule	The first strip of the cap will be implemented by 2037. Further strips of the cap will be progressively implemented until after disposals cease, around 2130.
Key sections of Optimisation and EPA reports	*'Optimisation and Site Development Plan'* [9]: Subsections 5.2 and 5.4.1; '*Engineering Performance Assessment*' [12]: Section 3 and Subsection 5.2.
Relevant RMS entries	See Subsections 5.15, 5.16, 6.15 and 6.16 of reference [37]
Additional key references for design, optimisation, and materials	References [33] [29] [27] [38] [39],
Priorities for ongoing optimisation and design	No significant further optimisation of the cap design is expected. Further minor refinement of the detail of the cap, e.g. contours, connections between components, are anticipated for Tranche 2 and beyond. This will also reflect experience from Tranche 1, and aspects such as the evolving understanding of inventory volumes and the detailed designs for future vaults (Subsection 5.4). The approach to gas venting, including the approach to decisions on closure of the vent at the end of the PoA, and alternative approaches, will continue to be reviewed (Subsection 3.2.6).

The main functions of the final cap are to provide isolation and containment. The optimised design ensures these main functions are delivered through:

- provision of layers to encourage evapotranspiration and drainage, above a composite (geomembrane and BES) barrier to reduce infiltration of water into the wastes;
- provision of a barrier, together with the profile fill, reducing the likelihood of, and impacts associated with, intrusion into the wastes;
- working with the profile fill, gas collection layer and gas vents, provision for management of bulk gases, and the reduction of doses from trace gases such as radon; and
- through the provision of a thick barrier, again working with the profile fill, reduction of direct and indirect external irradiation doses.

The cap will work with and be integrated with the cut-off wall (see Subsection 3.3). Together with the passive drainage systems in the vaults and the sub-vault drainage blankets (see Subsection 5.4), this will ensure that:

- water contact with wastes will be minimised for as long as practicable; and
- as the cap begins to degrade, any leachate that does arise will be preferentially directed to deeper (rather than surface) systems.

In providing these functions, the final cap, supported by the profile fill, also needs to [29, 39]:[23]

- resist damage due to movement and settlement;
- resist damage due to erosion (e.g. wind and rain), seismic activity and by plants, animals and to a limited extent humans;
- address visual impacts of the site to the surrounding land;
- perform passively without maintenance or any institutional intervention after the end of the PoA.

The final cap will be built over each vault and adjacent area of the trenches from north to south in sequenced strips to form a single dome cap on completion. The design detail for the initial strip and the assumption for the 2026 ESC is that each strip will have a leading edge ‘seal’ over the vaults and trenches. A seal is required as a temporary transition structure between capped areas and active disposal operations. It will include a resistive layer that will provide protection against infiltration (see Subsections 4.5 and, in particular, Subsection 5.5 for details). The timing of subsequent capping strips inclusive of leading-edge seals will be aligned with disposal receipts to the vaults.

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[23] See also Subsection 3.2.7 for more details on resilience aspects.

3.2.2 Basis and Evolution of the Design

The evolution of the design and associated optimisation arguments and assessment processes are described in reference [9, 38]. A brief description of design developments is provided below, drawn from that overall summary.

Proposals for a multi-layer final closure cap at the LLWR have been in place for many decades. The current layering design is very similar to that proposed for the 2002 PCSC [40]. This was in turn based on a layering system proposed in 1993 [41] as a development of designs proposed in the late 1980s (see e.g. reference [42]). The approach to the final cap is thus mature and robust having been reviewed through multiple optimisation and design iterations over many years. These continuing reviews, including taking account of LfE from other radioactive waste and hazardous waste and disposal sites, also ensure that the design is consistent with good practice and takes account of the latest information on layers and material performance from the literature.

Throughout, the basic approach to the final cap has comprised the following aspects. Further details of the layering system can be found in Subsection 3.2.4.

- Use of a composite low permeability barrier to reduce infiltration and manage gases.
- Placement of layers above the composite barrier to:
    - reduce heads on the barrier (achieved via evapotranspiration and drainage, and by ensuring appropriate gradients consistent with slope stability);
    - enhance stability (for example, through plant rooting zones and ensuring appropriate minimum gradients for run-off and maximum gradients for erosion considerations); and
    - protect it from intrusion (achieved by the inclusion of biointrusion barriers, and the overall thickness of the cap together with profile fill).
- Provision of an appropriate geometry and stable formation for the placement of the cap using profile fill, together with protection of the cap from gas pressurisation via gas collection layers and venting arrangements.

The original designs set out up to and including the 2002 PCSC featured a single domed cap. In the early to mid-2000s, the design changed to a two dome ('gull-wing') cap with a central valley between the trenches and vaults. The revised design also included deep vertical drains beneath the central gulley which formed part of the drainage concept being considered at the time (see references [20, 43]).

However, following optimisation work in advance of the 2011 ESC [25] the design reverted to a single dome. This was considered to be consistent with the change to maximising the use of the under-slab passive drainage approach rather than deep drains, and the conclusion that the single dome would not offer any additional constructability challenges over the construction of two smaller domes for the gull-wing cap. The steeper sided valley between the two domes was also considered to be susceptible to erosion. The resulting 2011 ESC design was very similar to that in the 2002 PCSC.

Updates since the 2011 ESC have included combining biointrusion and drainage layers for constructability reasons, increases to the thickness of the profile fill, and development of the cap contour, as part of the capping programme (see Subsections 3.2.3 to 3.2.5 for details and rationale). The resulting shape of the cap is provided in Figure 3.1.

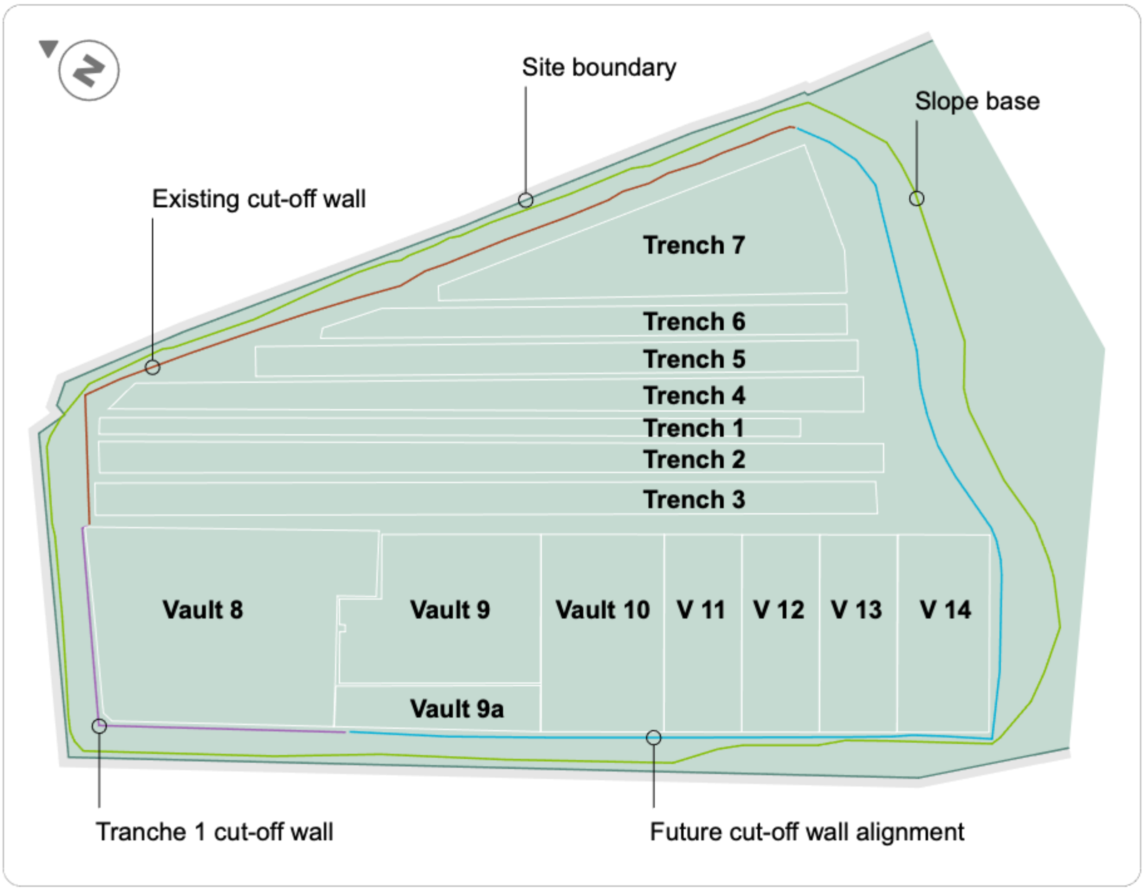

Figure 3.1: Schematic plan

3.2.3 Current Design Overview

3.2.3.1 Cap Layering System

The optimised cap layer structure including materials and thicknesses is set out in Figure 3.2.

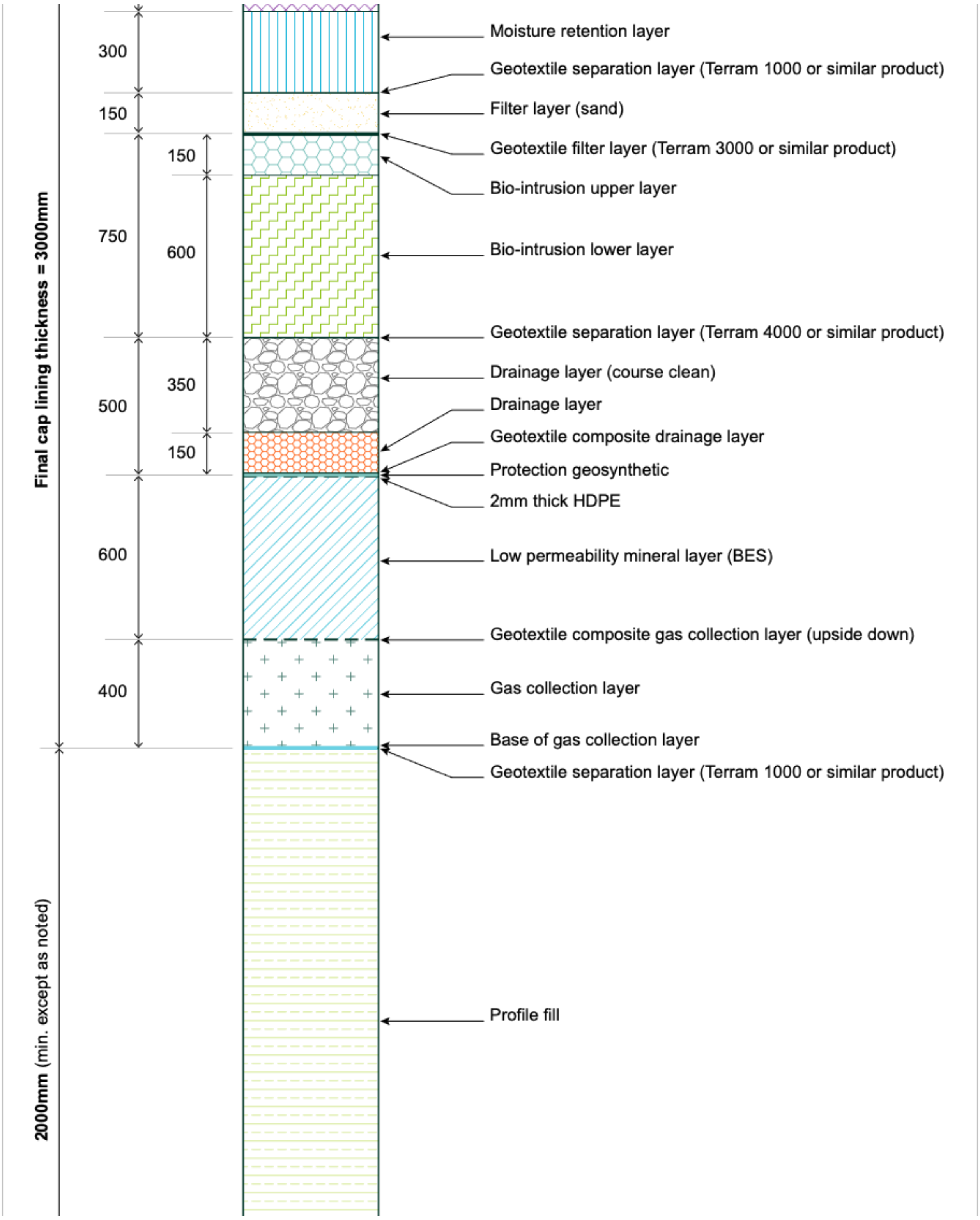

Figure 3.2: Layers of the final cap (taken from reference [38])

A summary of the layer structure is provided below to explain how the layers function collectively as an integrated system. Details are then provided in Subsection 3.2.4.

- The upper layers: These support vegetation, which contributes to cap performance by reducing hydrologically effective rainfall (HER) through evapotranspiration. Additionally, the vegetation attenuates surface drainage and the root systems enhance slope stability by reinforcing the upper soil structure.
- Biointrusion and drainage layer: This provides a dual function, providing additional drainage capacity as well as protecting the low permeability layers from burrowing animals and deep rooting vegetation, by providing a physical barrier and a low nutrient zone. The drainage features assist performance by minimising the hydraulic head acting on the resistive layers and providing preferential flow paths to the surface water drainage channels around the cap perimeter. These features, along with geosynthetic protection components, also help protect the integrity of the low permeability layers during construction activities.
- Geomembrane and BES: The primary layers responsible for limiting water ingress are the geomembrane and the BES. These form a composite barrier system, where the layers complement one another to enhance overall hydraulic performance. In addition to controlling infiltration, these layers also act as a partial barrier to gaseous emissions.
- Profile fill and gas collection layer: These lie below the low permeability layers and provide a stable foundation for the placement of them, whilst ensuring the correct cap geometry. The profile fill distributes mechanical strains, helping to mitigate the impact of differential settlement between wastes. A gas collection layer is incorporated to manage bulk gas emissions and is connected to venting infrastructure within the cap. This layer also functions as a capillary break, intercepting infiltrating water and directing it laterally toward perimeter drainage systems helping to further reduce moisture migration into the waste mass.

3.2.3.2 Geometry

Shape and profile

The final cap surface will generally be constructed with a minimum slope gradient of 1V:25H. However, the crest will be locally flattened due to geometrical constraints, including the requirement for the crest to be rounded, as described in reference [29]. Edge slopes will largely be at gradients of 1V:5H to 1V:10H, with the edge of the cap terminating beyond the alignment of the proposed perimeter cut-off wall.

Surface water run-off from the cap will be directed to the Drigg Stream via surface water drainage channels at the toe of the cap. The planned cap geometry is illustrated in Figure 2.2. The BES layer will be integrated with the cut-off wall to ensure hydraulic continuity and containment integrity; practical implementation details are provided in drawing RD 290 [44].

The cap will be founded on engineered profile fill. A key design requirement is that the combined thickness of the cap and profile fill must provide a minimum of 4 m, and preferably 5 m, of material between the waste surface and the final cap surface [9, 38, 45]. The current design achieves the preferred 5 m thickness (comprising 3 m of cap and 2 m of profile fill) across most of the waste footprint.

Exceptions to this thickness occur only for the first strip of the cap, in limited areas of Vault 8, specifically at the facility edges, such as the raised 'shelf' adjacent to the vault wall and a small number of containers in the north-west corner, where geometric and gradient constraints apply. In these locations, the profile fill may fall below the preferred 2 m thickness unless surcharge operations sufficiently compress the waste stacks. However, the minimum 1 m profile fill requirement is still met in all cases. These deviations have been evaluated in terms of cap resilience [39] and will not compromise performance with respect to settlement tolerance.

Figure 3.3 provides an illustration of the relationship between the cap profile and disposals.

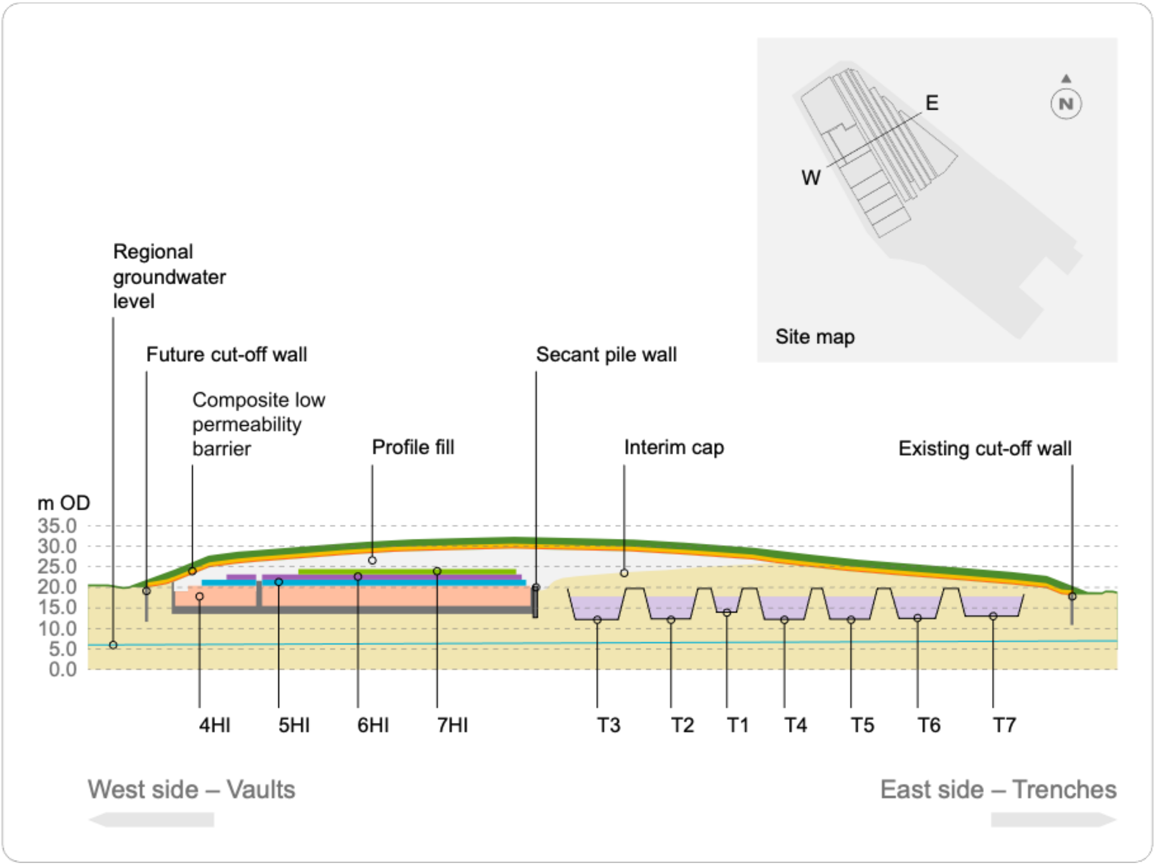

Figure 3.3: Cap design profile (Note: Vertical Scale exaggerated for clarity)

Edge details

The edge details are designed to suit the existing landform and site boundary, with slopes at 1 in 10 where possible and locally up to 1 in 5.

Vaults west and north-west sides

Figure 3.4 shows the planned detail for the west and north-west sides. This provides a 10 m wide reserve within the fence line, allowing 5 m for a 'roadway' for security and occasional access and 5 m for the Drigg Stream, which will be realigned and enhanced and will also take run-off from the cap.

Trenches east and north-east sides

Figure 3.5 shows the planned detail to the eastern and north-east side of the cap over the trenches area. This reduces the edge gradients as far as practicable. The design leaves scope to incorporate suitable screen planting around the perimeter and outside of the area of wastes to best suit planning requirements.

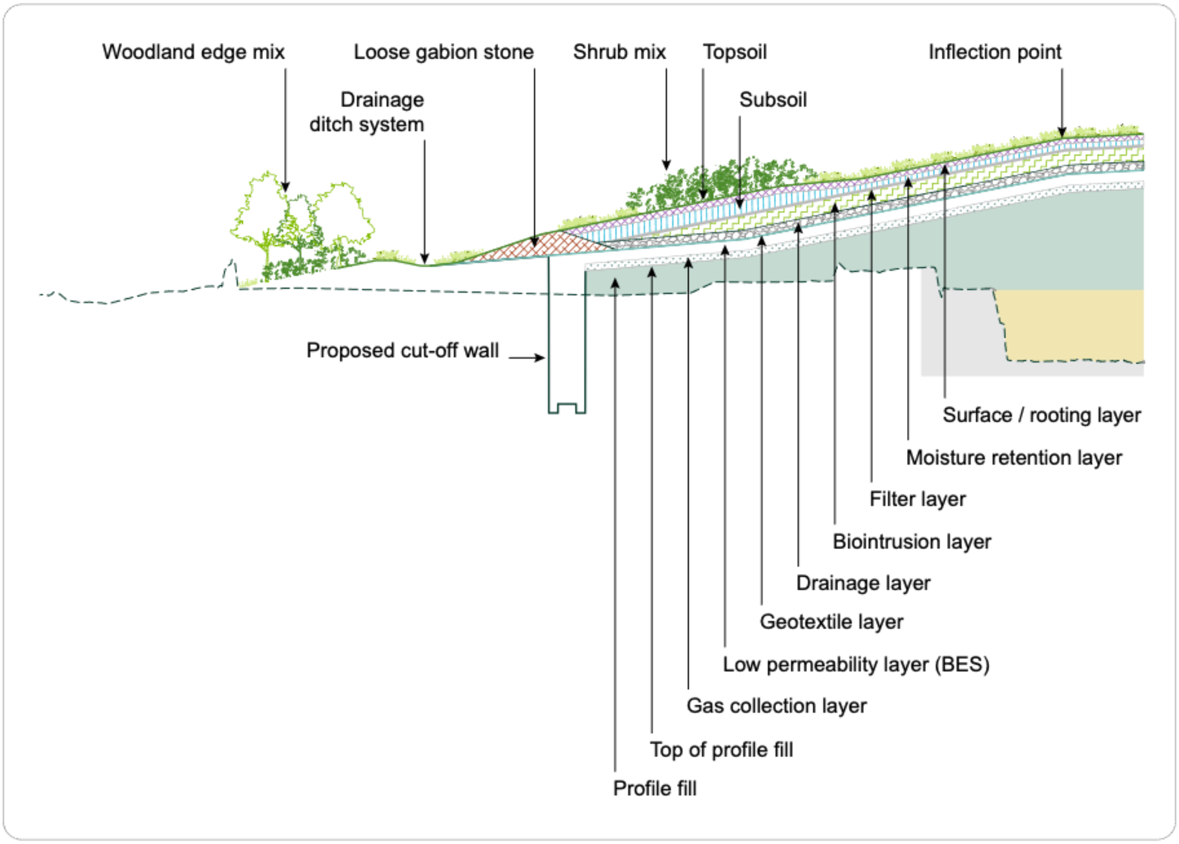

Figure 3.4: Typical detail west edge of vaults (Note: Vertical scale increased for clarity)

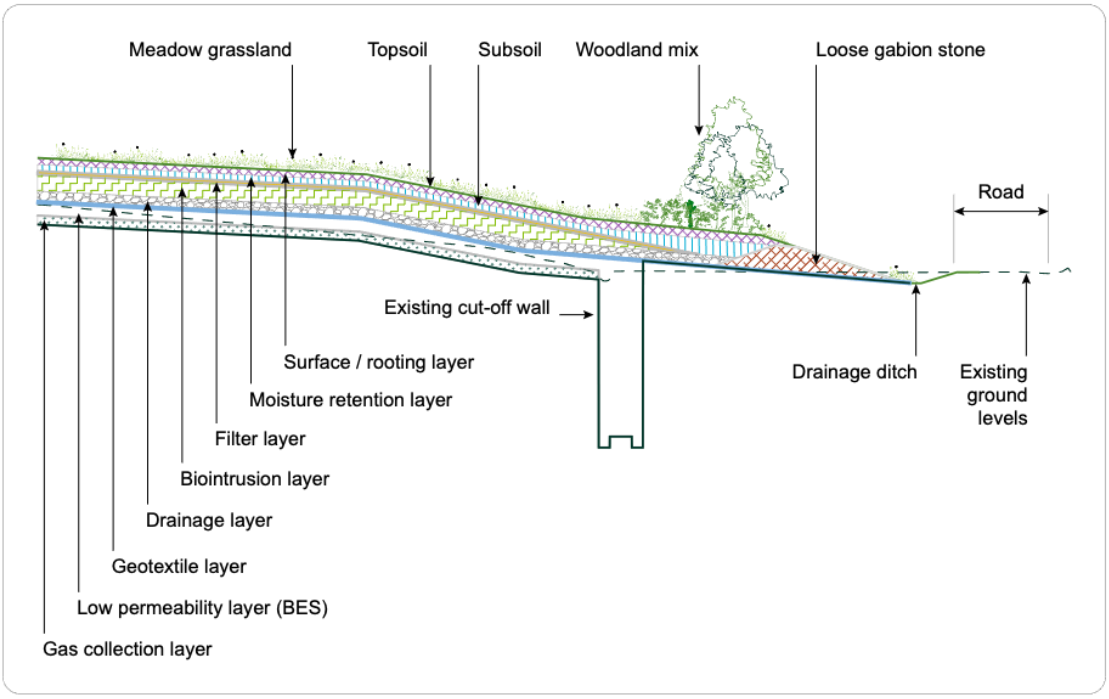

Figure 3.5: **Typical detail east edge of trenches (Note: Vertical scale increased for clarity)**

The railway cutting to the east is approaching 4 m deep at slopes of up to about 38°. Overall slopes back to the fence line are about 1 in 3 (18°). These pose no concern to the site but may be prone to erosion. However, the cap and the wastes themselves are well away from the cutting and are not at risk.

3.2.4 Layer Details

3.2.4.1 Overview

This section provides a summary of each of the individual layers of the cap that work together to provide the overall integrated capping system design. Further details including layer specifications are provided in references [33, 29].

3.2.4.2 Role of Man-made Elements in Support of the Main Functional Layers

The design includes several man-made filter and separation geotextiles layers to complement the main natural material layers. These are included to assist constructability and to reduce unintended material mixing during construction. In addition, the geotextiles above and below the low permeability layers provide a drainage function and additional drainage redundancy for both water and gas. The cap performance, once constructed, does not rely on the presence or performance of these layers. They do not change the performance of the other layers during or after degradation. The choice of the drainage geotextiles for the relevant layers was primarily made as a convenient additional source of redundancy in drainage provisions for water and gas and was a logical choice where a geotextile was in any case required.

3.2.4.3 Surface Soil and Vegetation

Table 3.2: Surface soil and vegetation layer design summary [24]

Category	Summary
Main functions	To provide a rooting zone with water retention, to: • promote vegetation on the cap; • maximise slope stability and minimise erosion; • encourage water shedding to the perimeter, including managing waters during higher rainfall events; • reduce overall infiltration via evapotranspiration; • ensure the final cap is aesthetically appropriate.

The functions outlined in Table 3.2 will be delivered by ensuring the provision of a growing medium for surface vegetation, whilst providing adequate water retention capacity (working with the moisture retention layer placed below; see Subsection 3.2.4.4) consistent with the subsequent vegetation, to attenuate infiltration of precipitation and sustain vegetation through dry periods, without compromising stability.

The vegetation will assist in preventing erosion, via the binding effects within the root zone. Erosion will also be reduced, alongside infiltration, via the contribution of the vegetation to water management. This includes evapotranspiration, but also the contribution of the vegetation to reducing erosive forces and standing heads during higher rainfall events.

The final specification for the soil and vegetation zone will be developed and agreed with planners and landscape specialists to:

- match the existing or preferred final ecology of the area;
- provide best practicable resilience and resistance to erosion;
- contain roots so that they will not disrupt the drainage or barrier layers;
- be capable of surviving and functioning without maintenance.

Following active ecological management, the vegetation will continue to evolve naturally in response to climatic and natural change.

Suitable surface soil will provide the main rooting medium for the plants in the vegetation layer. This forms the upper surface profile to the capping. The planned 300 mm thickness is considered suitable for the hardy and shallow rooting species that are able to withstand the weather conditions at the site. The planned mix is set out in reference [33].

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[24] Here and for other layers within the cap, only the specific function as a layer of the final cap system is highlighted. Other aspects remain as for Table 3.1.

Existing soils (both those currently in-situ and already stripped and stockpiled) will be suitable for re-use as sub-soil or topsoil in certain soft landscape areas, subject to appropriate amelioration and soil management, together with availability and depth. Where existing soils cannot be economically ameliorated by a fertiliser prior to planting or seeding, or where there is insufficient existing soil available, imported Low Fertility Topsoil is specified where Northern Hay Meadow and/or Wildflower Meadow seed mixes are proposed; and General Purpose Topsoil is specified elsewhere [46].

Reference [47] demonstrates that suitable tree species (having limited height and limited root depths) can be planted on landfill caps without deleterious effects to clay liners. The ESC cap will provide a considerably higher standard of protection than the landfill caps considered therein. Nonetheless, it is presently considered prudent to exclude deliberate planting of trees from the cap above the waste footprint, and remove or manage any trees that might try to establish themselves during the management control period.

This restriction does not extend to the edges where infiltration reduction performance is not required and the composite layers are not present (i.e. outside the interface with the cut-off wall) where trees can provide valuable landscaping and screening. The depth of cover soils increases here to match the site geometry. The associated edge slopes are considered to be appropriate locations for tree planting.

Geomembranes also act as effective barriers to root penetration [47]. Together with the 2 m of cover layers over the geomembrane (within the footprint of the cut-off wall), which include granular drainage layers and the bio-intrusion layer, the cap provides a substantial multi-layered barrier to root penetration.

3.2.4.4 Moisture Retention Layer

Table 3.3: Moisture retention layer design summary

Category	Summary
Main functions	Increase the water storage capacity in the upper part of the cap, to support the function of the surface soil and vegetation layer in sustaining vegetation. Reduce infiltration to underlying layers.

A 300 mm-thick moisture retention layer is planned beneath the surface soil. Its primary function is to increase the water storage capacity in the upper part of the cap, which will sustain vegetation and assist evapotranspiration. It also serves to limit infiltration to the underlying drainage layer, encourage run-off and provide protection for the underlying layers from erosion, frost penetration and desiccation.

The specification can accommodate a wide range of locally available soils generally classified as loams and sandy silts and clays. The materials should be well-graded and contain sufficient silt and clay so as not to dry out during periods of low rainfall. The soil should not be too clay rich, which could be prone to desiccation cracking.

The moisture retention layer is designed to be of sufficient thickness to minimise intrusion of plant roots into underlying components [29] but accommodate the root systems of the vegetation. The designed 300 mm thickness is consistent with good practice.

3.2.4.5 Filter Layer (Sand)

Table 3.4: Filter layer (sand) design summary

Category	Summary
Main functions within Final Cap system	To ensure the function of the bio-intrusion and drainage layers below by protecting them from clogging from soils and associated particles.

The 150 mm-thick filter layer minimises particle migration into the underlying bio-intrusion and drainage layers. Particle migration could lead to clogging of these layers, which would be detrimental to their performance.

The grading envelope of the sand is specified in [33], with particle sizes ranging between 2 mm and 63 microns.

A geotextile filter layer is proposed immediately below the filter layer (sand). This enables the development with time of natural self-filtering, such that the geotextile itself becomes redundant in the long-term.

3.2.4.6 Combined Bio-intrusion and Drainage Layer

Table 3.5: Combined bio-intrusion and drainage layer design summary

Category	Summary
Main functions within Final Cap system	To minimise the likelihood of damage to the low permeability elements of the cap by deterring intrusion from plants, humans and burrowing animals. To ensure effective drainage of cap waters for as long as practicable, to minimise the head of water on the low permeability layers.

Previous designs for the cap included separate bio-intrusion and drainage layers. Recent optimisation work [38] identified an opportunity to combine these layers to help simplify the overall constructability of the cap. As part of this it was noted the materials used for bio-intrusion barriers are consistent with providing drainage.

The result is a combined layer providing both bio-intrusion and drainage functions as described in references [9, 38] and summarised as follows.

Bio-intrusion functions

The bio-intrusion layer aims to prevent possible damage to the integrity of the low permeability barrier, and potential intrusion into the wastes below, by burrowing animals, penetrating roots and inadvertent human damage. The layer also provides protection of the underlying layers from water and wind erosion if the upper layers are locally removed by these processes.

The bio-intrusion component proposed at the LLWR site comprises an upper and a lower layer. The upper bio-intrusion layer is a 150 mm-thick layer of coarse gravel that is to act as a regulating layer on top of the 600 mm-thick lower bio-intrusion layer so that the filter layer above is supported. The lower bio-intrusion layer is a 600 mm-thick layer of cobbles in the range 125 to 300 mm in size.

The lower bio-intrusion barrier will include large, hard, durable, stone cobbles. This will be clearly recognisable as a construction layer that will help inform potential human actors who might inadvertently attempt intrusion into the capped system, as well as requiring determined human action using plant to penetrate. For example, in addition to providing direct physical resistance to intrusions, the cobbles will tend to form and then self-heal cavities upon disturbance by plant, which will provide additional practical challenges to intrusion activities [38].

Similarly, the cobbles will be difficult for animals to dig through both because of their size and self-compacting nature. They will prevent intrusion by the largest burrowing animals that could be present at the site (normally badgers). Intrusion by burrowing animals would result in the creation of preferential pathways for water, vapours, roots and other animals. They also increase the porosity of the soil and therefore infiltration.

There is limited guidance available on the design or performance of biotic barriers. Reference [48] cites research on biotic barriers in arid and semi-arid situations for plants unique to these environments. It indicates that 900 mm of cobbles, or 150 mm of gravel over 750 mm of cobbles, may be effective in stopping root penetration of some deep-rooted plants. Allowing for the contribution of the overlying 150 mm coarse gravel upper bio-intrusion layer and the underlying 500 mm drainage layer, the planned 600 mm lower bio-intrusion layer at the LLWR site can be expected to provide ample deterrent to deep rooting plants and burrowing animals.

This barrier would also provide additional lateral drainage capacity if the dedicated drainage layer capacity were to be exceeded. The layer will be poor in nutrients and free draining, hence will deter the intrusion of roots into the lower horizons. Roots will be more likely to extend laterally within the fine-grained, moist soils above. The filter layer above the bio-intrusion layer will minimise the fines content of the barrier, which will maintain the low nutrient and moisture content of the layer.

The bio-intrusion layer will also discourage deeper rooting vegetation. Over the life of the capping system, it is possible that some trees may start to grow on the cap, although this appears not to be the case for the adjacent dunes and SSSI, and is not expected. The depth of tree roots is largely dependent on soil conditions, although the majority of roots are generally found within a few tens of centimetres of the surface, i.e. consistent with the base of the moisture retention layer. The bio-intrusion layer thus provides an additional barrier function against development of significant trees.

Drainage functions

The drainage layer within the cap system will intercept infiltrating water above the low permeability barrier layers and redirect it laterally, thereby facilitating subsurface drainage. This function is important in preventing the accumulation of water above the low hydraulic conductivity layers and high hydraulic heads acting on the underlying resistive layers. The drainage layer also contributes to the stability of cap layers above by minimising pore water pressures in overlaying materials. This is important when there is sufficient rainfall to potentially saturate the cover soil.

The primary design criteria for the drainage layers are specified in reference [33]. They include:

- the minimum thickness of the cap drainage layer shall be 500 mm; and
- the hydraulic conductivity of the drainage materials shall not be less than 10^{-4} m s^{-1};

Drainage layers are sized and graded to mitigate the effects of clogging throughout the required design life by physical (particulate), chemical (e.g. precipitation) and biological (e.g. biofouling) reactions.

A 500 mm-thick layer of clean coarse gravel is specified to provide drainage from above the barrier layer to drains at the perimeter of the cap. The top 350 mm will comprise coarse gravel, with particles less than 80 mm in size. The bottom 150 mm will be less coarse, with particles less than 40 mm in size and without sharp or angular stone to minimise risks of damage to the underlying geotextile composite drainage layer, which is specified in reference [33].

The design also includes a geotextile composite drainage layer, placed underneath the natural material components of the drainage layers. This man-made drainage layer has the dual benefit of further enhancing confidence in drainage performance whilst its performance lasts, whilst also working with the geotextile protection layer below to maximise protection of the low permeability layers from piercing or other effects during construction.[25]

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[25] Consistent with the discussion in Subsection 3.2.4.2, the drainage function does not rely on the provision of the man-made component.

3.2.4.7 Protector Geotextile

Table 3.6: Protector geotextile design summary

Category	Summary
Main functions within Final Cap system	Protect the geomembrane layer from damage during the placement of layers above, in combination with the overlying geotextile composite drainage layer, and consistent with the specification for the lower drainage layer materials (i.e. particles that are not large, sharp or angular).

A geotextile protection layer will be required over the geomembrane. A needle-punched non-woven geotextile with high puncture resistance is specified, to prevent damage to the planned high-density polyethylene (HDPE) geomembrane from the drainage material above, in accordance with good practice design and construction guidance [49].

3.2.4.8 Composite Low Permeability Barrier

Overview

Table 3.7: Composite low permeability barrier design summary

Category	Summary
Main functions within Final Cap system	The geomembrane and the BES together provide an integrated composite low permeability barrier system to minimise infiltration and help manage gases (working with other gas management arrangements for the cap). The BES will continue to reduce infiltration, contribute to manage gases and strains into the longer term, after the geomembrane has degraded.

Composite Low Permeability Barrier - Geomembrane

The principal function of these layers is to provide a low permeability barrier to rainfall infiltration and upward moving gases. The barrier minimises infiltrating water:

- directly by resisting water flow;
- indirectly by promoting drainage or storage of water in the overlying layers.

The primary criteria for the low permeability barrier layers are:

- it comprises, as a minimum, a composite of the HDPE geomembrane liner and mineral capping layers;
- the mineral capping layer will be BES;

- the mineral capping layer will have a minimum thickness of 600 mm;
- the mineral capping layer will be of low permeability, with a hydraulic conductivity not exceeding 10^{-10} m s^{-1} (at the time of construction);
- the components of the low permeability layers will be suitably strain tolerant and shall be capable of resisting plausible long-term deformations of the cap;
- the low permeability layers will be located at a depth below maximum frost penetration depth.

Studies have shown the benefits of using a composite liner system of geomembrane on mineral liner, discussed further in the EPA [12]. The layers work together to mutually enhance protection. For example, the geomembrane protects the BES from flows and thus wash-out and cation exchange, and also protects it from desiccation. The BES in turn provides self-healing properties that help address defects in the geomembrane. Ensuring effective contact between the geomembrane and the BES is key to maximising performance as a composite (see the EPA report, [12]).

There will be defects in the geomembrane on placement (described in detail in the EPA [12]). These include, for example, pinprick and other small holes and wrinkles, inherent in the fabrication and placement of all such materials. Quality fabrication, appropriate transport and storage, and accurate construction is required to minimise the frequency of defects on placement. The frequency of defects will increase with geomembrane degradation (also detailed in the EPA [12]).

A 2 mm HDPE geomembrane is included in the cap design [33, 38]. HDPE is generally considered the most chemically resistant suitable polymer and the most suitable geomembrane for landfill and repository lining systems. A 2 mm thickness membrane is a typical and well-tried and tested thickness. Greater thicknesses do not give design advantages and are less flexible with potential for increased difficulties during installation, with a corresponding impact in confidence in terms of long-term performance.

Over recent decades, international experience, research and practical understanding of the performance of geomembranes have led to increasing confidence in long-term performance compared to past understanding. This is particularly relevant to geomembranes placed in low stress, low temperature locations, which is the case for the LLWR site cap. The '*Engineering Performance Assessment'* report [12] provides details and the implications for projections of infiltration. We describe in the '*Optimisation and Site Development'* report [9] how this understanding will inform final selection of the geomembrane, for each strip.

Design and construction will be in accordance with the latest industry guidance. We are also in the process of updating our existing specification for the geomembrane to reflect good practice in maximising confidence in geomembrane longevity based on other standards. This reflects the updated understanding of long-term geomembrane performance identified through the EPA [12] and [50]. Specifically, the updated specification will adopt a specific subset of requirements from the German BAM[26] certification guidelines [51] relating to durability. Our approach will also involve additional bespoke durability testing (recognising the outcomes of [50]).

The composite liner system will be implemented under a strict regime of CQA [34] to validate and test all the various component layers.

The geomembrane (and BES below) also serves to reduce and control transmission of gas by this route, and working with the gas collection layer, and the gas vent when open.

Composite Low Permeability Barrier - BES

A 600 mm-thick layer of BES is planned as the mineral layer, directly beneath the geomembrane and acting as the lower part of a composite barrier. In landfill engineering in a composite cap (using a geomembrane in contact with BES), the BES thickness generally ranges between 0.3 m to 0.5 m. In the final cap, 0.6 m has been selected to ensure robustness, taking into account self-healing properties and the ability to withstand plausible strains. A thicker BES layer does not significantly decrease infiltration through the liner system or necessarily increase its design life. However, thicker BES placed in a series of layers, consistent with our plans for the cap, improves confidence in construction and its mechanical robustness and helps provide redundancy and confidence in performance. The primary design objectives for the BES are to ensure:

- the selection of a suitable bentonite;
- the choice of an appropriate chemically inert and physically stable filler (usually sand, soil. fine aggregate or a mix of these) depending on its intended characteristics;
- testing to identify the optimum mix of bentonite and filler material;
- laboratory testing to confirm the suitability of the mixes;
- planning to finalise construction and layer design, sequencing and equipment selection;
- site testing with the selected design mix and placement equipment and protocols to confirm performance;
- implementation of routine checks, tests and compliance controls on source materials, mixing, placement equipment, layer thickness, moisture content, density and permeability;
- a high standard of construction control to ensure placement only occurs during pre-approved conditions; and
- implementation of strict CQA protocols

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[26] Bundesanstalt für Materialforschung und -prüfung

Design and construction approaches are set out in detail in reference [29]. The approach is consistent with good practice and specifically guidance supported by the Environment Agency [52]. These require:

- low permeability (hydraulic conductivity $<10^{-10}$ m s^{-1});
- suitable mix control, placement and compaction;
- suitable validation testing.

3.2.4.9 Gas Collection Layer

Table 3.8: Gas collection layer design summary

Category	Summary
Main functions within Final Cap system	To provide a means for managing bulk and trace gases including directing gases to the gas vent while open. The gas collection layer will be a granular feature that works with the profile fill to provide the functions described for that layer.

The gas collection layer must have a high in-plane gas transmissivity and must resist clogging by fine-grained materials located above or beneath. It also needs to have sufficient strength to provide an adequate foundation for the overlying layers of cap.

A 400 mm-thick layer of clean coarse gravel is planned for this layer. This would be ample even if significant gas flows were to occur. This layer will also act as a capillary break layer. The inclusion of a fine layer above a coarser one will encourage small volumes of water infiltrating through the composite barrier layer to move laterally along the interface and down gradient to the perimeter drainage around the sides of the vaults and trenches, rather than vertically through the profile fill and wastes. The EPA [12] provides confidence that the material will not clog significantly even over very long timeframes while cap integrity persists.

The top of the gas collection layer also includes an upside down geotextile drainage layer to aid construction and to provide additional redundancy in layer performance. A geotextile separator is also are included below the gas collection layer. These geotextiles will facilitate layer placement, and help minimise any potential clogging of the gas drainage layer by fine-grained materials.

3.2.5 Profile Fill

Table 3.9: Profile fill design summary

Category	Summary
Main functions within Final Cap system	To provide a stable formation for placement of the final cap, including ensuring the required cap geometry. To enhance the resilience of the final cap to settlements by distributing any strains.

The cap will be founded on profile fill. Its thickness, together with that of the final cap, will be sufficient to provide the required distance between the cap surface and the wastes as set out in Subsection 3.2.3.2. The profile fill will:

- reduce the effects of differential settlement on the cap through, spreading movements that reduce strains;
- employ inert, free-draining, low fines, granular material over the vaults;
- use excavated materials from on-site construction activities over the trenches, together with imported cohesive material that complies with specifications, with granular material in places to further enhance the ability of the profile fill to address waste settlements;
- provide a suitable foundation for the cap construction and performance, of the required geometry.

The fill will be selected and placed in accordance with standard engineering earthworks specifications [53], to ensure suitable compaction and minimal settlement.

The profile fill will be emplaced in layers from the edge of the facility, progressively across the wastes using a 'push and place' approach. This will be integrated as appropriate with surcharging approaches for relevant wastes. Granular fill will be used for surcharge above the profile fill, with the additional height of material then being removed and used for profile fill elsewhere.

The use of site-won and imported cohesive materials over the trenches also presents further benefits in terms of delaying radon migration, thus enhancing decay before release.

3.2.6 Gas Vent

Table 3.10: Gas vent design summary

Category	Summary
Main functions within Final Cap system	Provide a means for releasing bulk gases during the PoA, working with the gas collection layer, to minimise any risks to the performance of the final cap as a result of over-pressurisation. If required, the vent could be kept open after the PoA, should it be required. Further optimisation studies for the approach to gas venting are planned in advance of the implementation of the second strip of the cap.

3.2.6.1 Overview

The cap is designed to ensure that bulk gases generated within the waste body can be safely dissipated, without risk to the integrity or stability of the overlying layers, and in particular the low-permeability composite.

The gases include the normal range of landfill gases, such as carbon dioxide and methane, as well as hydrogen from metal corrosion. It is anticipated that bulk gas generation will continue for a prolonged period (see references [5, 14]).

A further question is whether the gas vent (or alternative) needs to be decommissioned at the end of the PoA. This was the baseline assumption for the 2011 ESC [20] and is retained for the 2026 ESC. However, the 2011 ESC also recognised the potential benefits of retaining the flexibility to keep the gas vent system open at the end of the PoA, and this flexible approach is also retained for the 2026 ESC. Indeed, in the 2011 ESC we assumed that a final decision on decommissioning the gas vent would not need to be undertaken until the end of the PoA. This would allow the final decision to be informed by many years of monitoring, modelling and analysis of gas generation and movements through successive strips of the final cap.

The flexibility in the 2011 ESC approach reflected uncertainty in the evolution of bulk gases but also the understanding at the time that bulk gas release should peak before the end of the PoA. This understanding has now developed with the near-field modelling and related work for the 2026 ESC [5, 14], which suggests that bulk gas releases will continue beyond the PoA. Uncertainties associated with projections of future release and the implications for pressurisation will continue to be assessed in our forward programme.

The situation is illustrated in Figure 3.6. At low pressures, the gas will be completely contained if the gas vent is decommissioned. Higher overpressures can be sustained by the cap, with the potential for gas migration through the BES and defects (holes) in the geomembrane, and potentially through, and under, the cut-off wall, without system damage. For very high overpressures which may be sufficiently high to damage the cap low permeability layers, gas venting is the mitigating response.

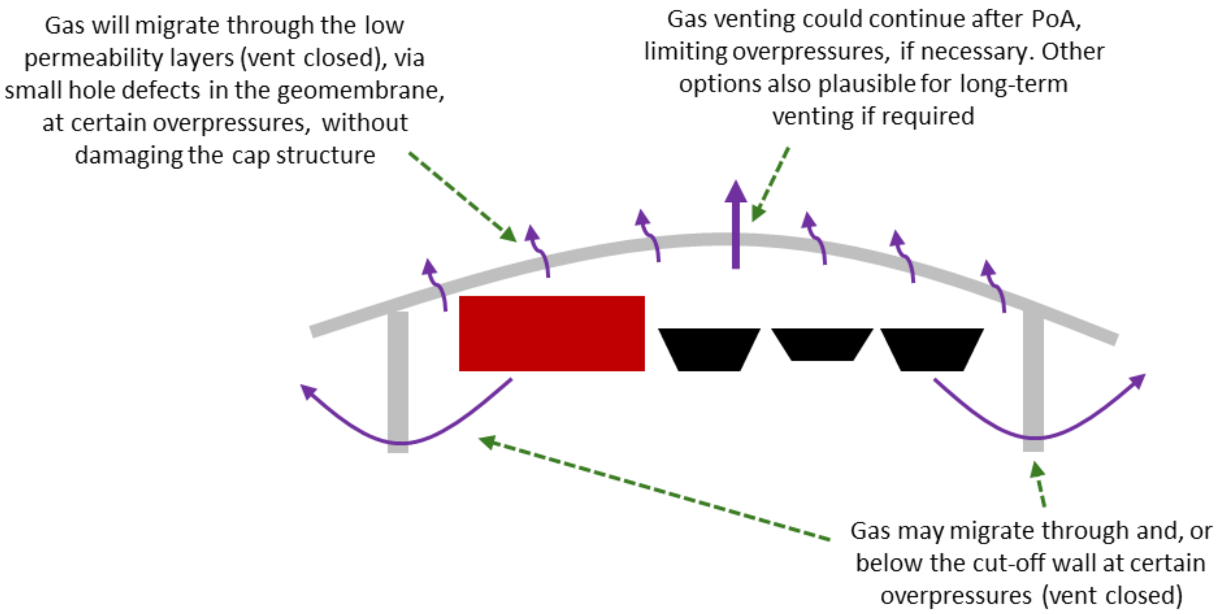

Figure 3.6: **Gas release schematic. Indicates different routes for gas release depending upon final gas venting decisions and the potential evolution of gas pressures**

While the gas vent design is mature in that it has been part of the cap design for several decades, it has not been subject to detailed design as it is not required to be implemented during early strips of the cap (see Subsection 3.2.6.2). In addition, the understanding developed for the 2026 ESC on bulk gas sources and flows provide additional information for consideration in further optimisation. For that reason, a programme is underway to review options for gas venting to feed into subsequent design stages, including detailed design.

The optimisation study will consider venting options more broadly, and not just whether to close the current vent design. The '*Optimisation and Site Development Plan'* report [9] provides an indication of the types of options to be considered in the ongoing optimisation process. The priority is to ensure the development in time for the implementation of the second strip of the cap.

In the meantime, the existing baseline vent design provides a firm and mature basis for the assessments for the 2026 ESC. In recognition of the remaining flexibility on closure of the vent at the end of the PoA, assessments (e.g. reference [14]) explore both the baseline design for the end of the PoA (vent decommissioned) and the key alternative (vent retained).

3.2.6.2 Details of the Current Design Concept

Figure 3.7 shows the conceptual design. Figure 3.8 shows details of the current planned cap venting arrangement. This is designed to prevent infiltration entering the gas vent structure by a 'mushroom' overlap system of the low permeability barrier layers, whilst retaining the facility to vent gases. Gas from the wastes is directed to the proposed vent via the gas collection layer.

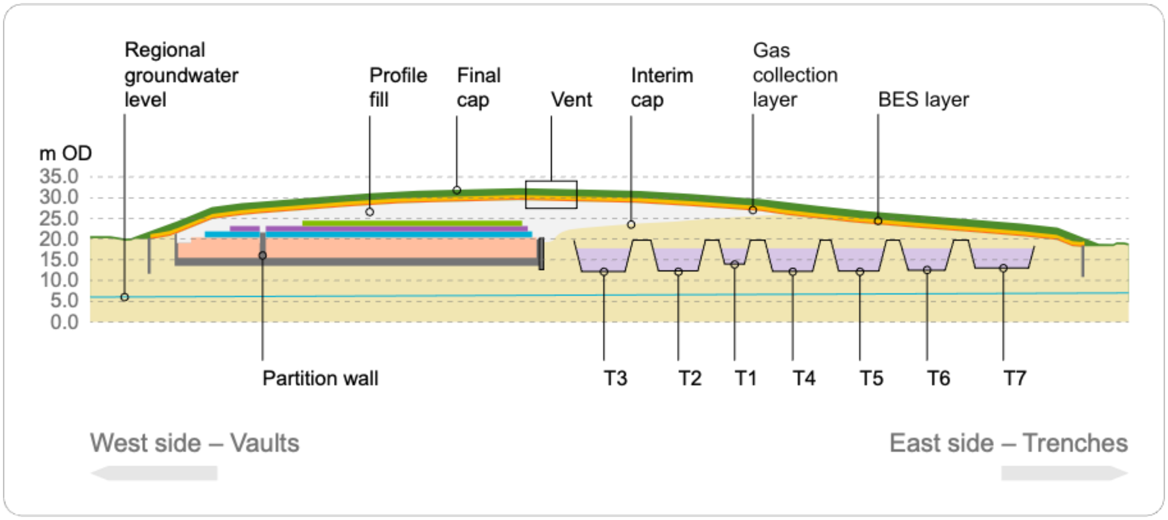

Figure 3.7: Gas collection and control system. Note: Vertical scale exaggerated for clarity)

The current design assumes that a gas vent will be emplaced as an approximately oval shape around the crest of the cap, consistent with the schematic in Figure 3.8. The cap vent will not be associated with the first or second strips of the final cap (i.e. Vault 8 and then Vaults 9 and 9a). The vent arrangements are based on the gas collection layer connecting with the drainage layers above the low permeability layers. These layers have been combined in the updated cap design. Note this figure shows the ‘mushroom’ arrangement in section whereas in the plan view, the gas collection layer would be shown to be in continuous connection with the drainage layers, around the crest of the cap.

However, gas vents will also be incorporated into the vault seal design (see Subsection 5.5) for these first two strips using a ‘top-hat’ penetration approach. This will ensure access to vents for each strip of the cap. The relevant strips will be implemented as follows.

- Strip 1 - leading edge over Vault 8 and the adjacent trenches, and the Strip 1 leading edge extending over the existing and committed containers in Vaults 9 and 9a.
- Strip 2 - leading edge over Vaults 9 and 9a and the adjacent trenches, with the Strip 2 leading edge extending over the first half of Vault 10.
- The main cap vent will then be constructed with Strip 3 over Vault 10, and leading edge vents will no longer be required for subsequent strips.

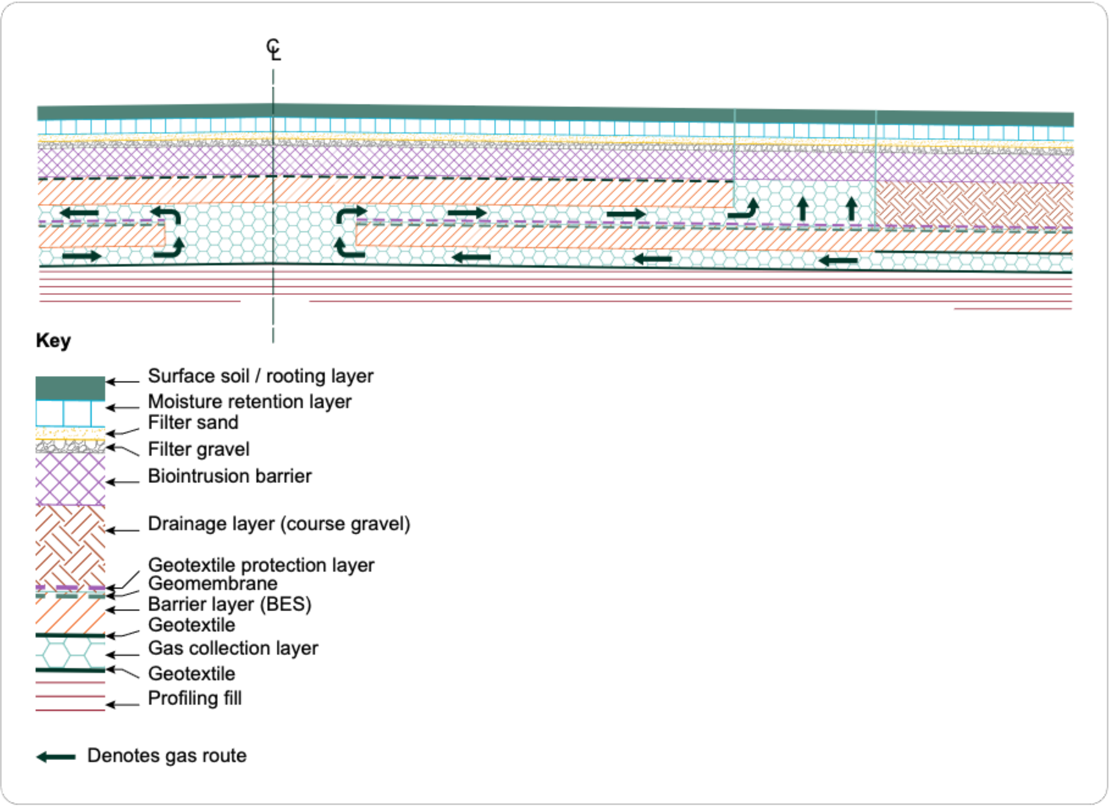

Figure 3.8: Gas collection and vent detail

3.2.7 Cap Resilience

The final cap has been subject to several iterations of cap resilience assessment. This is an important aspect of justifying the design and underpinning claims in the EPA on confidence in long-term performance. Specific aspects of the cap design that contribute to resilience have already been highlighted in the descriptions in Subsections 3.2.3 to 3.2.6.

Table 3.11 draws these aspects together to provide an overall summary. The '*Engineering Performance Assessment'* report [12] and underpinning references provide further details.

Table 3.11: Summary of the cap resilience assessment

Resilience aspect	Argument	Additional notes and references
Resilience to differential and general settlements	The final cap has been subject to several iterations of cap resilience assessments (reference [39]). have progressively improved and updated the calculations and arguments leading to substantial confidence that the cap, including its low permeability layers, will be resilient to potential general and differential settlements for a prolonged period. Developments since the 2011 ESC that contribute to this confidence include the following. • The addition of 1 m of profile fill since the 2011 ESC to help distribute strains, plus the decision to use granular profile fill over the vaults, which provides better strain distribution than that provided by cohesive materials. (Cohesive materials, including site-won material, have been retained as an appropriate component of trench profile fill.) • The decision to surcharge relevant categories of waste in Vault 8 and Vault 9 and 9a. • The assumption of a move to stronger containers in the future for both LLW, and any ILW to be disposed to the vaults. • Updates to the understanding of the strain tolerance of geomembranes and BES compared to assumptions in the 2011 ESC. • Current and future controls (via Waste Acceptance Criteria or WAC) on available and future voidage for vault disposals.	The calculation approach for the assessment of settlements has also been further developed since the 2011 ESC.

Resilience aspect	Argument	Additional notes and references
External irradiation (isolation of wastes from the environment)	The 3 m-thick cap, combined with the profile fill (2 m or more above almost all the facility wastes) is more than sufficient to reduce external irradiation from the wastes after closure and up to the point of facility disruption. Note that erosion (including thinning) of the cap is addressed below.	External irradiation as a result of facility disruption is considered in reference [14].
Plant, animal and inadvertent human intrusion	The use of bio-intrusion layers, and early planting of the cap surface with appropriate species, is consistent with good practice in minimising the likelihood of intrusions into the key performance layers.	
Material deterioration	Whilst some degradation of materials above the low permeability layers with time is likely, e.g. drainage layers may eventually clog, this will not reduce the overall performance of the cap as a barrier. The use of man-made as well as natural materials will maximise performance for as long as practicable. Material deterioration of the composite barrier will unavoidably occur but the BES will provide a long-term effective barrier even when cation exchanged. There is confidence that materials under the low permeability layers - i.e. the gas collection layer and the profile fill - will remain essentially unchanged and as placed, with minimal clogging, for a prolonged period.	Arguments on material degradation and cap evolution scenarios are further developed in the EPA setting out in additional detail the reasons for confidence in long-term performance (reference [12]).
Deformation	The provision of a stable formation for the low permeability elements and the use of appropriate mixes and formulation for the BES will ensure the BES will not deform during construction and loading, or as a result of subsequent settlements, sufficient to impair its function.	

Resilience aspect	Argument	Additional notes and references
Slope stability and erosion	The use of appropriate layering and construction methods, drainage provisions, and the use of appropriate minimum and maximum gradients and related aspects leads to significant confidence in slope stability over the longer term. These have been underpinned by successive iterations of slope stability assessments including calculations. In addition, the effect of plant roots plays an important role in binding the surface layers together and minimising soil loss through erosion. Analyses in reports such as the EPA [12] provide confidence that plausible future climates will remain consistent with sustaining appropriate surface vegetation. This mitigates the risk of significant loss of the plant zone, and associated erosion of the cap. In addition, the cap will be resilient to plausible seismic events, due to its layer design and low gradients.	Higher gradients are required in very specific locations during the PoA (e.g. near the north-east corner of Vault 8 where a higher slope is required to accommodate drainage arrangements and site access within the site boundary constraints). In these cases specific arrangements will be made to ensure stability (e.g. the use of a temporary retaining wall) which will be remediated prior to closure (see reference [29, 38]).

3.2.8 Installation of the Final Cap

The first strip of the final cap over Vault 8 and the adjacent trenches has been approved for construction. The construction will be underpinned by the approaches to construction quality management and assurance outlined in Subsection 2.6.

An overview of the approach to the installation of this first strip, follows, noting that future strips are likely to be implemented in a very similar manner.

3.2.8.1 Phase 1 and Phase 2 - capping 2024-2036

The planned timeline and sequencing for Phases 1 and 2 of the capping programme are outlined below.

2024 – 2029 Installation of the STIM cap

These works will deliver installation of the STIM cap over the southern portion of the trenches. This will also enable construction planning and flexibility for the final capping programme, as the STIM area will then be available for material storage.

2029 – 2031 Void filling of Vault 8

The voids that exist between the waste packages in Vault 8 will be filled using the specified void fill material. Prior to the filling around the ISO containers stacked six-high, access and retaining measures will be first installed.

Void fill material placement will commence from the edges of the Vault 8 and progress towards the centre of the vault. This outline method is preferred to prevent movement of containers and create a stable platform for subsequent activities.

2030 – 2034 Vault 8 profile fill and vault and trench surcharge

Existing stockpiled material on site will be augmented by imported material to provide the volumes required for profile fill and surcharging. The period of surcharging will be determined by active monitoring.

The excess material from this activity will be used across the works or re-placed in stockpiles.

2033 – 2036 Final cap construction over Vault 8 and the northern trenches

Phase 1 will be complete following placement of the final cap. This includes the planting and seeding of placed topsoil.

3.2.8.2 2040 – 2130 Future Capping Phases

Future capping strips will be constructed using a broadly similar sequence as described above. It is planned to complete strips at variable intervals consistent with waste package receipts.

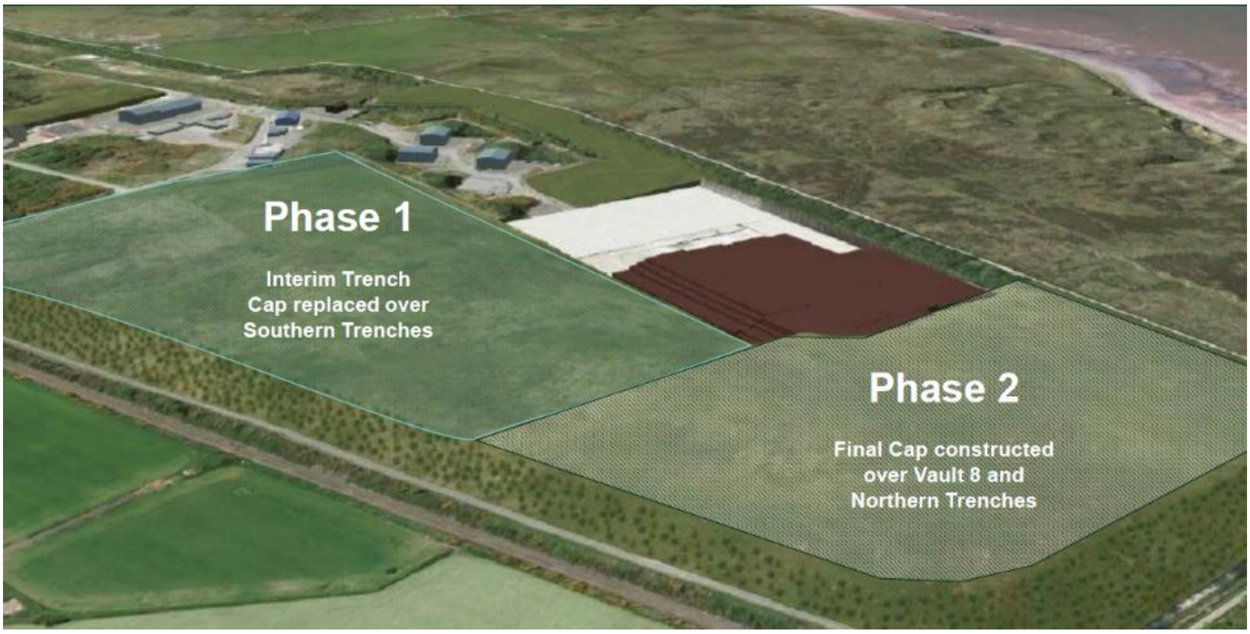

Figure 3.9: **Schematic the Implementation of Southern Trenches Interim Cap (see Subsection 4.3.3) and the First Strip of the Final Cap**

3.2.9 Construction and Long-term Monitoring of the Cap

The following discussion provides an overview of monitoring activities for the cap. Further details are available in references [54, 8, 29]

3.2.9.1 Monitoring during Construction

Observational monitoring will be implemented during construction and surcharging of the northern trenches (see also Section 4) and Vault 8 to provide systematic measurement of surface and sub-surface settlement and deformation, and to support construction-phase decision-making. The monitoring scheme will be designed to confirm expected engineered barrier behaviour under increasing load, to identify the magnitude and rate of settlement, and to determine when movements have sufficiently stabilised to allow progression to subsequent construction stages.

The waste in Vault 8 is containerised so is expected to behave somewhat differently than the trenches. The containers are expected to yield during construction of the cap and the intent is that the monitoring shall be able to identify this. The internal voidage within the containers shall then be expressed and the waste compressed, but the degree of settlement is difficult to predict due to the number of variables. The monitoring in the vault shall initially be limited to a trial area in which three different surcharge depths shall be trialled and the data collected continuously during surcharging and hold periods. A decision shall be made, based on this data, as to the surcharge depth to be adopted in the remainder of the vault. It is important therefore, to be able to relate the subsurface settlements to the corresponding depth of surcharge.

The monitoring system will comprise surface deformation monitoring using periodic topographical surveys (including Unmanned Aerial Vehicle photogrammetry, total station, laser scanning and GNSS[27]) and sub-surface deformation monitoring using LT-Inclibus[28] inclinometers, with rod settlement systems providing validation and redundancy. Sub-surface monitoring will be focussed on the existing trench cap, the container stacks within the Vault 8 trial area, and the vault base and walls, to capture differential settlement and deformation associated with staged profile fill and surcharging.

Monitoring data will be collected at defined frequencies during profile fill placement, staged surcharging and prescribed hold periods, with survey results and automatically logged data reviewed at regular intervals. The data will be assessed to determine settlement rates, trends and whether movements are continuing or have effectively arrested. These assessments will inform decisions on the duration of surcharging, the appropriate surcharge depth to be adopted across Vault 8, and the timing of construction of the final cap.

Once the surcharge material has been applied over the trenches and Vault 8, monitoring stations will be established to measure vertical settlement relative to a stable base station. These stations will track changes in elevation over time, and the data will be analysed until settlement rates have stabilised to acceptable levels. The activity will be deemed complete when there is enough confidence in the data that the materials are sufficiently compressed (consolidated) whereby excessive strains to the final cap will be as low as reasonably practicable.

Monitoring data will be reviewed by the Engineering Review Panel, which will be responsible for interpreting results in the context of construction activities and for determining whether it is appropriate to proceed, extend hold periods, or implement additional controls. The observational monitoring approach will be risk-informed and adaptive, with no fixed alarm thresholds; emphasis will be placed on trend analysis, correlation with construction sequencing, and professional engineering judgement.

The observational monitoring programme will be focussed on the construction and pre-cap phases and is not intended to provide long-term post-closure performance monitoring. LT-Inclibus instrumentation will be largely sacrificial, reflecting its role in capturing critical construction-phase behaviour. Upon completion of cap construction, the monitoring results will provide a baseline for subsequent long-term monitoring undertaken as part of the operational environmental monitoring programme.

Leachate monitoring will continue during capping, including evaluating any response to capping works such as changes to leachate levels, and using logger systems to monitor any leachate releases from wastes as a response to loading.

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[27] GNSS is a global satellite-based system that provides precise positioning, navigation, and timing information anywhere on Earth.

[28] The LT-Inclibus is an In-Place Inclinometer system designed by Sisgeo, Italy, for high-accuracy monitoring of geotechnical structures.

An initial minimum monitoring period of six months is proposed, which may be extended or curtailed depending on the observed settlement behaviour. Data collected from the earliest areas of trench capping, particularly those adjacent to Vault 8, will be of significant value in refining the design and planning of future capping works. This approach ensures that design uncertainties are progressively reduced through site-specific observations, enhancing the resilience and performance of the final cap system.

3.2.9.2 Monitoring after construction during the PoA and Active Institutional Control phases

There will be an agreed system of regular visual inspections, monitoring and reporting of the cap through the operational period and the subsequent active institutional control period. This is expected to include walkover inspections and topographic surveys of the cap at regular intervals by suitably experienced personnel, to identify any significant change. The walkovers will be used to check the condition of the cap generally and adjust the survey monitoring to suit if necessary. If any concerns are noted, remedial works will be implemented.

Settlement monitoring of the final cap will continue through the operational and following active institutional control phases. The post-construction settlement monitoring regime will be similar to that during the construction stages, but much reduced. Following the surcharging activity during the construction phase, anticipated settlement rates will be very low, and the primary value in such monitoring is to confirm slow rates of change, consistent with expectations. Survey monitoring will be of a higher frequency in the early years when the probability of change is greatest, and will then be reduced with time. Frequencies will be reviewed as a part of each inspection. A long-term records management approach will be used to ensure long-term trends can be observed. and any areas of concern or remedial works are logged for future generations.

A further planned component of the long-term monitoring of the cap, commencing with the first strip and planned to be carried out throughout the operational period as a minimum, concerns the use of specific approaches to progressively evaluate the performance of the geomembrane. This is defined in reference [8] on the basis of understanding developed in the EPA [12]. Specifically, the EPA notes that the literature provides confidence in much longer-term geomembrane performance, compared to other applications and locations, than previously assessed. This applies for geomembranes within composite systems implemented in low temperature and low stress and strain situations, such as those associated with the LLWR final cap. The literature is clear that the key control on geomembrane longevity is the activation energy for geomembrane anti-oxidant depletion. This cannot be directly inferred from qualities typically quoted in geomembrane specifications from manufacturers. Also, the activation energy can be influenced by environment-specific aspects such as water composition.

On that basis, options for long-term monitoring are under consideration. The BAT process identified a preference for long-term monitoring of the geomembrane performance and for testing membrane samples as part of the selection process prior to installation [50]. This would help develop understanding of the performance of the cap in 'as-implemented' conditions. It is anticipated that samples of the geomembrane, for example from an area of the cap outside the cut-off wall tie-in, will periodically be retrieved and tested to infer changes in activation energy. As for settlement monitoring, given the expectation that the geomembrane will perform into the longer term, this is expected to be confirmatory monitoring showing no or very low rates of change. Data would need to be analysed carefully to mitigate the potential implications of false positives or negatives. However, this approach, if carefully implemented, would provide for a method of testing EPA assumptions over time that would not be available via other approaches. These options will be considered further as part of the capping project.

3.3 Cut-off Wall

3.3.1 Introduction and Requirements

Table 3.12 provides a summary of the design status of the cut-off wall.

Table 3.12: Cut-off wall design summary

Category	Summary
Main functions	Preferentially direct any leachate that arises (e.g. during cap degradation) to deeper, rather than shallower, systems, working with the cap and the below-vault drainage. Minimise water flows into the facility, including the wastes and the drainage blankets to be installed below future vault bases. During the PoA, the existing cut-off wall will also continue to reduce flows and thus contaminant releases from the east side of the trenches into surface domains including the railway drain.
Design status	Already constructed (alongside the eastern edge of the trenches); approved for construction (for the first strip of the cap); mature design (for the remainer).
Design and optimisation history	Already implemented along the trenches. The remainder has been subject to many iterations of design, optimisation and review, informed by monitoring of the existing installation. The current design for the remainder of the cut-off wall is very similar to the existing section which has been shown to be operating effectively.
Implementation schedule	The cut-off wall along the eastern side of the trenches is already in place. The next part of the cut-off wall will be installed consistent with the first strip of the cap will be implemented in the coming years. Further strips of the cap,

Category	Summary
	and associated sections of the cut-off wall, will be progressively implemented until after disposals cease, around 2130.
Key sections of Optimisation and EPA reports	*'Optimisation and Site Development Plan'* [9]: Section 5.2 and Subsection 5.4.3; '*Engineering Performance Assessment'* [12]: Section 3 and Subsection 5.6.
Relevant RMS entries	See Subsections 5.12 and 6.12 of reference [37]
Additional key references for design, optimisation, and materials	References [55] [29] [56] [44] [27]
Priorities for ongoing optimisation and design	No significant further optimisation of the cut-off wall design is expected.

The main roles of the final cut-off wall, when completed, are as follows:

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

These supplement the roles of the existing cut-off wall (see also the discussion in Subsection 4.3.1) which is in place to help limit releases of contaminated waters from the trenches to domains such as the railway drain.

To achieve these long-term functions the existing cut-off wall, which runs alongside the north and east sides of the trenches, will be extended during the closure process. The existing cut-off wall is 1 m wide and extends approximately 7 to 9 m deep, into underlying clays. The proposed extension to the cut-off wall will also be 1 m wide. It will be a cement-bentonite slurry wall of similar mix to the section of the cut-off wall already in existence. In specific, limited areas where the depth of the cut-off wall installation overlaps with underlying bedrock, the rock will be grouted. The cut-off wall will be constructed as part of the strip capping schedule. Due to the edge gradients of the cap and the position of the low permeability layers, the cut-off wall will typically be set in several metres from the perimeter, with the exact distance from the perimeter varying depending upon local gradients and land form.

Cut-off walls are implemented in many contexts and the cut-off wall proposed is not complex and will be constructed using standard construction methods (a trench filled with a cement-bentonite slurry). The existing cut-off wall was successfully implemented and achieved an appropriate permeability on post-implementation sampling and testing. Its performance has been confirmed by inspections and monitoring since its installation. Therefore, there is high confidence in the constructability and as-installed performance of the remainder of the cut-off wall.

To deliver its intended functions, the cut-off wall needs to provide a permeability contrast with the surrounding geology. There is confidence that this will be maintained for a prolonged period, for reasons including the following.

- The surrounding geology is typically several orders of magnitude more permeable than the anticipated properties of the cut-off wall.
- The cut-off wall is located in a comparatively benign chemical environment and in a lower flow area under the cap. The cement-bentonite mix is expected to be stable and will be confined by the geology on either side and is unlikely to move or evolve significantly, with only limited wash-out with time. Cation exchange of the BES is expected, with a slow evolution from Na- to Ca-bentonite, but even with full cation exchange, the resulting permeability will still be low.

For the 2011 ESC, hydrogeological modelling (see reference [57] and supporting references) confirmed that there would be no benefit in the future cut-off wall extending vertically to depths more than 2 m below the vault bases. This depth is sufficient to protect the trench and vault wastes and the drainage blankets from inflows, and to direct any leachate to the underlying geology and away from surface systems. Because of this, deeper installations, apart from potential local adjustments to minimise inflows from engineering facilities e.g. from the MHT, were considered to offer negligible additional benefit.

The cut-off wall will be integrated with the low permeability layers of the cap to maximise hydrogeological performance. While this remains the baseline design, ongoing options studies for gas venting (see Subsection 3.2.6) may also consider options including allowing gas to be vented over the cut-off wall via approaches such as specific engineered features like pipes, or via gaps in the tie-in, for future strips of the cap.

3.3.2 Optimised Design

3.3.2.1 Overview

The design of the cut-off wall is presented in reference [55]. The current design remains the same as documented in the 2011 ESC, with minor updates consistent with minor changes to the cap geometry.

- Thickness 1000 mm.
- Hydraulic conductivity $\leq 10^{-9}$ m s^{-1} (at one year).
- Top: at existing ground level (varies, 14 – 22 m OD) fully sealed into cap.
- Base: 2 m below underside of liner (BES) for each vault lowest 7.5 m OD (cut-off wall toe at 11.7 m OD proposed around Vault 8).

Depth: typical 10 m, maximum 15 m.

Length: approximately 2.5 km.

The cut-off wall will be formed from a cement-bentonite slurry, with some granulated blast furnace slag (GGBFS) as a cement replacement. This mix is generally considered to provide the best balance of strength and low permeability for such walls. Detailed design of the mix will provide best available durability and constructability, but it is expected to be similar to that used for the cut-off wall constructed by the trenches (see Subsection 4.3.2), for which the design mix comprised 32 kg Cement (3%), 45 kg Bentonite (4%), 128 kg GGBFS, cement replacement (10%) and 1000 kg water [58].

3.3.2.2 Construction

Construction details are set out on drawings RD 289 and RD 290 [44, 56]. Industry-standard specification and installation procedures are described in references [29, 55].

Construction methods include excavating and placing the wall in suitably sized panels, and the use of guidewalls to minimise overbreak. Control of construction tolerances to ensure vertical installation and provisions for the construction of suitable joints are of particular importance.

3.3.2.3 Performance

The cut-off wall performance will be subject to validation monitoring post-construction with sampling of the wall and testing to confirm the required permeability has been achieved. In the longer-term monitoring either side of the cut-off wall will be used to assess water levels inside and outside the cut-off wall to match the various installations, as shown on Figure 3.10. This will require the installation of new monitoring boreholes as part of the extension of the cut-off wall.

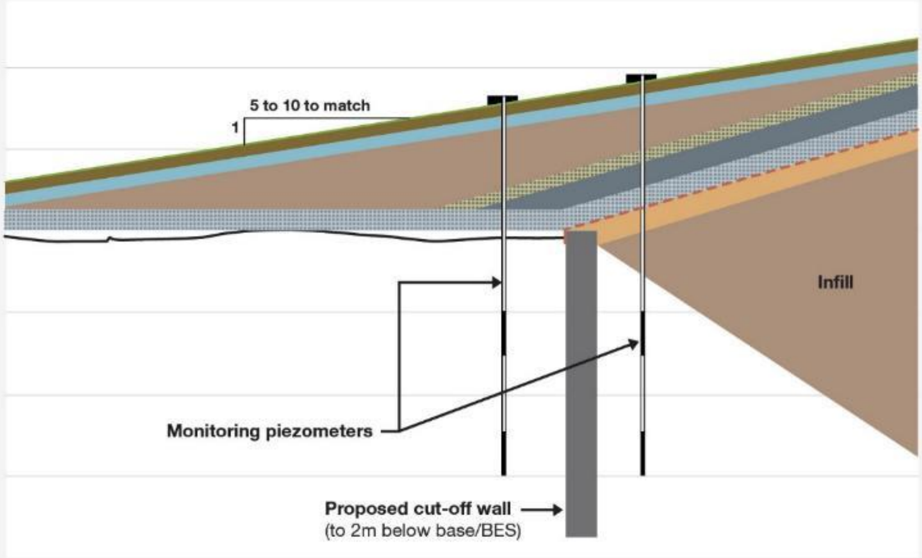

Figure 3.10: Cut-off wall planned performance monitoring – section

4 Design of the Trenches

4.1 Overview

This section gives a description of the trenches and their associated engineering. This includes the design functions and methods of construction of the interim trench cap, drainage systems, and other associated engineered components. It also addresses the wasteform and implications for engineering performance, and performance monitoring and interpretation. The design status of the trenches is first summarised in Table 4.1.

Table 4.1: Trenches design summary

Category	Summary
Main functions	To contain and control legacy loose tipped disposals. Hydrological management to reduce infiltration and to minimise lateral flows to other surface features, working with the cut-off wall.
Design status	Already constructed (trenches and disposals). STIM cap upgrade is currently being constructed.
Design and optimisation history	Designed, built and operated from the late 1950s until 1995, including placement of the trench cut-off wall and the initial interim trench cap. Since 2012, several iterations of monitoring, assessment, optimisation and design leading to the replacement trench cap that is currently being implemented.
Implementation schedule	Replacement trench cap is currently being implemented. Trench surcharge will be implemented consistent with final capping.
Key sections of Optimisation and EPA reports	*'Optimisation and Site Development Plan'* [9]: Section 6; '*Engineering Performance Assessment'* [12]: Section 3, and Subsections 5.3 to 5.5.
Relevant RMS entries	Not part of the RMS given their legacy facility status.
Additional key references for design, optimisation, and materials	References [59] [27] [60] [61]
Priorities for ongoing optimisation and design	No significant further optimisation of the design is expected.

The trench wastes were loose tipped into seven trenches of differing depths and sizes (see Figure 4.1 for an approximate plan view). They were constructed and filled in sequence from 1959 to 1995 and have now been closed for many years. The trenches range from about 3.5 to 6.5 m in terms of the thickness (depth) of waste as disposed, with side slopes typically at 1 in 1. The bases typically had a fall to the south of around 1 in 500.

Most of the trenches were excavated into clay and those that were not (Trenches 5, 6 and 7) had bentonite rotavated into their bases.

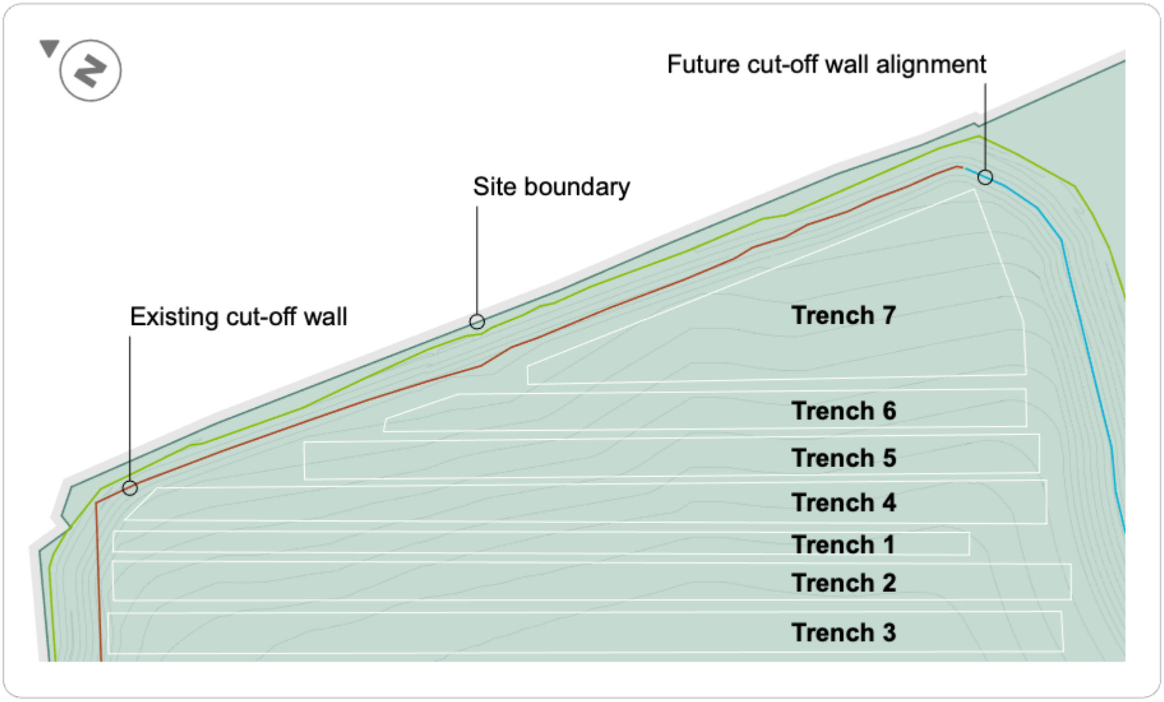

Figure 4.1: Trenches - schematic plan

As legacy facilities the trenches have been documented in detail in previous reports, notably in the 2002 PCSC [40] and the 2011 ESC [20]. References [62] and [63] provide key details.

Around 800,000 m^3 of waste was disposed to the trenches, now occupying a volume of around 450,000 to 500,000 m^3 in situ (including daily cover). The reduction is a result of processes such as degradation and both deliberate compaction and compaction under self-weight (see also reference [4]).

A plan of the trenches is shown in Figure 4.1. Figure 4.2 shows example photographs of tumble-tipped wastes being disposed to the trenches. A typical section through the trenches is shown in Figure 4.3.

Figure 4.2: Examples of Trench Disposals

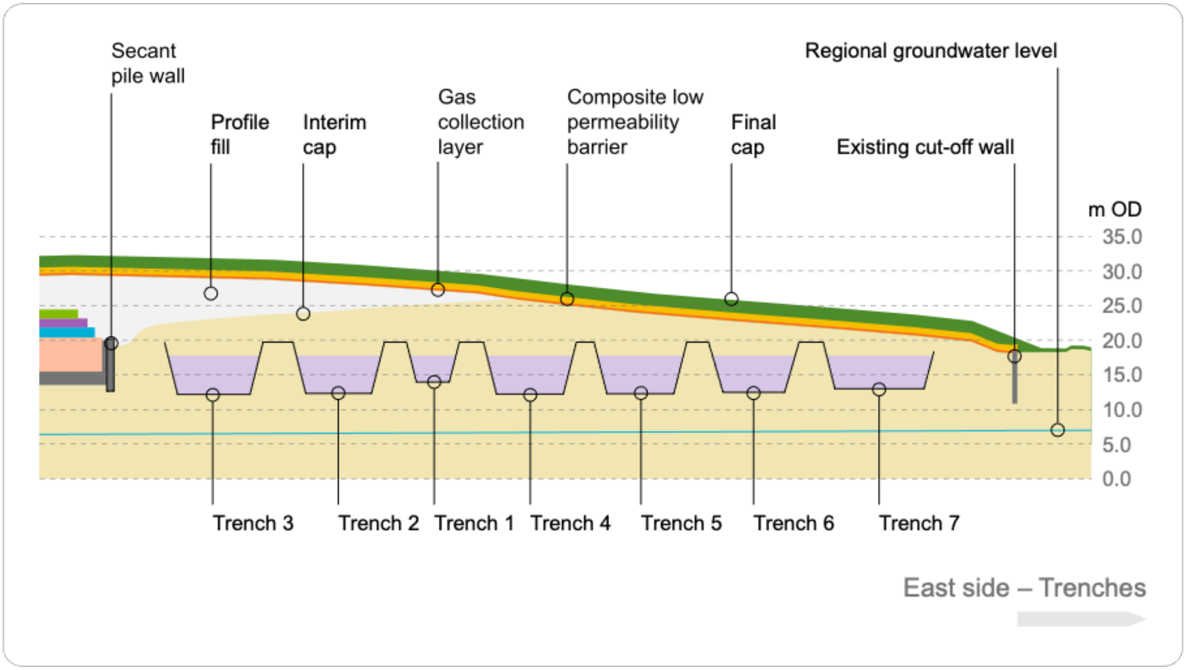

Figure 4.3: Trenches - schematic cross section (Note: Vertical scale exaggerated for clarity)

The cross section shows the top of waste, as at the time of disposal (i.e. prior to any settlement) for each trench. The final cap will quite closely follow the existing interim trench cap over the eastern part of the trenches. It will then continue to the west with increased profile fill – see Subsection 3.2 for details of this and the planned final cap generally.

4.2 Wastes and Wasteforms

The trenches were mostly filled from north to south. The wastes were untreated and generally loose tipped. There was routine daily cover using local materials excavated from the trenches, which were variable but typically sandy clays. The wastes included a wide range of materials, including metals, rubble, cellulosics, soils, plastics, wood and other materials. Full details of the inventory are provided in reference [4].

Fire breaks were installed in Trenches 2 to 5 and 6 (part only) at intervals. These varied but were typically 1 m nominal thickness and made of the same materials as the daily cover. In Trench 7, a concrete wall was installed, running north to south and dividing the trench into 7A to the west and 7B to the east.

The surfaces of the trenches [58] were completed with soil (from on-site) to cover the waste; a geotextile sheet; a layer of large stone (of the order of 100 to 150 mm), then some gravel or quarry waste to finish the surface.

4.3 Engineering Features

4.3.1 Trench Monitoring

The trenches are subject to operational monitoring, for which details are provided in reference [8].

There are also end-of-trench drains although a proportion of infiltrating waters are not intercepted by these drains as the trench bases are not fully impermeable. Probe holes have been inserted through the interim cap to monitor evolved gases and are also used to monitor water levels.

The trenches' leachate drainage is described as perforated spine drains [58]. There is a general fall from north to south. The drains lead to collection sumps. These historically discharged to Drigg Stream, but the system was refurbished in 1991, since when they have discharged to the MHT drainage system (see Section 2.1). Leachate from the trenches is routinely monitored and assessed (see reference [8]).

Leachate temperature and levels are important in providing information on the hydrology of the trenches and in understanding the potential influence of rainfall. Leachate temperature and level measurements are collected by automatic data loggers or through manual measurements with a dip tape. Automatic data loggers are installed in all trench cap probe holes that consistently contain more than 0.35 m of leachate.

During 2023 and 2024, 31 of the 83 trench cap probe holes were permanently decommissioned in preparation for construction of the final cap. These locations are no longer available for level and temperature monitoring.

During the profile and surcharging phase the monitoring infrastructure will be extended to the upper surface of the profile fill and covered over with a protective concrete ring and steel plate at this point, with data logging equipment for leachate/groundwater monitoring installed and connected up to a logger network for remote monitoring during the profile fill surcharging stage. It is recognised that some monitoring will need to be suspended for at least 6 months during the surcharging phase, which may extend beyond this timescale on some areas of the trenches. To supplement the above, selected monitoring infrastructure locations will have sacrificial loggers installed at or around existing trench cap surface ground level. The sacrificial logger network shall provide additional leachate data to supplement the monitoring information required during the surcharging phase.

Each quarter, the measured methane concentrations and flow rates at each of the venting and sealed probe holes are used to assess the extent of landfill gas generation across the trench disposal area. During the 2024/25 reporting period, four of the eleven sealed probe holes recorded methane levels above the lower explosive limit (LEL) (5% by volume of air), with one of these locations consistently above this LEL. In each instance the flow rate of gas at these locations was very low, therefore, any methane present would be quickly dispersed upon leaving the probe holes. As a result, the risk of ignition at locations where methane is present is considered negligible. Elevated concentrations of methane were also recorded in several unsealed probe holes. The recorded concentrations fluctuated across the monitoring period and do not appear to indicate a change in landfill gas generation in these areas.

Landfill gas migration is monitored at eighteen locations (perimeter wells) around the perimeter of the LLWR and in eighteen on-site buildings.

Minimising the number of penetrations through the final cap is considered to be an important consideration in ensuring the cap continues to perform as required. As such continued use of reduced number of probe holes is considered to be the BAT option [64] . Four probe holes in Trenches 1-6 and five in Trench 7 will be retained and extended through the final cap. The selected probe holes wells identified will give spatial coverage along the length of each trench. Figure 4.4 shows the proposed changes to the monitoring probe holes.

In addition, selected monitoring infrastructure locations will have sacrificial loggers installed at or around the existing trench cap surface ground level. The sacrificial logger network will provide additional leachate data to supplement the monitoring information required during the surcharging phase.

The gas composition at the trench perimeter wells was within normal atmospheric concentration limits throughout the monitoring year and, thus, did not display any evidence of landfill gas migration. In landfill gas building surveys, no landfill gases were detected at levels significantly above atmospheric background concentrations.

Further details of monitoring arrangements for the trenches are provided in reference [8].

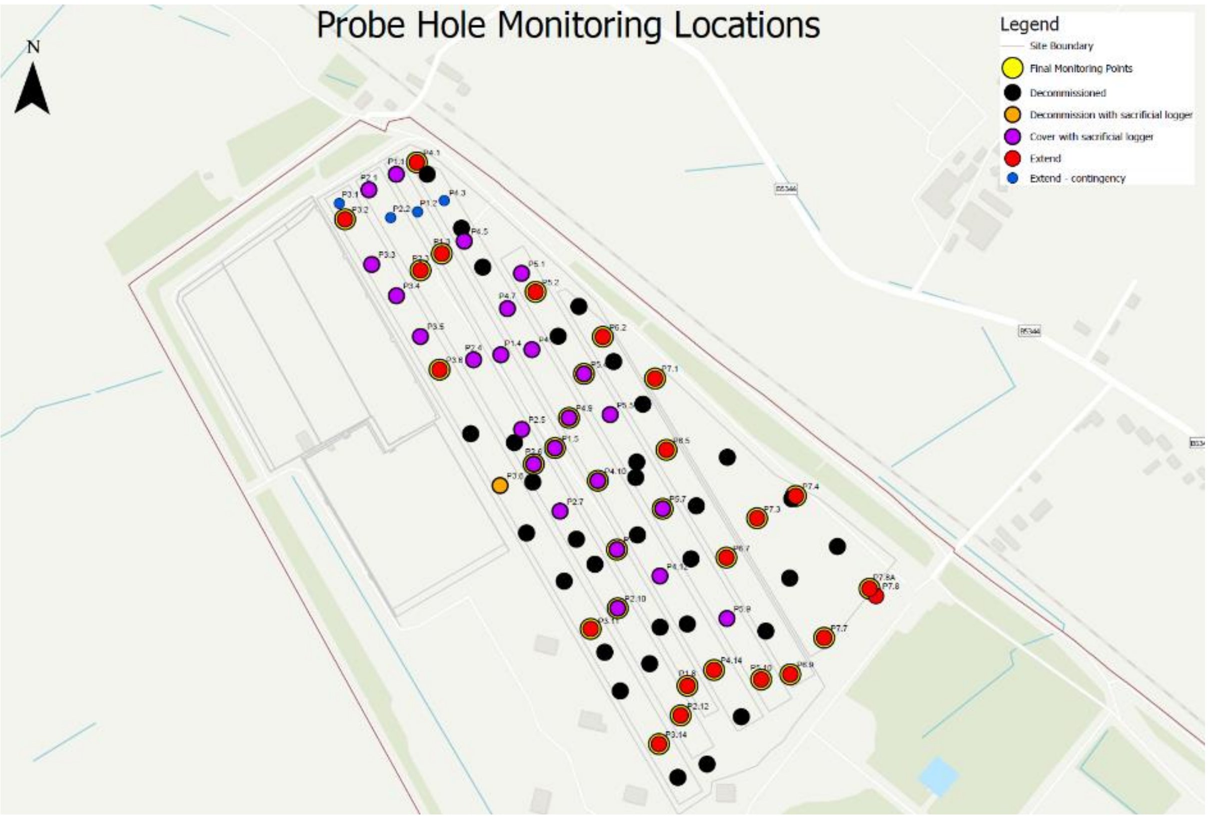

Figure 4.4: Proposed changes to trench probe holes

4.3.2 Existing Cut-off Wall

The cut-off wall around the north and east of Trenches 1 to 6 is 1 m wide, 450 m in length and 9 m deep (range 7.3 to 9.4 m) [58], with the depth being defined as 'taken at least 2 m into clays'. It was constructed from June to September 1988.

It was specified to have a minimum hydraulic conductivity of 10^{-8} m s^{-1} at 28 days and 10^{-9} m s^{-1} at 1 year. This was verified at the time of construction by permeability tests during construction, with values of approximately 10^{-8} m s^{-1} reported. The reported design mix comprised of 32 kg Cement (3%), 45 kg Bentonite (4%), 128 kg GGBFS Cement replacement (10%) to 1000 kg water (Appendix B of reference [58]).

The cut-off wall was extended along the eastern side of Trench 7 in 1995. Details are understood to be similar to the cut-off wall for Trenches 1 to 6, although there is no formal report. This comprised a further length of approximately 350 m length, making a total of some 800 m.

The opportunity was taken to inspect the areas of the top of the trench cut-off wall exposed during the 2010 trench cap perimeter drainage work [65], when the cut-off wall appeared in good condition and intact beneath the surface. However, there was weathering and desiccation of the slurry material in the near-surface environment. Some of this was clearly overspill around the top of the wall. It was not evident whether the top of the wall itself was affected. It is reported that that 1 m concrete cover was provided to protect the cut-off wall from desiccation [58], but this was not found in the locations accessed.

4.3.3 Trench Hydrological Management

4.3.3.1 Original Interim Cap

The interim cap and cut-off wall for Trenches 1 to 6 were constructed from September 1988 to August 1989. The details of the interim cap are described in reference [58] and include:

- 450,000 m^3 of fill over 14 ha, average of 3.2 m thickness.
- Minimum of 450 mm soil cover, typically around 1 m.
- 1:25 graded earth mound, mostly sandy clay.
- Geomembrane; Blackline low-density polyethylene at about 1 m depth, 0.375 mm thick.
- Joints were ‘welded’ by heat fusion, subject to inspections.

The interim cap was extended for Trench 7 after trench closure in 1995. Details are similar to those for Trenches 1 to 6, with the profile suitably extended to its present layout. This has been confirmed by subsequent excavations and monitoring (see e.g. reference [66]).

Figure 4.5, taken in 1988, shows progress on the capping of Trenches 1 to 6 at the time. It can also be seen that disposals both to Vault 8 and Trench 7 are progressing simultaneously.

Figure 4.5: Site status in Autumn 1988

4.3.3.2 Subsequent Performance and Implications

After the 2011 ESC was submitted, it was recognised that water balance data indicated that the interim cap over the LLWR trenches was not performing as intended. As a result, a larger fraction of precipitation than originally expected was entering the trenches (see, for example, references [59, 67]). It was initially assumed that the observed deficiencies in hydrological performance of the cap were primarily related to issues with the perforations in the trench cap associated with the trench cap probe holes. Two phases of excavation and survey, however, revealed that the interim cap membrane was damaged in several areas (resulting from installation errors during construction) and this damage was extensive, including substantial membrane tears, gaps and areas of wrinkling.

This information on the condition of the membrane was considered by successive BAT studies, with the most recent being that undertaken for the RD programme [27, 66, 61].

It was concluded that contaminant releases from the trenches are unlikely to lead to radiological impacts to humans above relevant criteria because groundwater is not expected to be extracted for drinking water in the vicinity of the LLWR. Nevertheless, tritium had been identified in groundwater between the facility and the coast [66]. In addition, other radiological and non-radiological contaminants are also influenced by the condition of the trench interim cap. Improving the hydrological management of the trenches was therefore recognised as important to reduce further release and migration of contaminants. An agreed core outcome of the studies, therefore, was that action needed to be taken to improve the cap over all of the trenches [61].

4.3.3.3 Design Summary

The design approach identified in response to the study outcomes is as follows (references [27, 66, 61]).

The areas of the trenches adjacent to Vault 8 are scheduled to be capped at the same time as Vault 8. This will provide the required step-change in hydrological protection. As part of this process, placement of profile fill (including fill material used for surcharge) will provide an improvement to hydrological management of the trenches, in advance of the final cap being completed. The material will reduce the overall permeability of material above the existing cap and promote run-off.

It was agreed that it is important not to delay the final cap emplacement, not least as that would also lead to delays for capping of the Vault 8 disposals. Therefore, it was agreed that it would not be logical to place a new membrane in this area prior to implementation of the final cap.

The remaining areas of the trenches will not be subject to final capping in the next few years. A new interim cap will therefore be constructed over these areas of the trenches. At the time of writing, construction of this interim cap is in progress (see Subsection 4.3.3.4).

This cap will be emplaced over the existing membrane so that it is not necessary to excavate down to levels that could lead to interactions with the existing wastes. The existing membrane will however be systematically punctured to ensure predictability of performance, and to ensure slope stability.

A geosynthetic clay liner (GCL) will provide the low permeability element of the design for the upgrade to the existing cap for the southern trenches.

Drainage will be assisted over the cap through the inclusion of a man-made drainage layer above the GCL. The inclusion of this is proportionate given the decades (as opposed to very long-term) of performance required for the interim cap.

An illustration of the layers of the interim cap design identified through the iterative BAT process is provided in Figure 4.6. Further details including optimisation history arguments are provided in references [9] and [59].

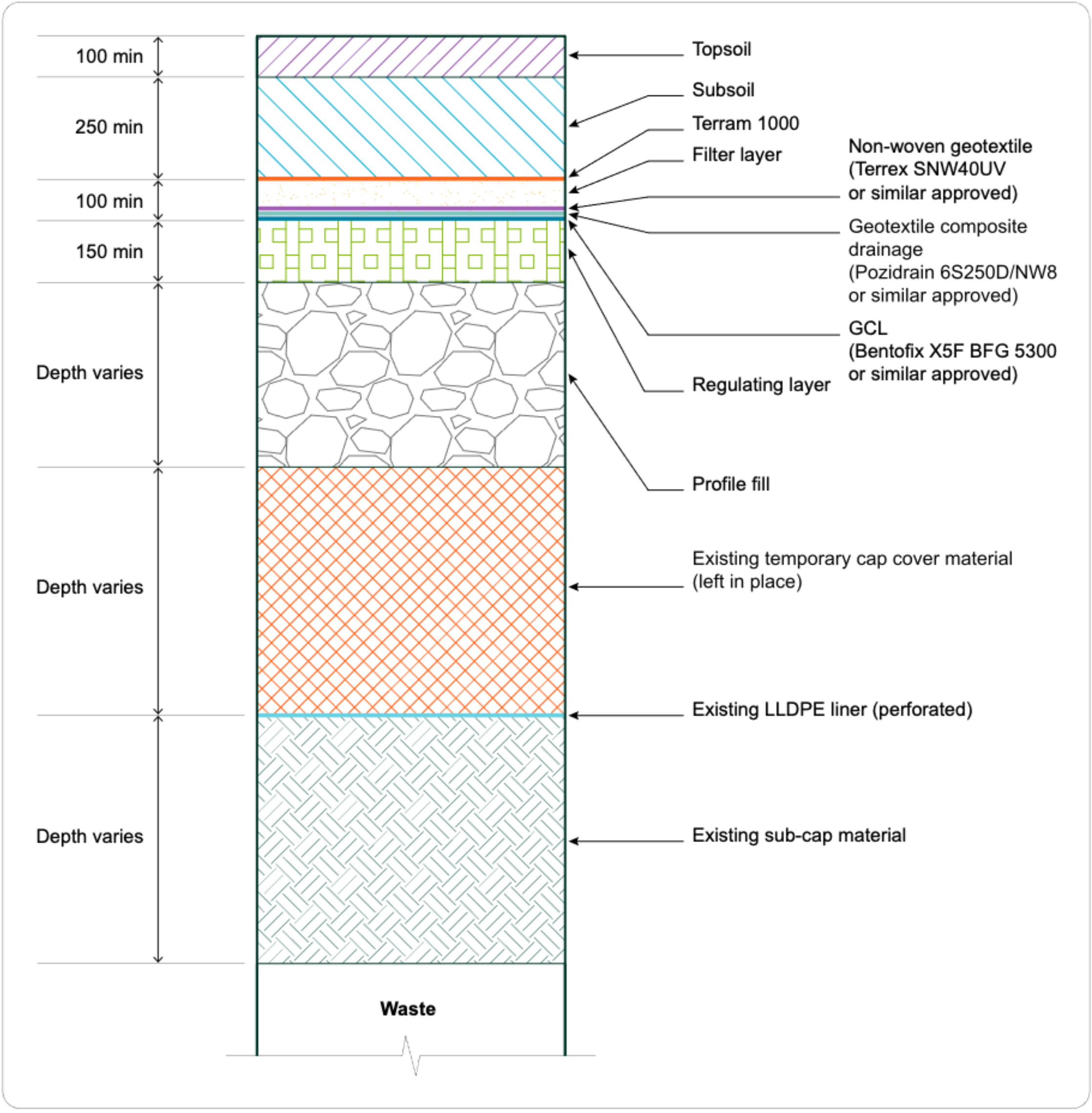

Figure 4.6: Basis of trench cap design. Illustration taken from [59] . Note this is illustrative and the design varies slightly in specific areas (round the stockpile and haul road) but the basic approach illustrated remains.

4.3.3.4 Progress on Implementation

The programme to implement the improved cap over the southern trenches - the STIM project - is currently in progress and will be followed by implementation of the first strip of the final cap including over the northern trenches. Figure 4.7, Figure 4.8 and Figure 4.9 provide an indication of progress, including showing herring-bone drainage implementation to improve the ground conditions prior to undertaking the earthworks, stockpiling of materials, and the implementation of initial panels of the GCL (pictures taken in Spring 2025).

Figure 4.7: Progress on STIM including GCL Panels (site view from south)

Figure 4.8: Progress on STIM including GCL Panels (focussed view from south-west)

Figure 4.9: Example of Progress on STIM Supporting Works: Stockpile D

4.3.3.5 Monitoring Arrangements

The original trench cap included segregated perimeter drains allowing monitoring of run-off from separate catchments. The monitoring of trench cap run-off and the wider water balance will be subject to a hiatus in part while the STIM project is ongoing and the first strip of the cap is installed, including surcharge arrangements.

Afterwards, monitoring of trench run-off, using appropriate catchments that take into account the updated trench cap approach, perimeter drains, and monitoring of flows to drains via the cap seal, will resume. This will periodically be interrupted and modified consistent with the construction of future strips of the final cap.

4.4 Surcharge Approach

As part of the implementation of the final cap, the trenches will be surcharged. That is, they will be loaded by material up to an equivalent height of the final cap (references [29, 60]). This is to ensure the expression of any available settlements. This will ensure the final cap is founded on a stable formation, and will also help minimise settlements after completion of the cap. It is possible that settlement will be limited given several decades of waste degradation and compaction since emplacement, but this approach will minimise uncertainty associated with future settlements.

Reference [60] includes an analysis of potential settlements before, during and after surcharge, and implications for the surcharge hold-point period. The timeframe for surcharge is flexible; a minimum 'hold-point' duration of six months has been estimated [60] . If no movements are observed, or if movements have significantly slowed such that they are no longer observable at the end of the six-month period, the surcharge material may be removed at that point. If significant deviations from expectations are observed, the hold-point will be extended as appropriate.

4.5 Final Cap Seal Over the Trenches

The final cap design incorporates a temporary seal that is installed progressively with each strip of the cap. The seal is more complex over the vaults and is therefore discussed (for both trenches and vaults) in Subsection 5.5.

5 Design of the Vaults

5.1 Introduction

Table 5.1 provides an overview of the functions and requirements for the existing and future vaults.

Table 5.1: Existing and Future Vault design summary

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

Category	Summary
Design and optimisation history	Vault 8 was designed and implemented in the late 1980s. The basic vault design has been retained, and further optimised and augmented, since then. The approach to passive leachate management post-closure was optimised for the 2011 ESC. Over the last few years, the closure approach for Vault 8 has been further optimised and taken through detailed design, including requirements for surcharge. The approach to future LLW and any ILW to be disposed has also been subject to optimisation over recent years.
Implementation schedule	Vault 8 will be closed in the coming years. There is the potential for ILW disposals to commence in Vault 9 on similar timeframes. Vault 9a will also be built on a timeframe that allows early closure (via cap sealing) of the first strip of Vault 9 and Vault 9a as a priority. Vault 10 will be constructed on a timeframe sufficient to provide interim warehouse protection for future LLW disposals. There will be concurrent updates to the operational leachate management strategy including a move to a gravity system. Closure of the remainder of Vault 9, and construction and closure of the remaining future vaults, will then occur over the following decades up to the 2130s, consistent with the rates of disposals.
Key sections of optimisation and EPA reports	*'Optimisation and Site Development Plan'* [9]: Section 5; '*Engineering Performance Assessment'* [12]: Section 3; Subsections 5.3 to 5.5; and Subsections 5.7 and 5.8
Relevant RMS entries	See Subsections 5.1 to 5.11, and 6.1 to 6.11, of reference [37]
Additional key references for design, optimisation, and materials	References [68] [69] [28]
Priorities for ongoing optimisation and design	Detailed design of Vault 9a, and then Vault 10, will be required prior to construction. Further optimisation of the approach to strengthened containers in Vaults 9 and 9a, and stacking above current levels in general, together with slab assessments (Vault 9) and slab design and assessment (Vault 9a) will be taken forward. Any updates to the design for Vault 9a will also be reflected in the concept for future vaults.

Category	Summary
	The approach to ILW in Vault 9 and the future vaults (including Vault 9a) will similarly be subject to ongoing optimisation and design.

The vaults provide an engineered system for the disposal of wastes which, to date, have been predominately in HHISOs. The reinforced concrete slabs provide a running surface for placement and disposal of the wastes. The low permeability mineral arrangements underlying the concrete slabs, and the geomembrane (for Vault 9 on), together with equivalent systems in the Vault 9 walls, provide for operational leachate management, working with the concrete elements of those structures.

Leachate is currently managed in Vault 8 and Vault 9 by active pumping to the operational drainage system including the MHT and the marine pipeline, prior to discharge out to sea. As part of the construction of Vault 9a, a move to a gravity-based system is intended, including the construction of a new gravity drain that will accept leachate from the vaults (which is distinct from the long-term, post-closure passive drainage arrangements described below). The operational leachate management system will be progressively decommissioned as the site is closed. Operational leachate management requirements for individual vaults are described in subsequent subsections.

Any infiltration that builds up in the closed vaults, once the cap begins to degrade will be managed via passive drainage features. Waters that overtop the circa 1 m level in the vaults will be discharged via the extensive drainage features in the east and west future vault walls, to the basal drainage blankets underlying the future vault bases. For Vaults 8 and 9, passive drainage features will be back-fitted at around the 1 m level so that any leachate within the vaults above that level will be directed to future vaults, and in turn to their drainage blankets.

The overall aim of the drainage blankets for future vaults is to maximise the interface with the natural drainage capacity provided by underlying geological formations and, together with the cut-off wall, to preferentially direct leachate to deeper systems (i.e., away from the surface). The drainage blankets will be laterally extensive under the vaults but different vault drainage blankets will not be directly connected. This will minimise the possibility of axial flows down the length of the facility. This could, otherwise, lead to enhanced flows of contaminated waters to the south of the site.

Free-draining, inert, low-fines granular void fill material will be emplaced between container stacks wherever the stacks are wide enough accept such material. This will happen before construction of relevant strips of the final cap. The backfill will provide preferential flow-paths for waters around the waste containers, and lateral constraint between the containers stacks.

The remainder of this section describes how this overall approach has been, or will be, implemented for the design of successive vaults.

5.2 Vault 8

5.2.1 Introduction and Requirements

This subsection gives a description of the as-built Vault 8 engineering.

Vault 8 was built in the late 1980s and received its first wastes in 1988. Vault 8 was constructed to provide a step-change in disposal practices compared to trench operations. It was originally intended to receive loose-tipped wastes. Prior to completion of the vault however, the approach changed to focus on wastes disposed within HHISOs. These were backfilled with grout, primarily to fill voids. In addition, smaller numbers of containers of other sizes, including third-height and full-height ISOs, were also accepted, in particular in the early years of operations. Several individual, large disposal items were directly grouted into the vault. WAMAC containers very similar to HHISOs were also accepted. Treated Radwaste Store drums and bagged VLLW wastes have recently been placed in remaining volumes on an opportunistic basis.

Original plans were based on four-high container stacks. Six-high stacks are also present in a section of the vault. The containers above the four-high level were ostensibly placed on a temporary 'storage' basis. Stacking to eight-high ('higher stacking') was not considered in detail until the late 2000s but was assumed during the development of the 2011 ESC; this assumption has since been rescinded (see reference [9]).

The inventory is described in more detail in reference [4], and the containers, their contents and their implications for biogeochemical evolution are described in reference [5]. A brief summary of key engineering features of the wastes follows.

Conditioning and Treatment

The main disposal containers, the HHISOs,[29] were selected to maximise disposal volume whilst minimising handling requirements and operator exposure to the waste.

At Sellafield in particular, super compaction via the WAMAC facility has been used to maximise the efficiency of use of container volume and reduce voids, but this is not the case for all disposals.

On arrival at the LLWR site, the ISO containers are transferred to the grouting facility where voidage within the containers is filled with grout. This facility can handle up to four containers at one time. Each HHISO container contains a grouting port consisting of a removable flange with a baffle arrangement beneath to ensure satisfactory flow of grout around the pucks or other wastes.

The mix design of the grout used to fill the residual voidage was selected to ensure that the grout exhibited [70]:

- a low viscosity and good flow characteristics;

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[29] See Subsection 5.7 for supporting geometrical data on the containers.

- no bleed after 16 hours (that is no free water after grout is set);
- low shrinkage on set (<2%);
- a compressive strength of >150 kN m^{-2} at 48 hours and >400 kN m^{-2} at 90 days;
- a preliminary set within 16 hours to prevent the grout spilling or overflowing the ISO container during movement.

Based on work reported in reference [70], the grout adopted comprises a 3:1 mix of PFA and Ordinary Portland Cement with a super-plasticiser and an initial water to solids ratio of about 0.4.[30] During grouting, the containers are tilted to help ensure that air is able to escape and are returned to the horizontal for the final filling. A diagrammatic illustration of the ISO containers is shown below.

The grout formulation used reflects its main function as void fill. In many containers an effective spanning grout and waste matrix is achieved. For others the grout may primarily provide an annulus around waste items or bagged waste, or for well-packed HHISOs may primarily provide a layer above the wastes. For Vault 8 assessments suggest there are non-trivial levels of inaccessible voidage, considered most likely to be associated with metal disposals [71].

For this reason, the grouted waste matrix cannot be relied on, especially for older disposals, to form a spanning structure within the HHISOs that will help distribute loads away from the container load-bearing elements. Therefore, assessments of the strength of the containers under load have taken no credit for contributions from the grouted waste matrix. Cautiously, such assessments therefore assume that all loads are transferred through the container structures only (e.g. reference [28]).

Figure 5.1 gives a schematic view of a standard ISO container. Figure 5.2 gives a photograph of a HHISO prior to grouting, from a grouting demonstration project [72].

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[30] Work is ongoing to explore potential alternative options for the grout formulation, in particular recognising that the supply of PFA may become limited in the future.

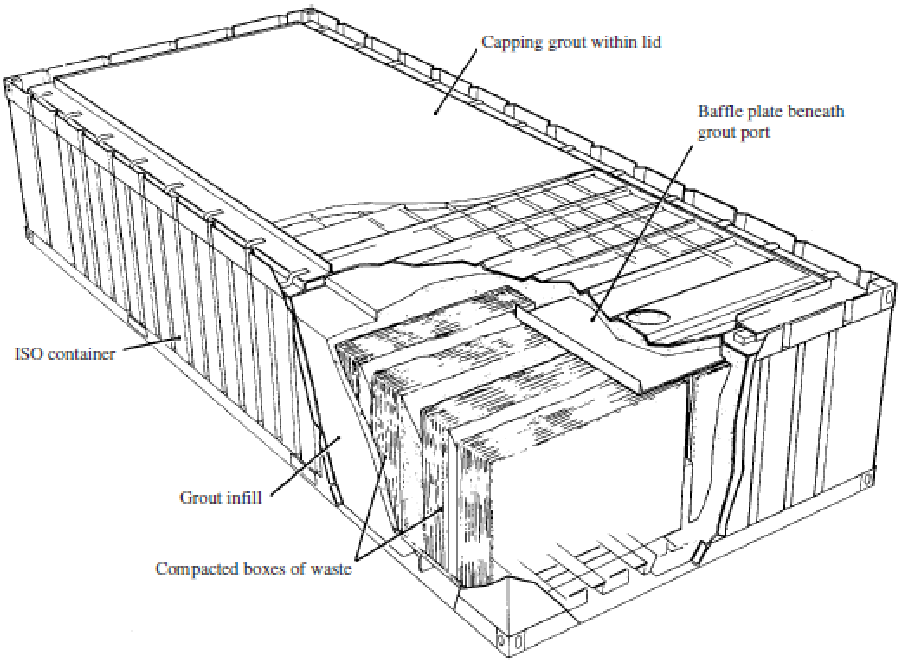

Figure 5.1: View of typical ISO container

Figure 5.2: View of demonstration ISO prior to grouting

The resulting grouted ISO containers (with a maximum filled mass of 42 tonnes) are placed within the vaults using conventional large capacity forklift trucks.

The design of the steel containers is based on ISO standards, but with modifications to the top, base and side panels, made to:

- ensure good grout flow during filling;
- minimise voidage associated with the ISO container structure;
- provide a more uniform load distribution across the base in order to reduce point loads acting on the vault base slab.

Surcharge and higher stacking approach

Higher stacking (e.g., to eight-high) of HHISO containers is no longer planned for existing containers at the LLWR, or for future wastes that are already committed to the existing container design. This is due to the current understanding of container performance - in particular the load-bearing capacity of the vertical corner elements - and the acceptance that the existing HHISOs will be damaged by the loads associated with closure engineering [28].

These containers will instead be surcharged during the closure process to ensure container deformations occur, and available voidage, is expressed prior to cap placement. This will ensure a stable formation for cap construction. Surcharge will lead to some damage to the contribution of the containers to the multi-barrier concept. The sides, bases and walls will remain largely in place due to the constraining effects of other containers and the void fill that will be implemented around the stacks, and so the contribution to containment will be reduced, but not entirely removed.

Voidage

There are several sources of voidage associated with the vault wasteform. These include both voidage that already exists, and voidage that will only occur in the longer term e.g. due to waste degradation. Together these are termed Total Potential Voidage (TPV) and are controlled by WAC. TPV associated with the wastes includes:

- ullage voidage, consisting of voids at the top of the containers, especially around the grouting port-hole, where the containers have been incompletely filled with grout, or the waste and grout has shrunk after filling;
- inaccessible voidage, which the grout has not been able to penetrate, including for example pipes, inner parts of disposed plant, or wrapped items;
- compression voidage, associated with the potential for wastes to compress under load;
- biodegradation voidage, associated with materials such as cellulosics, which will degrade over time, leading to additional voidage.

In addition, there is voidage associated with the structures of the containers themselves.

These sources of voidage will be common across the vaults. However, the older containers in Vault 8, and also older containers that may be disposed in Vault 9 (Subsection 5.3.2.2) are known to be subject to higher levels of TPV than recent and future disposals. Older containers were not subject to the same strict voidage controls as have since been enforced by WAC. As a result, studies including reference [71] demonstrated that TPV in containers in Vault 8 was non-trivial.

Actions were undertaken as a result of this understanding to manage any settlements that may arise with time as a result of expression of voidage. This included the addition of 1 m of profile fill to the vaults, compared to the 2011 ESC design, and confirmation that the vault profile fill will be granular in nature, to maximise the distribution of strains through the profile fill. The later decision to surcharge the Vault 8 containers is also consistent with minimising settlements after cap construction. Together these measures contribute to the high levels of confidence in cap resilience above Vault 8 despite the comparatively high TPV associated with older disposals (see references [12, 39]).

Remaining disposal volume and containers stacked above four-high

A small section at the northern end of Vault 8 remained clear of disposals for many years. This was in part due to the presence of six-high stacks of containers to the south of this area. Access was required as these disposals above the four-high standard stack height were initially classified as 'storage' and thus may have needed to be removed.

Optimisation studies since the last ESC led to the decision that the containers stacked above the four-high level will be retained as disposals, converted from the original storage intent [28]. In addition, as far as practicable, the remaining disposal volume would be used by disposals. It was identified that this should include HHISOs as a priority. It was also identified that bagged VLLW would also be disposed in the remaining volume. At the time of writing, implementation of this approach is nearing completion.

Figure 5.3: **Progress in Vault 8 Remaining Disposal Volume Utilisation Ahead of Final Capping (Photographs capture different stages of work in progress)**

5.2.2 Design

5.2.2.1 Overview

Key details of the design and construction of Vault 8 are elaborated in Subsections 5.2.2.2 to 5.2.2.8. Existing features include:

- the basal liner and slab;
- vault walls; and
- leachate management arrangements including surface and subsurface systems.

In addition, the closure design includes:

- void fill; and
- plans for surcharge of the Vault 8 wastes.

Figure 5.4 to Figure 5.6 provide an overview.

Properties of engineered barriers and their evolution (e.g. permeabilities of the vault bases and walls with time) are reported separately (reference [12]).

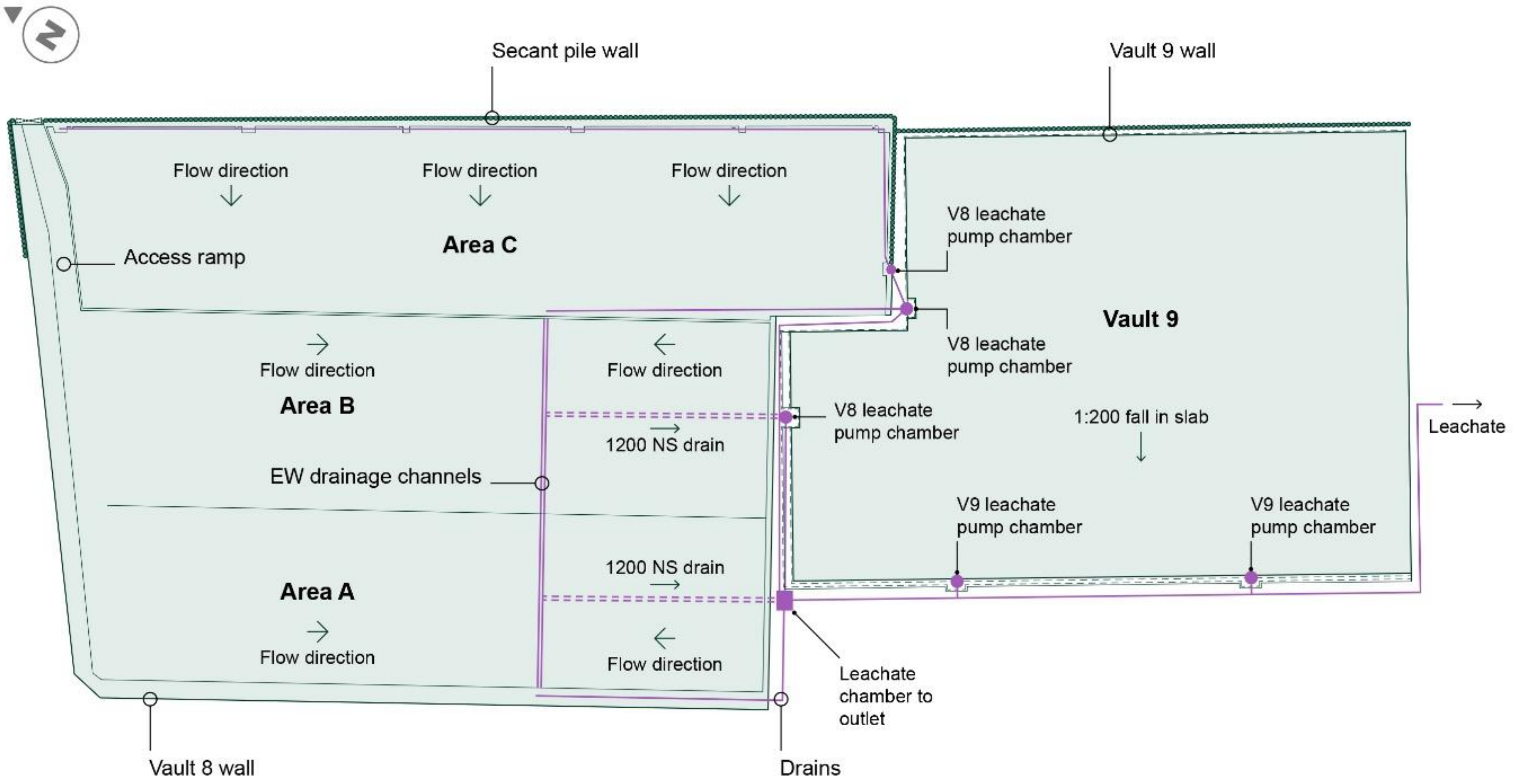

Figure 5.4: Vault 8 and Vault 9 operational drainage details

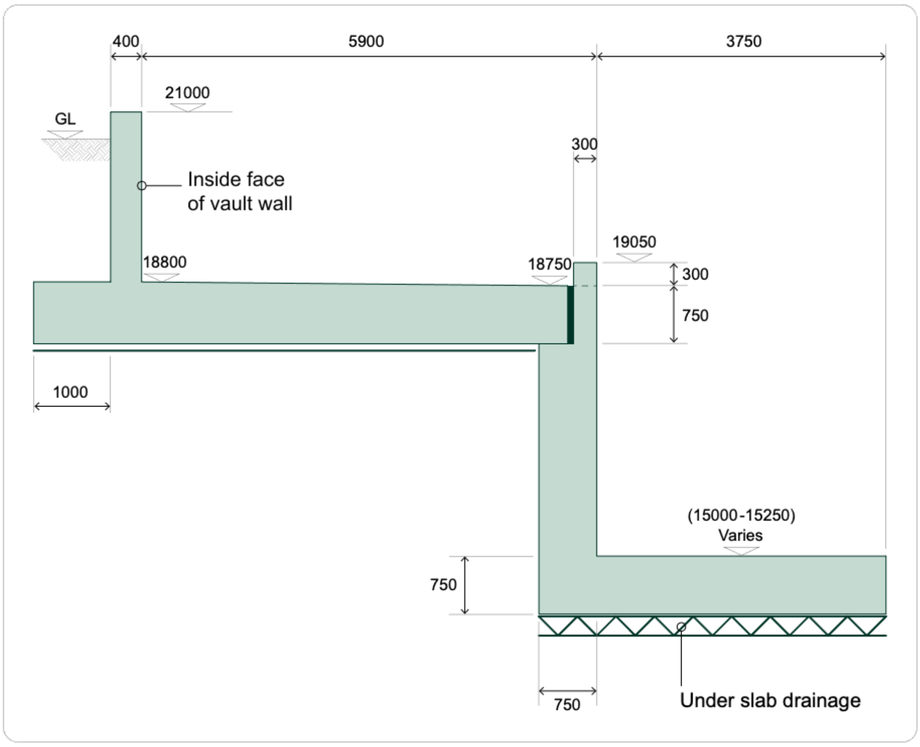

Figure 5.5: Vault 8 typical section, west and north walls and terrace or ‘shelf’.

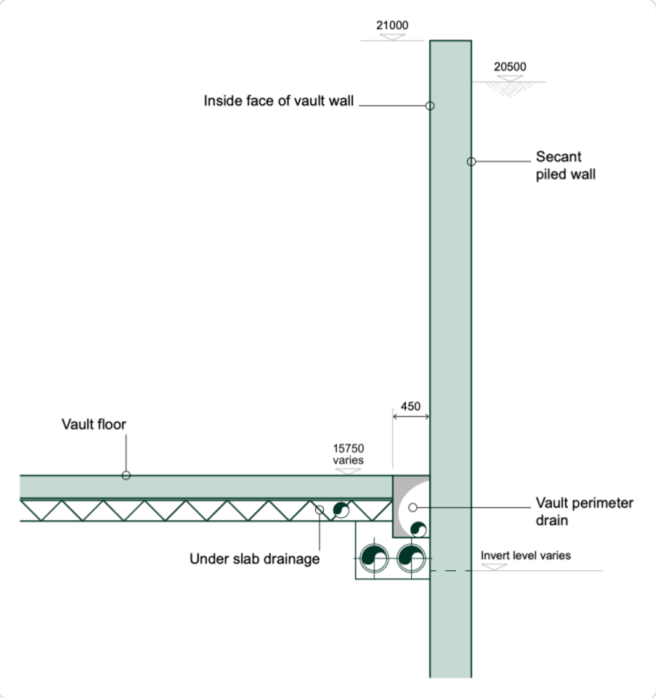

Figure 5.6: Vault 8 – Section through secant pile wall

5.2.2.2 Basal Liner and Slab

The design intent for the Vault 8 reinforced concrete slab was primarily to provide an operational running surface for disposal operations. As it was cast in sections with joints, and it was expected to be subject to some cracking upon loading by disposals, it was never the design intent for the slab alone to provide a waterproof surface for drainage. Rather, this is ensured by the associated low permeability mineral layers. For Vault 8, this function was originally intended to be delivered by the existing underlying clay. However, on construction this was found to be intermittent, and where the clay was missing or otherwise insufficient in quantity or quality, bentonite was mixed in-situ with local soils to form BES prior to slab construction.

Vault 8 was therefore primarily founded on a minimum of 1 m of clay having in situ hydraulic conductivity of 10^{-9} m s^{-1} or less. The BES created in-situ as necessary was specified and tested to achieve in situ hydraulic conductivity of 10^{-10} m s^{-1} or less, and installed to a depth of 300 mm. Reference [58] reports that laboratory tests in 1989 gave hydraulic conductivities of around 6 10^{-11} m s^{-1}.

Four samples of the BES were tested in 2009, taken from two areas at the southern edge of Vault 8 exposed in connection with Vault 9 construction [73]. One area gave two results of around 7 10^{-11} m s^{-1}, suggesting that the BES had maintained its low permeability for over 20 years. The second area gave two results an order of magnitude higher, 4 to 6 10^{-10} m s^{-1}. These may indicate some degradation or alternatively may be due to poorer original construction; the samples were noted to have more coarse material than would now be accepted.

The base slab is of conventional reinforced concrete construction. It was formed in three bays, with the first stage, western bay Area A 250 mm thick. The middle bay, Area B, and eastern bay, Area C, have base slabs 300 mm thick. There are reinforced concrete walls between the bays for operational purposes; these walls are typically 600 mm thick and to the whole height of the vault.

In between the slab and the low permeability clay and BES layer is the under-slab drainage layer of stone and perforated pipes (see Subsection 5.2.2.5).

Finite element analysis (FEA) has been used to assess the slab performance further under closure loads. It confirms that the slab will crack under such conditions but to an extent consistent with the design intent; importantly the BES will remain undamaged [74].

5.2.2.3 Secant Pile Wall

A secant pile wall provides structural support along the eastern side of Vault 8, adjacent to the trenches. Details are shown on Figure 5.6. The secant wall will remain in place long term. It is not relied on to provide an impermeable barrier; indeed, there are leachate drains from Trench 3, though the secant pile wall into chambers within Vault 8.

5.2.2.4 Exterior Walls

The perimeter north and west walls are of reinforced concrete 400 mm thick. Both of these walls have a complex profile, with a terrace (or shelf) stepping out at around mid-height. The arrangement is shown in Figure 5.5; the height of the wall to the terrace is typically around 3.8 m, and the height of the terrace to the top of the outer wall typically around 2.2 m. There is also an access ramp on the northern wall, (see Figure 5.4 and Figure 5.5). The perimeter walls have no impermeable wall liner. There is currently some reported inflow from groundwater which will be addressed by the future cut-off wall.

The internal south wall is of similar reinforced concrete construction except for the secant pile wall section. There is no reinforced concrete wall on the east side, the waste containers being stacked directly adjacent to the secant wall. In past hydrogeological modelling iterations, the Vault 8 walls were not considered to provide any significant barrier to flow.

5.2.2.5 Operational Drainage System

Vault 8 was constructed with both surface and sub-surface drainage systems. The surface base slab drainage system (Figure 5.4) has complex falls of around 1 in 275 and drains to culverts that exit beneath the southern wall of Vault 8 to a collection chamber. The surface drainage also includes drainage collected along the eastern side of Vault 8 adjacent to Trench 3, where seepage occurs through the secant pile wall. A pipeline took leachate under gravity initially to a discharge point into Drigg Stream and then after 1991 to the MHT from where it was discharged to sea via the marine pipeline. During Vault 9 construction, the culverts for the surface drainage were intercepted where they exited Vault 8 and pumps installed in the manhole chambers and the collection chamber removed.

The subsurface drainage system for Vault 8 comprises a 225 mm-thick under-slab drainage layer of stone and includes a grid of perforated collector pipes. Like the overlying base slab, the grid of collector pipes also has complex falls and interconnections but ultimately drain westwards to a 300 mm diameter peripheral collector drain that originally drained to just outside the south-west corner of Vault 8 before draining eastwards along the southern edge of Vault 8 to the collection chamber, which then connected to the gravity drain. During Vault 9 construction the collection chamber was connected to the new pump chamber that was constructed between Vault 8 and Vault 9.

Leachate is currently pumped from this and the three other pump chambers noted above to a gravity pipeline that flows southwards along the western margin of the site to the MHT and then onto the disposal system. In the medium term, the intention is to convert the Vault 8 drainage system back to a gravity flow arrangement as part of the construction of Vault 9a and a new connection with the current Vault 8 drainage system at its south-west corner. Further details can be found in the LLWR Leachate Management Strategy [75].

5.2.2.6 Long-term Passive Drainage

The operational drainage system will have been decommissioned during the PoA, and passive drainage arrangements will have been made to ensure any waters overtopping the 1 m level in Vault 8 are directed into the future vaults, either directly or via Vault 9.

5.2.2.7 Void Filling

The current design assumption is that all voids in the vaults that are wide enough to be effectively filled will have void fill emplaced within them. This is to fill voids for cap stability reasons, and to provide lateral restraints so that stacks (including surcharged stacks) remain vertically aligned, as well as providing drainage pathways between stacks (and between future modules where relevant). The void fill will be granular, free-draining, inert, low-fines material (as specified in the RMS). Void fill and other drainage material throughout the system will have an initial hydraulic conductivity of not less than $1\ 10^{-4}$ ms^{-1}.

5.2.2.8 Surcharge Design

As noted in Subsection 5.2.1 higher stacking of existing and committed LLW is no longer being considered on the basis of updated understanding of container performance under load. On that basis, Vault 8 will be loaded to at least the level of the BES in the final cap (and potentially to the level of the full final cap upper surface level; this will be decided finally following implementation of an initial ‘trial’ area of surcharge). This will ensure a stable formation for the implementation of the final cap low permeability layers.

5.3 Vault 9

5.3.1 General

This section gives a description of the as-built engineering of the existing Vault 9, and proposals for its future use and development.

Vault 9 was constructed between 2008 and 2010. Figure 5.7 gives a view of the completed structure.

Figure 5.7: Vault 9 – view as completed

The design of Vault 9 was developed over many years and involved extensive studies, reviews and optimisation. Design details are summarised in the *Design Justification Report* [76] and are discussed further for particular components below.

The design was undertaken at a time when the site did not have a permit allowing disposals beyond Vault 8. The design therefore has a slightly different focus to the preferred design now identified for future vaults (Subsection 5.4). Moreover, the optimisation process for the 2011 ESC occurred during the later stages of Vault 9 construction, allowing a late decision not to include the membrane and BES liner above 1 m within relevant walls.

A decision was made not to extend the base slab to the west to align with the Vault 8 wall and instead to undertake a two-phase approach with later construction of Vault 9a (Subsection 5.4). This was in part for pragmatic reasons associated with the postponement of work to move the Drigg Stream.

5.3.2 Waste Categories and the Modular Approach

5.3.2.1 Overview

Three different categories of wastes are anticipated to be disposed of in Vault 9. These are listed below. Further details of the waste containers are given in Subsection 5.7.

- Existing and committed LLW, including LLW disposals already present in HHISOs within the vault, and wastes that are already committed to the HHISO approach (as for Vault 8; see Subsection 5.2). These containers are likely to occupy around a third of the vault disposal area.
- Future LLW, for which an updated (stronger HHISO) approach can be implemented.
- ILW that can be managed as LLW. (No ILW that requires additional measures compared to LLW will be disposed in Vault 9.)

5.3.2.2 Existing and Committed LLW

Vault sealing and surcharge

The existing and committed LLW will be subject to early sealing, as an extension of the Vault 8 closure process, and later surcharge (prior to final capping). This will also be applied to relevant strips of Vault 9a. Early sealing will provide early levels of protection equivalent to the final cap.[31]

Stacking of existing and committed LLW

Existing and committed LLW containers, on the basis of container testing undertaken for the Vault 8 programme, will be subject to limited stacking heights for operational safety reasons. Based on physical container testing and FEA together with an appropriate factor of safety (see reference [28] and underpinning references), TC-08 HHISO containers will be stacked to a maximum of five high. The current baseline assumption is therefore for five-high stacking. TC-01 containers are considered to be stronger than TC-08 variants, and future

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[31] The approach to the vault (and trench) seal is described in more detail in Subsection 5.5.

work will explore whether safe operational higher stacking (e.g. to seven-high) can be substantiated.[32]

5.3.2.3 Future LLW

Future LLW will comprise wastes within a strengthened container design. The assumption arising from optimisation work to date is that these will be HHISOs, which will be similar to the current design except for enhancements to the strength of the load-bearing elements. These enhancements will ensure the container is capable of safe operational higher stacking, and will resist closure loads. It is assumed (pending ongoing substantiation work) that these containers will be higher stacked to seven-high within Vault 9 (and indeed the future vaults).

To protect the lids of the uppermost container lids in each stack, reinforced concrete container protection units (CPUs) will be required. These will fix to the existing HHISO twist-lock mechanisms and be capable of placement by a fork-lift (or reach-stacker) as for the HHISOs. They will be around 70 cm[33] thick [28] and thus will add to the stack height. This might have an influence on the extent of higher stacking, due to the need to fit within the disposal envelope that is limited vertically by the requirement for a minimum of 2 m fill material beneath the underside of the cap.

The CPU approach is illustrated in Figure 5.8 below.

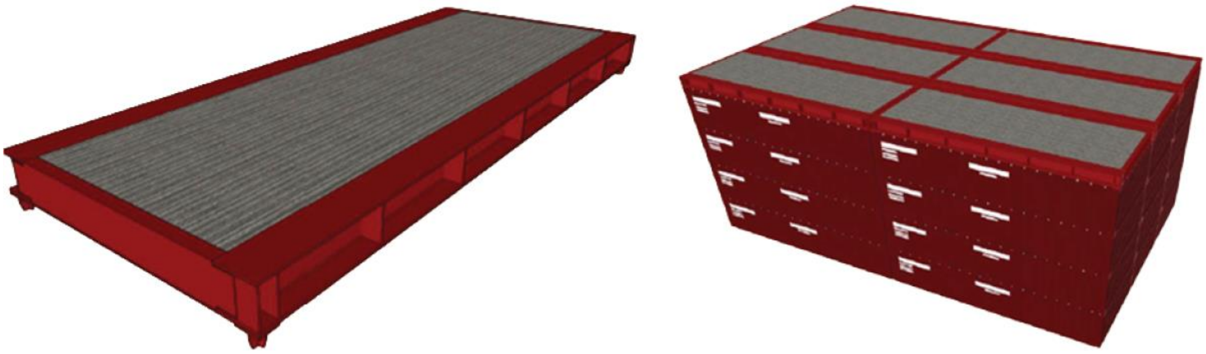

Figure 5.8: Illustration of the CPU approach for Future LLW (see reference [28] and supporting references for details)

5.3.2.4 ILW that can be managed as LLW

If ILW disposal in the vaults is taken forward, it is possible that some ILW that can be managed as LLW will be disposed in strengthened HHISOs, as for future LLW. However, our assumption is that the majority of disposals will be within alternative containers, for transport reasons (e.g. specific activity limits). We have assumed that these containers would be mild steel containers, in many ways similar to HHISOs, except for the size. The strength would be provided by the container framework and in particular the vertical corner elements, and a

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[32] Both categories of containers would still require to be surcharged.

[33] We have assumed 70 cm for the 2026 ESC assessments.

CPU or equivalent would be required at the top of stacks. The size will be determined by transport container requirements, and the baseline assumption is that they would be compatible with Standard Waste Transport Containers (SWTC)s.[34]

We assume that ILW that can be managed as LLW will be emplaced in stacks that are interspersed with standard future LLW stacks, and will approximately match HHISO stack heights (i.e. a maximum height of seven containers, noting that the proposed heights of the containers are close to those for HHISOs).

ILW that cannot be managed as LLW (e.g. wastes that require shielding) will not be disposed in Vault 9.

5.3.2.5 Modular Approach in Vault 9

The use of different approaches for the above waste categories in Vault 9 implies a modular approach for disposals on the same base slab. This will include an ‘existing and committed LLW’ module that is subject to early sealing and later surcharge. The disposals for surcharge will be segregated from areas containing future LLW, and ILW that can be managed as LLW.

5.3.3 Design

5.3.3.1 Overview

Key details of the design and construction of Vault 9 are elaborated in Subsections 5.3.3.2 to 5.3.3.6. Existing features include:

- the double composite basal liner, and slab;
- vault walls; and
- leachate management arrangements.[35]

Any voids that are sufficiently large to be void filled during closure will utilise the approach set out for Vault 8 in Subsection 5.2.2.7.

5.3.3.2 Reinforced Concrete Base Slab

The base slab is of conventional reinforced concrete, 350 mm thick.

The slab was designed to support [77] six-high stacking of LLW grouted in HHISO containers on a bay with an open face against an unloaded area. This is consistent with operational requirements for emplacement. The intention was that higher stacking levels will be achieved by limiting any differentials in elevation to six containers (for example, eight HHISO containers would be placed by operating over stacks of two high).[36] The 2026 ESC assumes this approach for containers that can be higher stacked.

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[34] Note that stainless steel or concrete (i.e. durable) ILW containers will not be permitted in bulk in any of the vaults.

[35] Variations in disposal and closure arrangements for different waste categories are as described in Subsection 5.3.2.

[36] This statement, taken from the 2011 ESC, is currently being reviewed in order to deliver a formal, calculation-underpinned substantiation of higher stacking to eight high. Note that the slab involves some novel features to

The reinforced concrete slab extends about 10 m beyond Vault 9 southern wall to provide an operational area and effective transition zone with Vault 10 to the south. This will be used, managed and incorporated in Vault 10 in due course. It is envisaged that similar provision will be made for future vaults.

The reinforced concrete is not specifically designed to be impermeable but will nonetheless provide a significant barrier at early times, but degrading over time.

5.3.3.3 Vault 9 Base and Walls Composite BES and Geomembrane Liner System

The summary presented below is based on reference [78] which provides details. Figure 5.9 shows the various component layers. The design is more complex than for either Vault 8 or subsequently identified for future vaults.

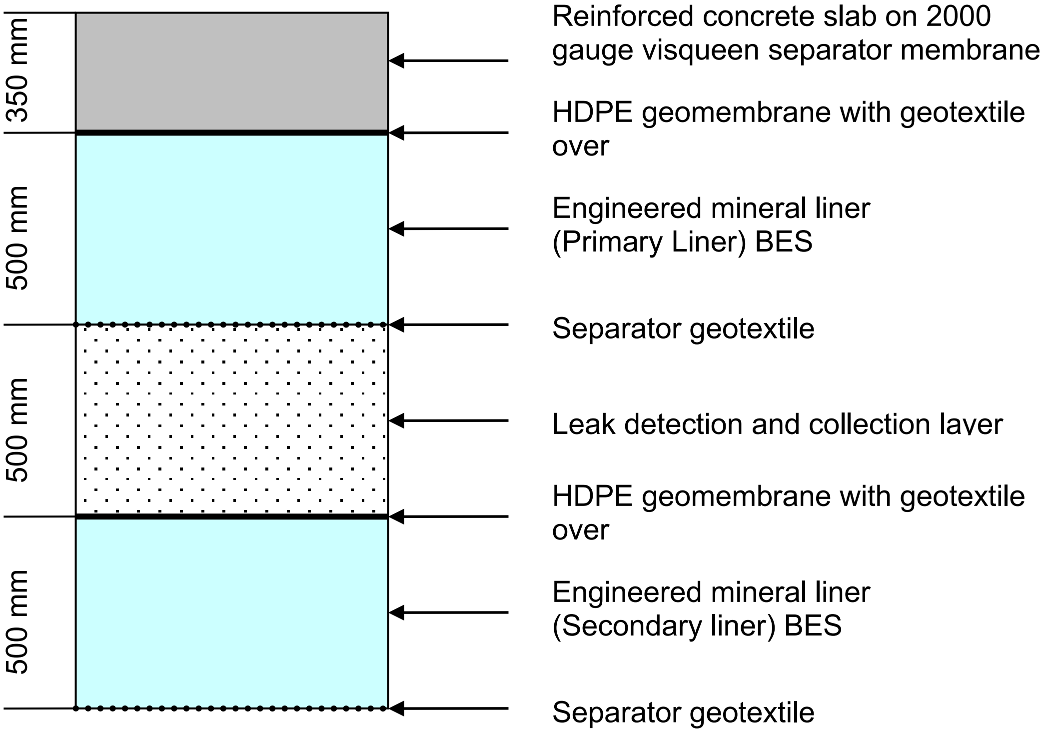

Figure 5.9: Vault 9 composite liner system

A detailed design and specification was developed, approved and successfully implemented for Vault 9. These required, for the geomembrane:

- 2 mm minimum thickness;
- hydraulic conductivity $<10^{-14}$ m s^{-1};
- suitable weld details;
- suitable validation testing.

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facilitate higher stacking; for example, two layers of reinforcement rebar delivered through grids angled 45 degrees to one another.

For the BES:

- 500 mm minimum thickness;
- hydraulic conductivity $\leq 10^{-10}$ m s^{-1};
- suitable mix control, placement and compaction;
- suitable validation testing.

The liner system was implemented under a strict regime of CQA, to validate and test all the various component layers. Figure 5.10 gives a view of the liner system during construction.

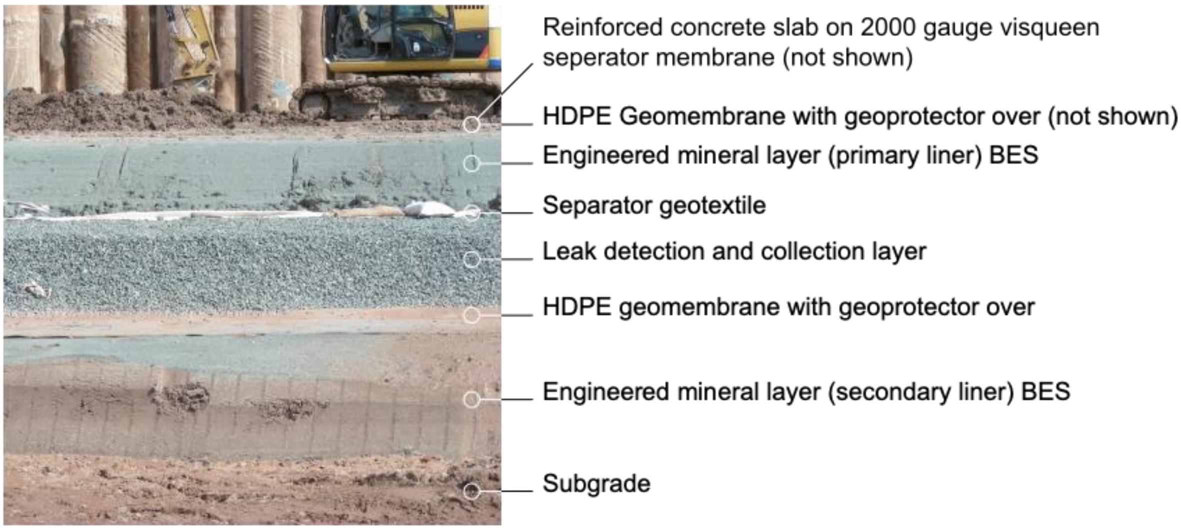

Figure 5.10: View of Vault 9 basal liner system and walls during construction

Vault 9 incorporates a leachate detection and collection layer beneath the upper basal geomembrane and BES. The intent was that any leachate (if any) penetrating the upper composite geomembrane and BES during operations and active control stages would be collected and monitored, in order to provide confidence in the performance of the system. After some years of monitoring with no leachate being observed, and noting that the current concept does not require the bases to remain impermeable post-closure, the case was made to cease monitoring. Given the change in concept, the optimised design does not require this layer for the future vaults.

There is a sacrificial construction membrane (Visqueen) and then a 1200 g m^{-2} geoprotector layer beneath the concrete and a minimum 3000 g m^{-2} geoprotector layer beneath the leachate detection and collection layer to protect the underlying geomembrane from damage.

5.3.3.4 Reinforced Concrete Walls

The perimeter walls are shown on Figure 5.11. The perimeter west and internal north walls are comprised of double-leaf reinforced concrete walls each 350 mm thick, separated by 1 m or more of infill, including BES to provide an internal liner of low permeability with hydraulic conductivity not exceeding 10^{-10} m s^{-1}. The 2 mm-thick HDPE geomembrane is also extended up the inside wall here, in continuity with the basal liner system. The east wall is similar, but with the reinforced concrete secant pile wall providing the outer wall.

These hydraulic barrier features were originally planned and designed to extend up to full height of the Vault 9 walls. At the time the optimisation approach for the future vaults design was finalised, the concrete walls had been built, but the BES infilling was just commencing. It was therefore decided to terminate the geomembrane and BES wall infilling at 1 m height. The existing void space at and above this level will be infilled with free-draining stone, to provide an overflow drainage system post-closure.[37]

The internal south wall is a single wall of reinforced concrete construction to 2 m high, over about half the length of the southern boundary to operations. It identifies the limit of Vault 9, but is not intended as a retaining wall.

5.3.3.5 Secant Pile Wall

A secant pile wall provides structural support along the eastern side of Vault 9, adjacent to the trenches. Details are given in reference [79]. It consists of 1200 mm diameter, heavily reinforced structural hard piles at 1600 mm centres to 18 m depth. These were bored between and intersecting 7 m long, 750 mm diameter soft piles that were installed earlier to provide integrity to the 6.5 m upper subsection, which acts in cantilever above the level of the base slab. Construction of substantial secant piled walls is relatively routine and no significant issues arose during the works. Figure 5.11 shows further details.

The secant pile wall was not designed to be water-retaining. It is not relied on to provide an impermeable barrier, but will remain present in the long-term.

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[37] It is important to note that the planned drainage systems during operations include passive gravity-fed components, but are separate from the post-closure passive drainage arrangements which require a different approach.

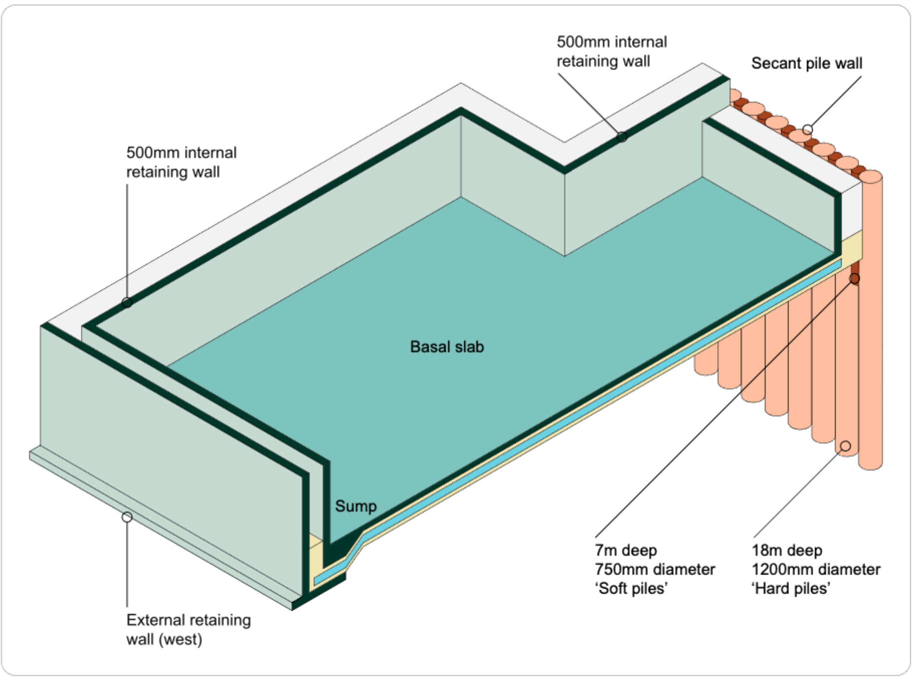

Figure 5.11: Vault 9 and secant pile wall

5.3.3.6 Operational Drainage Systems

A schematic plan of the operational drainage layout is presented in Figure 5.4. The base has a 1 in 200 transverse fall from east to west, to two perimeter manholes. Leachate is currently collected at pump chambers and pumped to the discharge system. It is intended that this will then be replaced by a gravity system with implementation of Vault 9a. This will in turn be decommissioned during closure, after which passive drainage arrangements will be used for the vaults.

5.4 Future Vaults: Vault 9a and Vaults 10 and beyond

5.4.1 Introduction and Requirements

The layout of the future vaults is captured in Figure 3.1, and will be as assumed in the 2011 ESC, consistent with the figures and drawings provided in [20]. The future vaults will accept relevant categories of wastes as follows.

- Existing and committed LLW will be disposed to the northern end of Vault 9a. These wastes will require early cap sealing followed by surcharge, consistent with equivalent areas of disposals in Vault 9.
- Vault 9a will also accept future LLW and ILW that can be managed as LLW in the remainder of the vault (i.e. as for Vault 9).
- The remaining future vaults (i.e. Vaults 10 and beyond) will accept 'future LLW' disposals. No LLW requiring surcharge will be accepted.
- As for Vault 9, ILW that can be managed as LLW will be disposed alongside future LLW disposals in the future vaults.

- In addition, ILW that requires additional measures (i.e. for shielding for dose management) will also be disposed in the remaining future vaults (see Subsection 5.4.4).
- Vaults 10 and beyond will also be used for interim storage warehouses for future LLW and ILW that can be managed as LLW.

The descriptions presented include the designs of vaults up to Vault 14. However, current inventory projections suggest that not all the vaults may be required, with disposals up to Vault 12 being likely to be sufficient [4]. This document considers all potential future vaults, to ensure completeness of coverage, recognising uncertainties inherent in future inventory projections.

Modular approach

The modular approach to future vaults is a direct consequence of the use of different approaches for different waste populations.

The baseline assumption for the ESC and its assessments is that they will be implemented on contiguous slab units within each of the future vaults, with locally thickened arrangements where necessary (principally for shielded modules for ILW; see Subsection 5.4.4). This means the broad definitions of vault sizes and drainage arrangements continue to apply.

The existing vault sizes are governed by topography and the desire for simple geometries, in particular continuing the line of existing vaults. This ensures, for example, that cap and cut-off wall geometries are not unnecessarily complicated. However, the modular approach offers greater flexibility in terms of how and when disposal capacity is provided, consistent with the overall disposal geometries already identified. The sizes of modules can be flexed in response to updated disposal projections with time.

Therefore, the assumption is that the same broad future vault geometries will continue to be used, but delivered in a modular fashion. Other more detailed aspects that could be flexed in the future, within this overall approach, include choices around whether or not to segregate slabs between module units, and options for implementing passive drainage (e.g. using smaller, module-specific arrangements).

5.4.2 Scope and Design Strategy

During operations and the rest of active control, the design intent is to ensure that leachate can be collected, and its release managed for as long as required. The basal liner system is therefore designed to have a very low permeability. It will extend up the side walls to a height of 1 m above the base, to ensure containment through this period. Leachate quantities following capping will be very small and handled during active control by gravity systems that will be decommissioned prior to the end of the PoA.

After the period of active institutional control, under passive conditions and with no appreciable leachate from the vault leachate collection chambers (or sumps), leakage through the basal liner is expected to be very small. The basal drainage layer provides a high horizontal permeability to support dispersal of drainage waters to the underlying geology.

Post-closure, it is possible that inflow will eventually exceed outflow through the base as the cap degrades; that is, if cap degradation occurs faster than base degradation, then leachate levels will build up within vaults.[38] The low permeability east and west walls will extend only to 1 m in height, so that above this level leachate would overflow to side drains and thence to the basal drainage layer under the same vault.[39] The internal north and south walls of the vaults will be set slightly higher than the east and west walls to give preferential drainage pathways to the sides.[40]

As the development of future vault modules continues southwards, base levels reduce to match the existing topography. This removes the need to construct a disposal platform above the local ground level. Consequently, the top of the base slab reduces from 15.9 m OD (current Vault 9) to 11 m OD for Vault 14. The drainage layers beneath individual vaults are isolated by east-west containment structures.

5.4.3 Common Design Details for the Future Vaults

5.4.3.1 Overview

Key details of common features of the design and construction of the future vaults are elaborated in Subsections 5.4.3.2 to 5.4.3.7. These include:

- the single composite basal liners, and slabs;
- vault walls; and
- operational and post-closure leachate management arrangements.

Additional requirements for relevant categories of ILW are discussed in Subsection 5.4.4.

Any voids that are sufficiently large to be void filled during closure will utilise the approach set out for Vault 8 in Subsection 5.2.2.7.

5.4.3.2 Layouts

The western perimeter walls will continue the line of Vault 8. Vault 9a will extend Vault 9 out to this line to match and enable a consistent final cap profile. It thus makes best use of the available space within the footprint of the vaults area. It will be constructed and filled before or coincident with Vault 10, to enable it to be capped at the same time as Vault 9. The figures that follow provide further details, underpinned by the drawings provided in the Appendices.

Figure 5.12 and Figure 5.13 show a schematic plan and sections. With construction of Vault 9a, the leachate drainage system will be revised as indicated in Figure 5.14. The system will have the 1 m high ‘spill over’ level to basal drainage. The optimum arrangement will be subject to further detailed design.

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[38] Central projections of cap performance suggest infiltration will remain very low for a prolonged period [12].

[39] Flow through the vault base will flow directly to the same features.

[40] The exact height will vary by vault and take into account slab slopes and topography, but will typically be a few tens of centimetres higher.

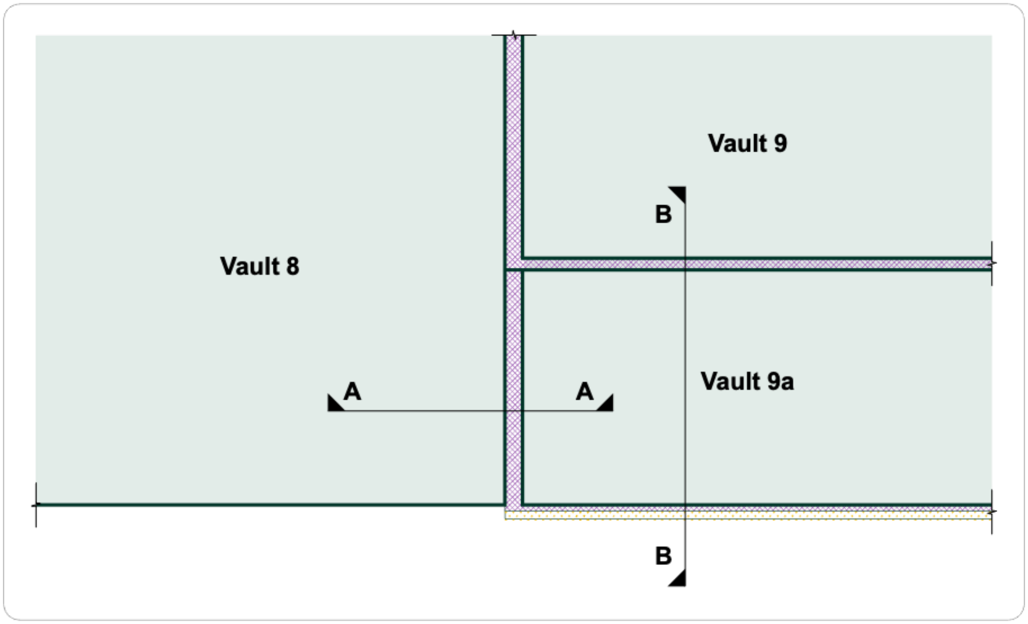

Figure 5.12: Vault 9a operational connections (A and B) to Vaults 8 and 9 (schematic plan)

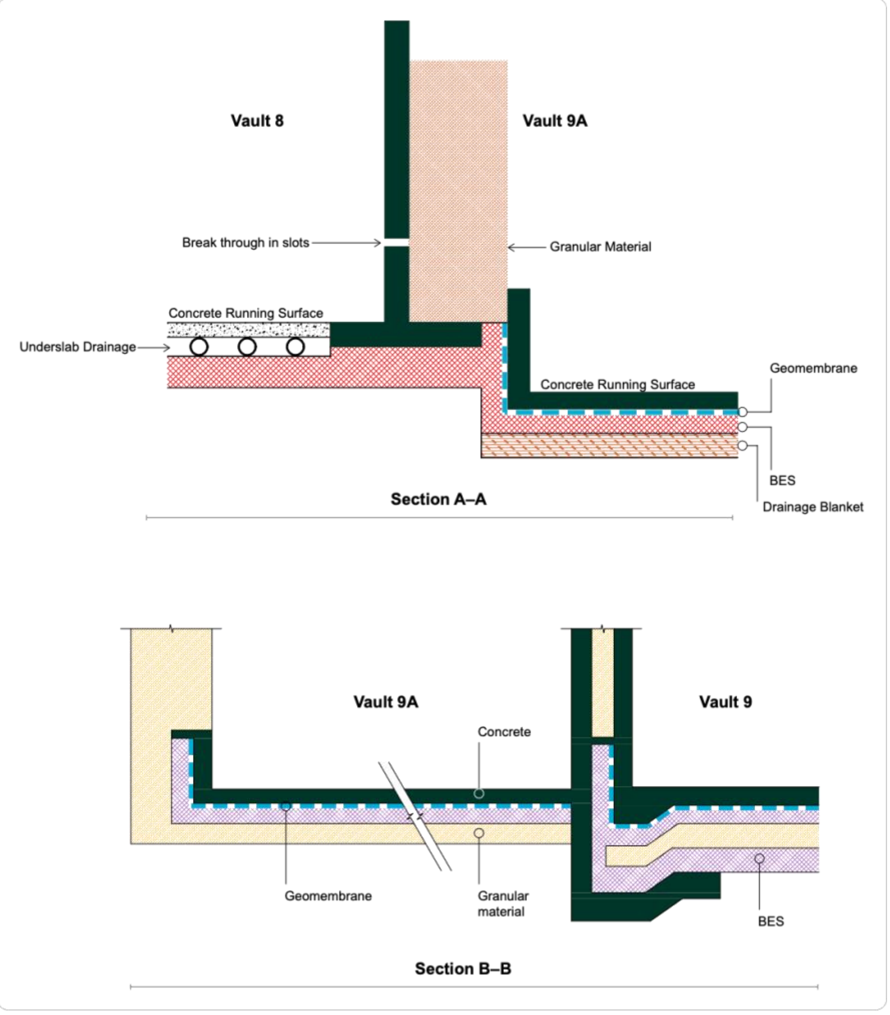

Figure 5.13: Vault 9a connections to Vaults 8 and 9 (typical sections)

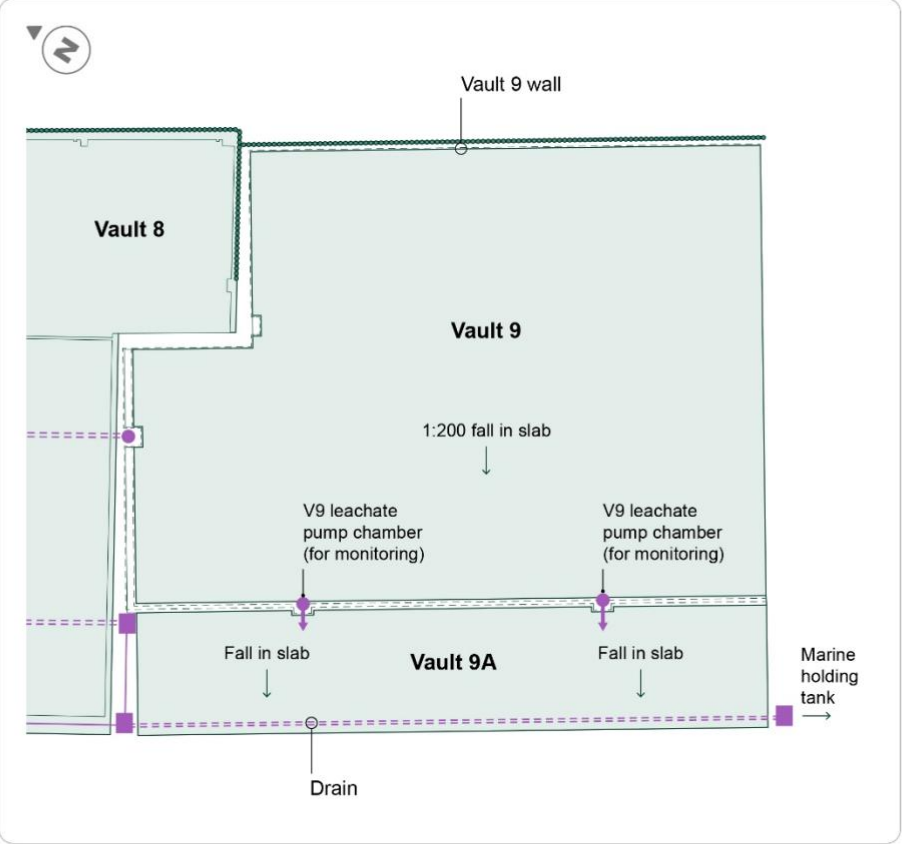

Figure 5.14: Vault 9a – Plan of the operational drainage system. As noted in the main text, a change to a gravity based system for the operational period is planned.

5.4.3.3 Secant Pile Wall

As Vault 10 and other future vault modules are developed, the secant pile wall on the west side will be continued southwards to provide support to the adjacent Trench 3. The design and construction will be similar to that for Vault 9, i.e., heavily reinforced structural 'hard' piles at around 1200 mm diameter and 1100 mm centres, cut into 'soft' piles to provide lateral continuity and integrity to the upper cantilever subsection. Excavations and wall heights increase to the south, to about 10 m maximum by Vault 14.

The functional requirements are similar to those described for the Vault 9 secant pile wall. This wall will be adjacent to the 1 m high east wall and long-term overflow drainage system. As elsewhere, the secant pile wall will not be water-retaining, nor relied on to provide an impermeable barrier, but will have a presence and an effect long-term.

5.4.3.4 Composite Geomembrane and BES Liner

A composite basal liner is planned, consisting of geomembrane on BES. The detailed requirements for the geomembrane are as follows:

- minimum 2 mm thickness HDPE;
- hydraulic conductivity $<10^{-14}$ m s^{-1};
- suitable weld details;

- suitable validation testing.

For the BES:

- minimum 500 mm thickness;
- hydraulic conductivity <10^{-10} m s^{-1};
- suitable mix control, placement and compaction;
- suitable validation testing.

5.4.3.5 Reinforced Concrete Slab

The base slab will be of reinforced concrete, nominally 350 mm thick. It is assumed that the reinforced concrete slab will extend about 10 m beyond each vault southern wall to provide an operational area to the south, as has been done for Vault 9, and with suitable detailing to be incorporated into each succeeding vault module.

The reinforced concrete slabs will again not be specifically designed to have a long-term hydraulic barrier function but may nevertheless provide a barrier to flow at early times, degrading over time.

5.4.3.6 Walls

The perimeter west and east walls for each of the future vaults will be of reinforced concrete around 350 mm thick (subject to detailed design) with a composite 2 mm geomembrane and 500 mm thickness of BES on the outside, both in continuity with the basal composite liner. This will provide a composite low permeability liner system to a nominal height of 1 m above base of slab. The crest will be level on both sides so that eventual spill-over to the long-term drainage system to east and west will be similar. The concrete will extend over the BES across the crest to give it suitable physical protection. The crest profile will have a slight (1 in 20 or 50 mm in 1 m) gradient back towards the vault, so that prior to overtopping any waters from the free draining materials above will be directed back into the vaults.

Behind and above these walls will be stone drainage material connected to the basal drainage system. This will also extend some 150 mm minimum thickness inside the vaults, adjacent to the HHISO containers, to provide internal drainage for any waters within the vaults during the operational stage. The drainage material will be free-draining granular fill, similar to the basal drainage layer below. These free draining ‘walls’ will be laterally separated with a minimum of 2 m width of low permeability material at each vault boundary so as not to present a preferential north to south drainage pathway for leachate overtopping the 1 m walls (consistent with the gaps between basal liners under the vaults which aim to prevent all flows travelling preferentially to the southernmost basal liner). The separators will be of BES or locally available clayey materials having hydraulic conductivity not less than 10^{-9} m s^{-1}.

The eastern wall drain will be constructed by building up free-draining material as the perimeter containers are placed, with the secant wall providing the back support. The western wall drain may be built up with the placement of containers and with backfill raised at the same time to provide lateral support. If preferred for operational reasons, an outer wall may be formed of simple blockwork or other construction.

The internal north and south wall will be of reinforced concrete construction, just over 1 m high to provide the internal boundary during the operational stage. The crests will be 100 mm higher than the crests of the side walls, so that the east and west walls provide the preferential long-term (passive) drainage route. Free draining stone will be raised above the north and south internal walls as adjacent containers are placed. Infill behind the western perimeter walls and southern perimeter wall to the southernmost vault (Vault 12 according to current inventory projections, or Vaults 13 or Vault 14 if projections change), will be of suitable fill materials from prior excavations for the vaults, compacted into place in accordance with the standard earthworks specifications [53].

5.4.3.7 Operational and Post-closure Drainage Systems

The base slabs will have a 1 in 200 fall to a collection chamber for each vault on the western perimeter. During operations and the rest of the management control period, leachate will be collected at these manholes, monitored and directed to the discharge system. Following the management control period, the long-term, post-closure passive drainage system will apply.

Post-closure, waters in the vaults reaching the 1 m level will be directed via the drains associated with the east and west vault walls to the basal (that is, under-slab) drainage blanket under each of the future vault bases (including 9a), and thence to the underlying geology. These will be formed of free draining stone, 500 mm thick and specified to have a hydraulic conductivity not less than 10^{-4} m s^{-1} and generally in accordance with standard specifications [53]. The basal drainage will be separated axially from each other with at least 2 m width of low permeability (hydraulic conductivity $<10^{-9}$ m s^{-1}) material, which may be the local clay, at each level step in vault boundary.

5.4.4 Additional Requirements for ILW that cannot be managed as LLW

5.4.4.1 Overview

The provisional details provided in Subsection 5.4.3 apply to all future vault modules including those intended for disposals of LLW and ILW that can be managed as LLW, and also for modules for ILW that cannot be managed as LLW. However, there are additional requirements for the latter category of wastes, which are expanded upon here.

Optimisation of the approach is described in reference [9]. The design approach is to ensure consistency with the overall concept including passive drainage, whilst also ensuring protection of workers and the public from possible irradiation doses associated with wastes with dose rates that are too high to be treated directly as LLW.

The optimisation work to date describes a clear overall concept and rationale and a robust basis for the ESC. Future iterations of the design will necessarily lead to further developments and refinements within this overall framework.

5.4.4.2 Shielded Module Design

Basis of approach

ILW that requires dose management arrangements for vault disposal will be placed within modules which are termed 'shielded modules' [80].[41] These shielded modules have the following overall requirements.

- They must provide shielding of workers and the public.
- Shielding and wider operational (that is, disposal) practices should be consistent with ALARP.
- The structures required to provide the shielding should be sufficiently robust to support the profile fill and the cap, such that waste containers are protected and there is no loss of control or unintended exposure to workers or the public during the closure process.
- The overall approach must remain consistent with the overall vault philosophy e.g. associated with passive drainage and progressive capping.

The design for the shielded modules will therefore be as follows.

- Modules will consist of a series of reinforced concrete corridors of sufficient thickness to provide both shielding and structural support.
- The corridors will be founded on a reinforced concrete base slab that is locally thickened compared to the standard future vault bases for LLW disposals, to ensure rigidity of the overall external structures system. Otherwise, the base unit and underlying engineering will be as for the standard future vault bases.
- The corridors will be capped by reinforced concrete roof tiles progressively with disposals, which will then form part of a thick reinforced concrete roof cast upon completion of disposals to a module. The roofs will be designed with a slight fall to shed precipitation.
- During operations, corridors will be shuttered at the open end. Thick reinforced concrete walls will be present at either end at the time of closure. Corridors will only be ‘open’ when disposal operations are active and will be closed at all other times. The open end will be orientated so as not to face areas with active disposal operations to protect workers; the current working assumption is that the open ends will face the vault walls adjacent to the trenches.

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[41] During the options development work described in reference [72], these were termed ‘external structures’ units, of which this option was the ‘ES1’ variant. This was in part to differentiate them from other categories of shielding options that were also considered, and also recognising their ability to directly support the cap through structures external to the containers.

- Drainage channels will be incised in corridor bases to encourage passive drainage. Arrangements will be made (small holes with coves) to allow drainage through the corridor sides also whilst ensuring shielding is maintained.
- The corridors will be backfilled with standard vault drainage material, which will also be emplaced around the shielded modules.

The outcomes take into account the principle of ALARP, including in outline operational approaches, shielding thicknesses, plant requirements, and the location of shielded modules [80]. This is important to provide confidence that the options, following further development during design phases, will be consistent with the demonstration of ALARP prior to construction.

The shielded modules will not be back-fitted to Vault 9 and will not be included in Vault 9a. They will be constructed first in the area currently designated as Vault 10, and then in the areas designated for the other future vaults. Flexibility to vary external structure unit sizes is a key part of the approach.

Containers for disposal will be as for other ILW disposals in the vaults, i.e. SWTC-compatible mild steel containers (see Section 5.4.3).

As for other modules, the sizes of shielded modules (i.e. the extent of the future vault slab areas they occupy) will intentionally be kept flexible. Disposals to shielded modules are not anticipated until the late 2030s. Illustrations presented in this document are based on the prioritised inventories presented in reference [80]. A minimum size of 20 m by 20 m will apply for Vault 10, with the flexibility to use larger unit sizes both for this and future vaults. If for any future vault the volumes of ILW requiring shielding are not sufficient to fill a minimum size unit, the corridors may be filled with disposals that do not require shielding to avoid wasting disposal volume.

The design is illustrated in Figure 5.15. Details are further elaborated in Subsection 5.4.4.3.

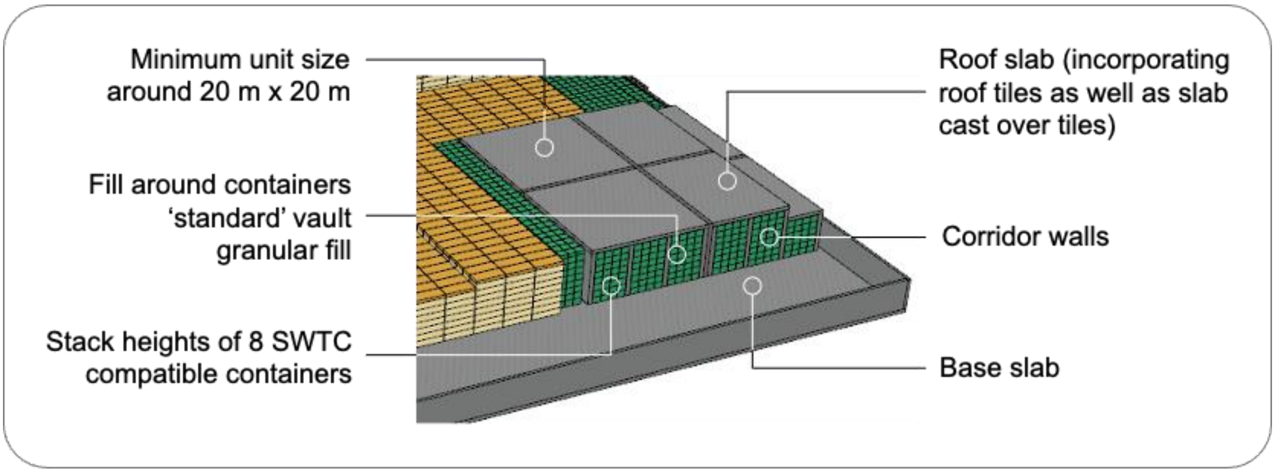

Figure 5.15: Shielded Modules – illustration

5.4.4.3 Additional Engineering Details

The following materials thicknesses have been estimated on the basis of engineering and dose management principles.

- Reinforced concrete slab thickness: 750 mm.
- Reinforced concrete roof slab thickness (including the roof tiles cast into the slab): 750 mm. Slab surface at the same height as other disposals in the same vault area.
- Individual corridor reinforced concrete walls: each 600 mm.
- Indicative width of corridors: three or four SWTC-compatible containers plus clearance (typically therefore around 5.5 to 7.2 m).
- Standard stack height of eight SWTC-compatible containers (typical stack therefore 10.8 m high).
- Clearance of 300 mm is required between upper stack containers and the underside of the roof tiles (to allow placement of void fill and provide clearance when placing tiles).[42]

The default assumption is that shielded modules will always be the maximum height that will fit under the cap. However, there is flexibility to adopt approaches in the future that would allow disposals of containers that do not require shielding on top of the roof slabs. This however has not been assumed in the 2026 ESC.

5.5 Vault and Trench Cap Seal

A ‘temporary’ vault and trench seal will be constructed for each strip of the cap. The seals will:

- stabilise and secure the leading edge of the cap layers during phased construction;
- enable structural continuity and integrity across the cap system; and
- provide a low-permeability layer over the waste and profile fill which will perform as an interim cap.

This seal will create pseudo-closure conditions within the ‘closed’ vault segments, promoting progress towards anaerobic conditions. Each seal will be formed from overburden laid to an appropriate stable angle. This will be covered with a membrane together with appropriate supporting material and drainage.

Figure 5.16 and Figure 5.17 illustrate the potential membrane and associated material arrangements for the vault seal, using the Vault 8 design as an example (here using the phrase ‘leading edge’ to refer to the relevant engineering aspects of the vault seal). Relevant details are then expanded upon below.

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[42] As an indication, a 20 m x 20 m unit all stacked to eight-high could house 11 x 11 containers in three corridors of 4, 3 and 4 containers wide = 968 containers in total.

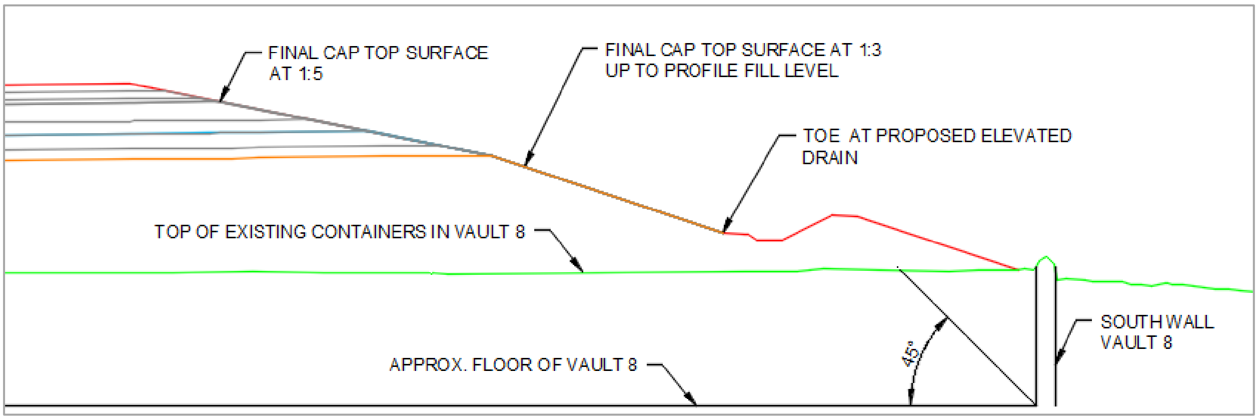

Figure 5.16: Schematic of the vault seal geometry assumed for Vault 8. This basic approach will also be applied, subsequently modified, for future strips including sealing of the existing and committed LLW in Vault 9.

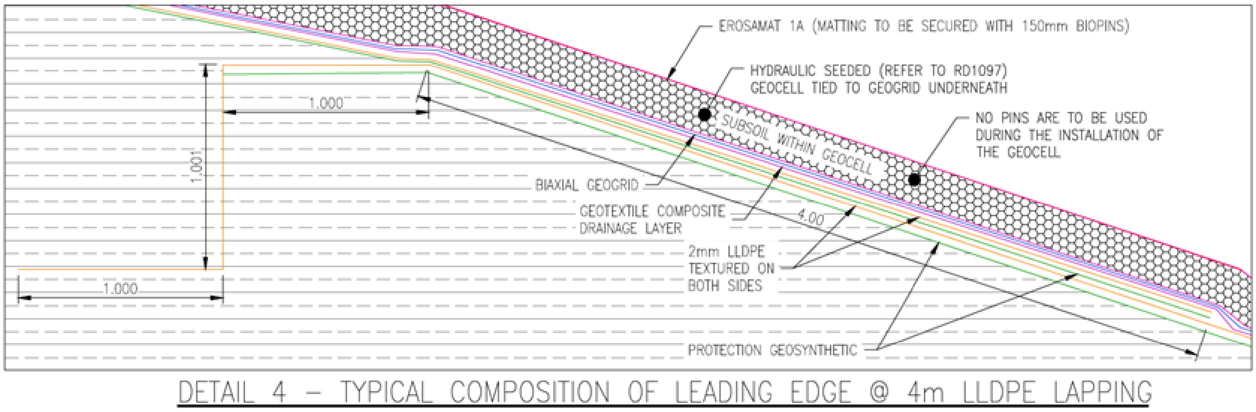

Figure 5.17: Detail of current Vault 8 designs to illustrate the vault seal concept. When this design is developed for extension into Vault 9, the membrane would be tied into the retaining wall or vault base in a manner that ensures a complete seal. NB the seal will be removed prior to surcharge and final capping.

Vault seal

For the vaults, the seals will extend to seal and provide an interim cap for disposals, connecting either with the end-of-vault walls, or a retaining wall within the vaults, depending on the strip. Waters from the final cap will then be discharged to the adjacent vault base slab, or via vault walls to relevant drains, depending upon the strip of the cap.

The seals (for initial and also for subsequent strips for the cap) will be removed as part of the capping and surcharge process. Therefore, they are not part of the post-closure engineering arrangements. However, the seals will influence the condition of the wastes and containers going into the post-closure period.

For the strip of the seal to be implemented part-way within Vaults 9 and 9a (to cover the existing and committed LLW), a retaining wall will prevent material slopes from taking up disposal space by ensuring cap materials do not need to extend to the vault floor (illustrated in Figure 5.18). The wall will remain in place in the post-closure period, but will no longer provide a function after the next strip of the cap is complete, as it will no longer be supporting material slopes. The seal will extend across the width of Vault 9 (and Vault 9a). The vault seal membrane will be built into the retaining wall.

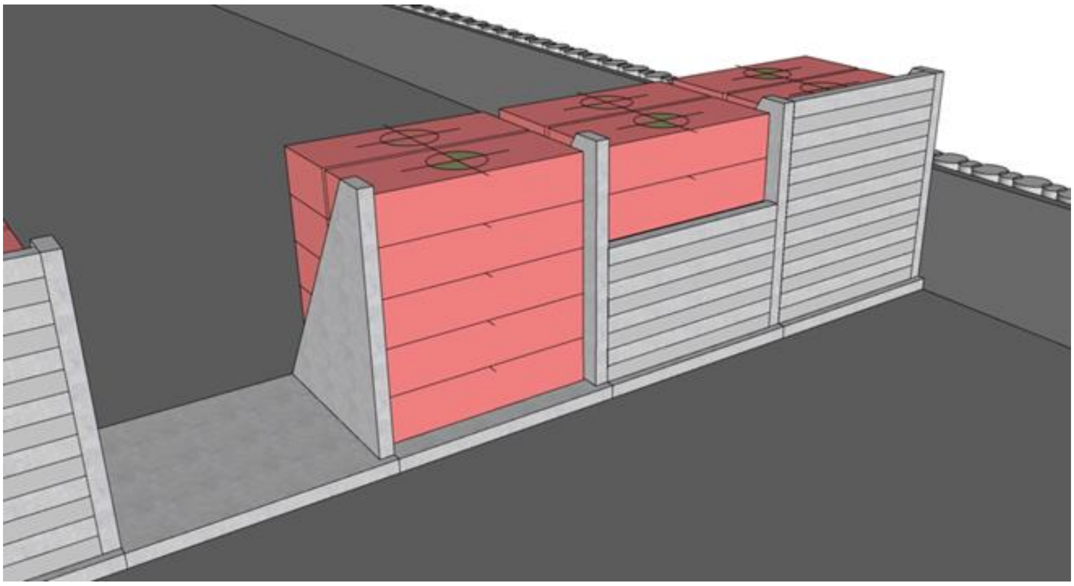

Figure 5.18: Illustration of retaining wall design to support an in-vault cap seal

This seal will be implemented as an extension of Vault 8 capping, and surcharge will be implemented later, consistent with final capping of Vault 9. Material slopes and associated controls adjacent to the open vault will mean that surcharge of these wastes cannot be undertaken in advance of full vault closure.

Appropriate leachate management arrangements will be made to ensure that the construction of the wall supports both pre-closure passive leachate management requirements, and also delivers post-closure passive leachate provision consistent with the design above. Gas vents will also be included in the vault seals associated with Vault 8 and Vault 9 (including any leading edge extension into Vault 10), as vents will not be included in the final cap itself for those strips of the cap (see Subsection 3.2.6).

Figure 5.19 illustrates the approach to gas venting in the vault seal. The vents are based on a tubular approach linking the gas collection layer to the atmosphere above the seal surface, with a vent cap to prevent ingress of precipitation.

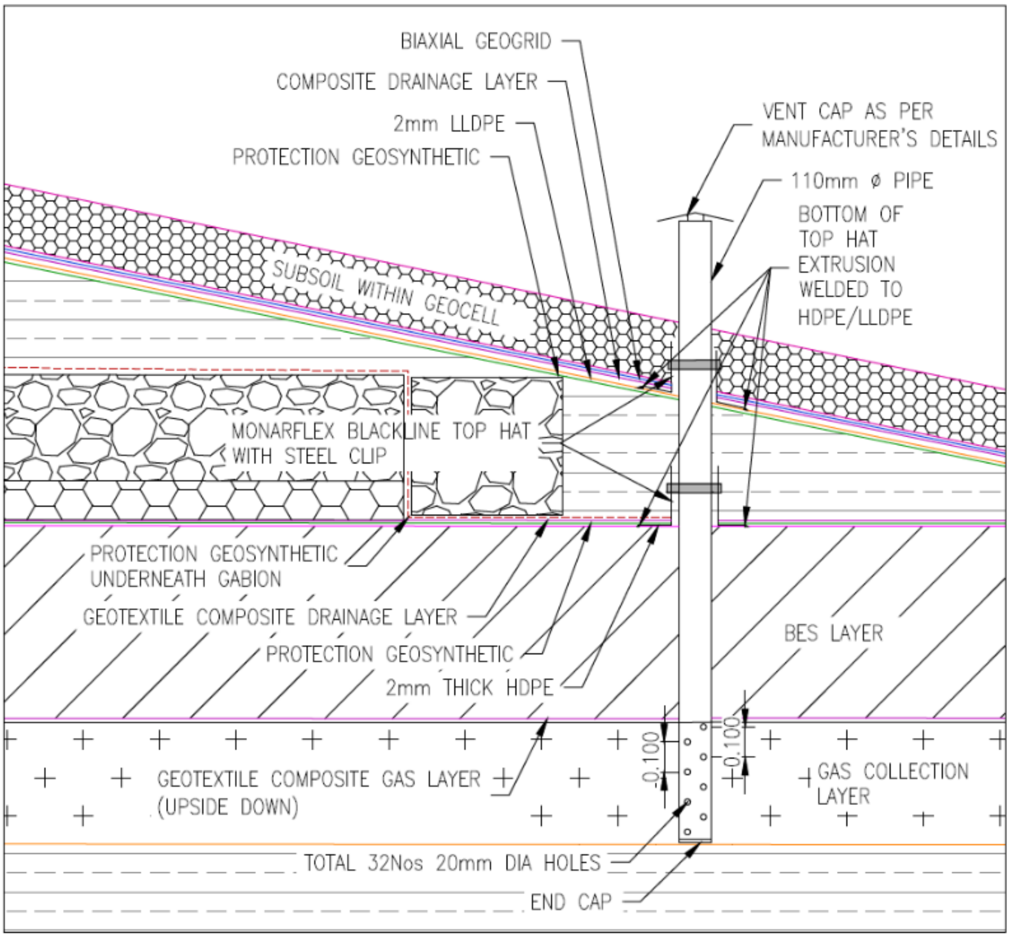

Figure 5.19: Gas vent design for the vault seal using an arrangement referred to as the 'top hat' approach. This will be applied to strips of the cap executed over Vaults 8 and 9 (including any cap seal extension into Vault 10 during the Vault 9 closure process) but will not be required for subsequent strips of the cap.

Trench seal

For the trench areas, the primary concern is ensuring a robust interface between the seal membrane and the STIM cap.

Effective water management and drainage at the toe of each seal strip are required. Since the STIM cap sits at a higher elevation than the vault tie-in points, the seals in the trench areas will be less extensive than for the vaults. Additionally, each strip of the seal does not need to follow a direct linear continuation from the vault section. The greater height of the trenches allows the seal to taper progressively while maintaining required gradients and structural tie-ins.

This geometry and approach are illustrated in Figure 5.20, using Vault 8 as an example.

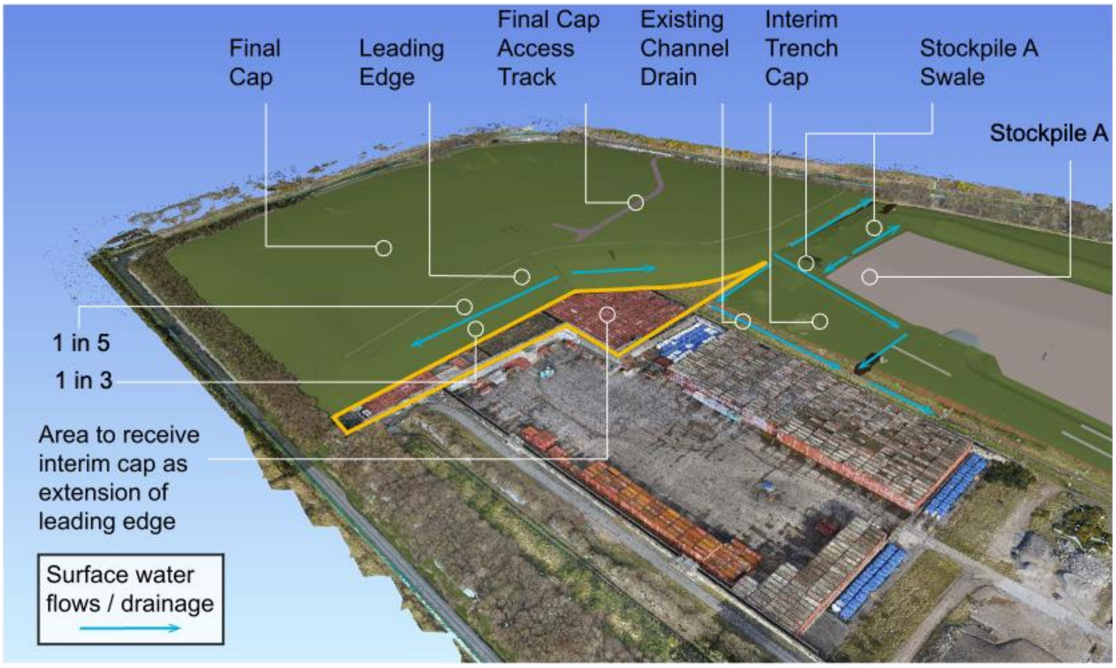

Figure 5.20: Illustration of Cap Seal Geometry over the trenches

5.6 Further Engineering Aspects and Illustration of the Overall Approach

5.6.1 Interim Storage Warehouses for LLW

Past optimisation studies for the LLWR (see reference [9]) have recognised the importance of protecting waste containers from environmental effects such as precipitation and wind-blown chlorides. Early protection will minimise the potential for enhanced degradation of containers (e.g. via corrosion) prior to final closure.

Although a significant proportion of the existing containers have been in the open vault for a prolonged period without any notable negative effects (e.g., no enhanced releases observed through leachate monitoring) this is not considered optimal. A guideline target of protection within 10 years of future receipts was therefore identified [9, 81, 82]

Protection will be fully provided by the final cap and seals. Other measures are plausible to enhance protection in the interim.

On the basis of optimisation work [69] we plan to implement ‘interim storage warehouses’, similar to standard industrial warehouse designs.[43] The first warehouses will be constructed on slabs that will subsequently be used as Vault 10 disposal modules. They will provide interim storage of containers, with protection from environmental effects. Containers will then be moved to their final disposal positions shortly before the implementation of relevant strips

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[43] The aim is to provide levels of protection proportionate the hazard. Full climate-controlled buildings equivalent to ILW stores are not required (see reference [69]).

of the cap. After warehouses in the Vault 10 area have been removed, warehouses will then be created in the Vault 11 area and so on. All warehouses will be removed prior to closure.

If future rates of receipts increase (e.g., with the onset of broad-front decommissioning) then it may be that strips of the cap can be implemented with sufficient frequency that the interim warehouses prove unnecessary. However, the default is that they will be required.

5.6.2 Order of Construction

The process for installation of the final cap will deliver closure of Vault 8 in the 2030s[44]. It is assumed that this programme will be extended to include early vault sealing of the existing and committed LLW in Vault 9 (as in Subsection 5.5). This will require construction of (and disposals to) relevant sections of Vault 9a, in advance of the sealing works in Vault 9. This is because the cap and therefore the vault seal will cover part of Vault 9a as well as Vault 9.

Modules in the area designated as Vault 10 are also required to be built in the 2030s. This is to accommodate the interim storage warehouses, and any ILW modules. It will also assist in accommodating uncertainties in future LLW arising rates; if decommissioning waste receipts accelerate, Vault 9 capacity could be challenged on these timeframes.

5.6.3 Illustration of Potential Future Disposal Arrangements

Figure 5.21 shows an illustration of the disposal model optimisation outcomes [9] for Vault 9 and the future vaults. [45] The figure uses a cut-away approach which does not show the profile fill, final cap or the cap leading edge and vault seal. It is not a definitive projection or design but aims to help visualise how the options could work together. For simplicity the illustration only shows disposals to the end of Vault 10 but similar approaches would also be implemented in the areas currently associated with the future vaults. Container numbers are also illustrative only. Further shielded modules would be present in subsequent vault modules.

The figure provides an indication of a potential approach to distributing ILW containers so they are spread across the east to west of the vaults, rather than being concentrated in one area, and without being disposed immediately adjacent to the western edge. This is again illustrative and the final approach will be informed by future optimisation, design and inventory work.

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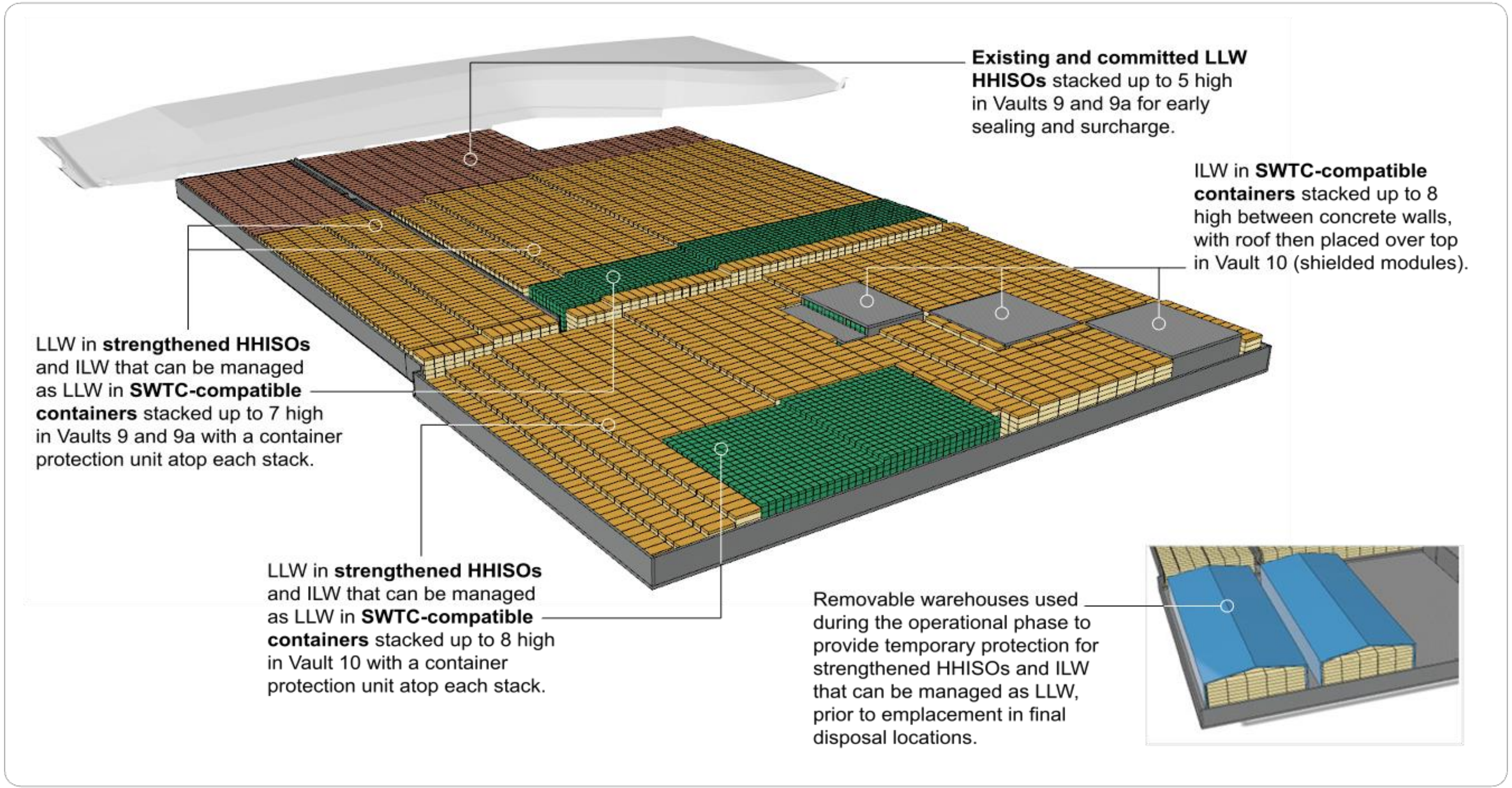
[44] Current programme dates for completion of Vault 8 capping are March 2034 – May 2037 (see Subsection 3.2.8).

[45] The numbers of containers for different waste categories in Figure 5.21 are related to a specific set of inventory assumptions developed for the illustration during the optimisation work, and are not applicable to the current inventory cases. The distribution of different wastes and containers is also illustrative only. They are sensitive to inventory assumptions, in particular for those associated with shielded modules. Shielded modules are only shown in Vault 10 in the schematic, but in practice, disposals would be split across modules, to be implemented in the areas designated for Vault 10 and for future vaults. The ends of the shielded modules, and of the warehouses, would be closed whenever not in active operation.



Existing and committed LLW HHISOs stacked up to 5 high in Vaults 9 and 9a for early sealing and surcharge.

ILW in **SWTC-compatible containers** stacked up to 8 high between concrete walls, with roof then placed over top in Vault 10 (shielded modules).

LLW in **strengthened HHISOs** and ILW that can be managed as LLW in **SWTC-compatible containers** stacked up to 7 high in Vaults 9 and 9a with a container protection unit atop each stack.

LLW in **strengthened HHISOs** and ILW that can be managed as LLW in **SWTC-compatible containers** stacked up to 8 high in Vault 10 with a container protection unit atop each stack.

Removable warehouses used during the operational phase to provide temporary protection for strengthened HHISOs and ILW that can be managed as LLW, prior to emplacement in final disposal locations.

Figure 5.21: Illustration of the optimisation outcomes for the vaults [9].

5.7 Disposal Container Geometries

This subsection presents the geometrical details of the primary containers used for bulk disposals to the LLWR.

HHISO containers for existing and committed LLW

The standard HHISO containers have the following properties (see reference [83] and underpinning references). Note that the majority of containers in Vault 8 are TC08 variants; a more even split between TC08 and TC01s for existing and committed wastes in Vault 9 is anticipated, once disposals are complete [69]. The TC01 dimensions also represent an appropriate assumption for strengthened HHISOs for future LLW.

TC01 variants:

- Dimensions of 6.058 x 2.438 x 1.325 m.
- External volume of 19.57 m^3.
- Internal volume of 18.64 m^3.

TC08 variants:

- Dimensions of 6.058 x 2.5 x 1.345 m.
- External volume of 20.37 m^3.
- Internal volume of 19.15 m^3.

HHISO containers for future LLW

These containers would be strengthened to provide the required strength to allow higher stacking and to resist closure loads (and therefore to avoid the requirement to surcharge), as set out in Subsection 5.3.2.3. In addition, future LLW stacks will be topped by reinforced concrete container protection units. The assumption for the ESC is that these will match the areal dimensions of the tops of the containers but will have a thickness of the order of 70 cm, subject to detailed design.

Containers for ILW

ILW disposals, whether for ILW that can be managed as LLW or ILW that requires shielding, will predominantly use new containers (Subsection 5.3.2.4). Our preference is for a strong box that can fit inside an SWTC. A schematic of such a container is shown in Figure 5.22. The external dimensions of the container would measure 1700 mm(L) x 1700 mm(W) x 1350 mm(H), with a payload of 2.6 m^3 [69]. The container illustrates the concept but there is confidence that a container of this type could be efficiently manufactured and used.

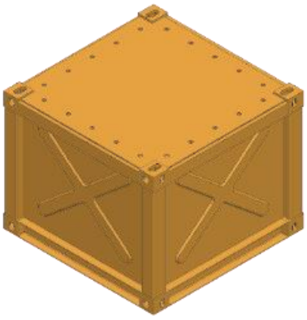


Figure 5.22: Mild steel strong SWTC compatible container (Illustration)

6 Summary of Design Developments Since the 2011 ESC

This section highlights the main areas of design development since the 2011 ESC. The resulting designs have already been discussed in Sections 3 to 5.

Firstly, design changes to the final cap and profile fill since 2011 are summarised in Table 6.1. This includes design changes that will impact the cap but are external to it (i.e. surcharge of wastes). Discussions following Table 6.1 then address changes to other aspects of the system.

Table 6.1: Summary of main updates to the cap and profile fill design since the 2011 ESC. See Section 3 for details.

Design element	Change since 2011 ESC design
Biointrusion and gravel filter layers	The previously separate biointrusion and gravel filter layers have been combined into a single layer. This change simplifies the cap profile and thus its construction.
Geotextile layer above the biointrusion layer	A new geotextile layer has been introduced above the biointrusion layer to improve constructability during installation.
Geocomposite drainage layer above low permeability layers	A geocomposite drainage layer has been added above the low permeability layers. This enhances drainage performance and facilitates construction.
Geocomposite drainage layer below low permeability layers	An additional geocomposite drainage layer, installed in an inverted orientation, has been included below the low permeability layers. This provides redundancy in gas management and supports constructability.
Minimum profile fill thickness	The thickness of the profile fill has been increased to at least 2 m across most of the cap area[46] - an increase of 1 m compared to the 2011 ESC. This change enhances cap resilience to differential settlement. The extra metre of isolation of the wastes from the environment is also included in our human intrusion assessment.

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[46] In practice geometrical constraints in specific locations mean that for a very small fraction of wastes the thickness of the profile fill may be below 2 m, but above 1 m; see [29].

Design element	Change since 2011 ESC design
Granular profile fill above the vaults	The design now specifies the use of free-draining, low-fines granular fill above the vaults. This material choice improves strain distribution (compared to cohesive fill) and contributes to cap resilience. It will also minimise the risk of clogging of drainage features.
Surcharging of legacy waste	Legacy trench and vault wastes will be surcharged to eliminate voids and reduce post-placement settlement. This approach also ensures a stable formation for the cap and thereby contributes to maximising confidence in construction and subsequent performance.[47]

In addition to the design changes for the cap, the learning generated from cap resilience assessments and the EPA has provided an enhanced understanding of cap performance compared to the 2011 ESC. This has led to the conclusion that the performance of the composite layer is likely to persist for a longer period than previously assumed (Subsection 3.2.4; [12]).

For other engineering components, updates since the 2011 ESC are as follows.

- Upgrade (via replacement) of the interim trench cap for those areas of the trenches that will not be covered by the first strip of the cap (i.e. other than those areas adjacent to Vault 8).
- A move to strengthened containers for future LLW disposals, to provide support to the cap and remove the need for surcharge. Use of reinforced concrete CPUs spanning the tops of stacks to protect against damage to the lids during closure.
- Container protection (from environmental effects such as precipitation and wind-blown chlorides). This will be addressed by the following.
    - The approach to strip-capping, including the use of the leading edge and vault seal approach to provide protection of containers adjacent to, but not immediately under final cap strips.
    - Construction and use of ‘interim protection warehouses’ in future vaults, which will receive and protect containers from environmental effects prior to them being moved to final disposal positions.

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[47] See also Subsection 4.4 (trench surcharge), Subsection 5.2.2 (Vault 8 surcharge) and Subsection 5.3.2 (Vault 9 and 9a surcharge for existing and committed LLW).

- Adoption of a modular approach to future disposals.
- Confirmation that Vault 9a will be built to provide disposal capacity and also passive drainage arrangements, helping to link Vault 8 leachate with the under-slab drainage associated with the future vault design. This will need to be implemented prior to implementation of the first strip of the final cap seal in Vault 9.
- The potential for disposal of ILW (Subsections 5.3.2 and 5.4.4). This includes:
    - ILW that can be managed as LLW (i.e. not requiring any additional measures such as dose management), which would be disposed of alongside LLW in the open vault;
    - ILW that requires additional measures (e.g. dose management) in shielded modules consisting of reinforced concrete corridors including roofs, to manage doses during the operational phase.

7 Leachate Management

7.1 Purpose and Scope

The existing leachate management system and general drainage schematic for the site are shown in Figure 2.5. The aim is to collect and transfer leachate to the MHT and thence to the authorised discharge route. This will minimise saturation in the trenches and minimise water interactions with vault wastes and associated leachate volumes.

The system has functioned satisfactorily through the full range of operating conditions experienced. It is expected to continue in similar form, with routine maintenance and development to suit the further vaults through the operational period and thereafter, as described below. The leachate quantities are largely controlled by the run-off from the open area of vaults, which will reduce with time as capping proceeds. Details of the strategy for leachate management are set out in [75].

In addition, the modular approach for the future vaults will allow opportunities for the enhanced segregation of clean waters and leachates from different disposal areas, to reduce overall leachate volumes as well as the mixing of waters. The use of temporary storage warehouses will further reduce water contact with wastes and overall leachate volumes. In addition, the use of shielded modules will also minimise leachate for ILW disposals that require shielding. These aspects will be considered further as optimisation and design of the existing concept designs continues, and the leachate management strategy is updated consistent with those designs. During operations and the rest of the active management phase, the leachate will be collected, monitored and disposed via the existing MHT to the consented outfall, as now [75]. Leachate quantities and qualities will continue to be monitored. Pumping will be terminated when there is a move to gravity systems following completion of Vault 9a. The leachate management system will be required up to the point that it can be demonstrated that there is no significant leachate generation. At that point the leachate management system from the trenches and vaults to the MHT and the marine pipeline will be decommissioned. Monitoring of leachate levels in the trenches and vaults is expected to continue for a period to confirm performance is as expected.

7.2 Vaults

Any leachate will continue to be actively managed by collection in the pump chambers for each vault and pumped away, until the move to a gravity system is complete. At this point, leachate from the vaults will be routed to the MHT via a gravity drain feature installed to the seaward side of the vaults.

The operational system is currently constrained by the MHT pumping capacity. In practice, the system can comfortably manage anticipated heavy rainstorms. In the case of extreme events, there is provision within the system to manage overflows by use of the automatic diverter valve system or by management intervention to limit discharges from the vault pumps to the MHT.

It is intended to cap each vault once disposal is completed in preparation for construction of each next future vault (i.e. cap Vault 8 in preparation to construct Vault 10, and so on in sequence). This will preclude increased leachate flows and the need for additional discharge capacity.

The final cap will greatly limit infiltration and leachate quantities. Future monitoring will confirm actual quantities. Once capped, each cell will thus have very small leachate quantities and minimal pumping.

The MHT system has a consented volume limit of 6,500 m^3 per day and quantities are anticipated to continue to be well within this. There are also existing controls on leachate quality under the site discharge consent. It is anticipated that these will continue to be met, with planned operations expected to result in improvements in quality with time.

The vaults' leachate drainage collection and extraction systems are designed in accordance with good practice [84]. The system for Vault 8 is described in Subsection 5.2 and that for Vault 9 in Subsection 5.3. The engineering for future vault bases and connections to integrate with existing vaults is given in Subsection 5.4.

Existing vault bases have falls to manhole pumping chambers on the west side wall for ease of access. Currently leachate is pumped from the manholes to a collector drain, then gravity fed to the MHT. Pumping will cease with the move to a passive, gravity-based system, which will form the basis for future vaults. The proposed line for the new gravity drain is shown on Figure 2.6.

Each future vault will have at least one or more reinforced concrete leachate manholes located on the perimeter wall. Vault 9 has two such manholes. Vault 9a will be integrated with the Vault 10 system when it is constructed. Vault 8 has three manholes along its southern wall, which will continue in use through the operational stage as monitoring points with the potential to be used for pumping if required. As part of capping, four new monitoring points will be established in Vault 8. These will provide leachate levels across the vault floor and allow gas and leachate sampling. This arrangement is expected to be repeated in future vaults. When demonstrated that they are no longer required – e.g. on the basis of monitoring data showing no flow, and at the latest at the end of active institutional control - the manholes and monitoring points will no longer be required and will either be broken out to below the level of the cap, and the cap restored, or re-used for monitoring with later cap reinstatement.

7.3 Trenches

Leachate is gravity piped from the base of the trenches to collection chambers and thence pumped to the MHT and thence to the Marine Pipeline. Leachate heads in the trenches and leachate flows will reduce to a low level with the planned STIM and final capping work.

Leachate collection from the end of the trenches is expected to continue until there is not sufficient leachate to justify discharge to the MHT. When demonstrated that they are no longer required – e.g. on the basis of monitoring data showing no flow, and at the latest at the end of active institutional control - the leachate collection chambers will be sealed and the headworks removed as part of the decommissioning of the leachate system.

As noted in Subsection 4.3.1 probe holes are used to monitor leachate levels, composition and gas in the trenches. These probe holes will be extended as part of capping and will continue to be used for monitoring until it can be demonstrated that they are no longer required. The probe holes will then be sealed, the surface headwork removed and the cap restored.

7.4 Decommissioning of the Marine Holding Tank and Associated Infrastructure

Once monitoring of both the trenches and the vaults has ceased, the drains to the MHT, the MHT itself and the sea pipeline will be decommissioned. The process of decommissioning will include ensuring that no fast pathways are introduced, for example during the transition to fully passive drainage arrangements for the vaults.

7.5 Post-closure Leachate Management

Post-closure leachate volumes will continue to be minimised by the final cap, and any leachate that does arise will be managed via passive drainage arrangements. These are set out in Section 5 and not repeated here.

8 Implementation

8.1 Overview

This section addresses considerations that apply to the ongoing implementation of optimisation, design, and construction programmes for the LLWR. It builds on the design aims and principles set out in previous sections. A full overview of the implementation of the ESC is provided separately in reference [17].

8.2 Timescales and Flexibility

Timeframes for the construction of the first strip of the cap are set out in Section 3. The text in this section builds upon that to outline key aspects of plans for the future engineering, highlighting the need for flexibility. In doing so it builds on timeframe discussions for individual components set out in Sections 3 to 5.

The creation of future vault modules and cap strips (and associated sections of the cut-off wall) will be flexible, linked to inventory projections, which are associated with unavoidable uncertainty, for example due to the nature of decommissioning programmes for legacy facilities. The current inventory projections and associated fill dates are set out in reference [4]. The programme of vault module creation will reflect those projections. For example, it is intended that future LLW (and ILW that can be managed as LLW) disposals will not be left in the open vault without being capped for more than around 10 years after receipt. Interim storage warehouses will provide contingency between iterations of cap installation if rates of disposal, and therefore, the frequency of cap strips, do not support this target (see also Subsection 5.6).

A further link is that excavation material from vault construction is a valuable source of profile fill material for use over the trenches. Its use is also beneficial to minimise the need for and extent of large long-term stockpiles. This is a further aspect in planning strip-capping schedules, alongside inventory projections.

Flexibility of timeframes for construction and closure is essential given the nature of uncertainties in the UK decommissioning programme. In addition, it is important that the engineering design does not unnecessarily foreclose options to manage future wastes, for example if treatment, conditioning or containerisation technologies evolve. The flexibility retained in ongoing gas venting decisions (Subsection 3.2.6) is an example.

In general, the robust but comparatively simple nature of the LLWR engineering concept means it is flexible. The adoption of the modular approach for different waste categories is a further example of how the basic design has led to flexible options for future wastes, and in turn the modular approach will further enhance the overall flexibility of the system in the future.

8.3 Key Principles for Implementation

The ongoing design, optimisation and construction programme will be led by a range of key principles. These include the engineering good practice, construction quality management and assurance, and safety requirements described in the context of cap construction (but which are widely applicable) in Subsection 2.5. Further principles include, but are not limited to, the following.

- The requirement for optimisation is recognised as a primary over-arching aspect of all future developments, from the overall disposal concept to detailed design levels. This will include the use of BAT and ensuring that processes demonstrate both ALARA and ALARP (see reference [9] for details). Continual demonstration of optimisation will be fundamental to ongoing operation of the site and development of the ESC.
- An integrated team of civil and mechanical engineers, ESC, NSC and operations experts will continue to be used. Use of an appropriate team, together with appropriate regulatory and wider stakeholder engagement, will help ensure well-rounded, logical implementation of decisions that take into account the full range of practical factors as well as wider socio-economic considerations.
- Links to, and integration with, the EPA and RMS specifically will also be maintained and further developed and enhanced as relevant optimisation and design programmes progress.
- Appropriate installation and long-term monitoring of the performance of the system as a whole, and engineering components specifically where appropriate, will be maintained.
- The approach to operations and related aspects such as worker dose management will be controlled to be consistent with design decisions (e.g. for ILW disposals) and experience from operations will also continue to feed into optimisation and design choices.
- Approaches such as WAC will be used to ensure that disposals to relevant vaults and associated modules are controlled and consistent with the design.
- The continued use of dedicated processes and embedded culture of reviewing ‘learning from experience’ and documenting the benefits in the next phases of tasks across the full engineering cycle.

These are examples of engineering-relevant controls. Further details on the approach to ESC implementation are found in reference [17].

8.4 Links to Waste Acceptance Criteria and Wider Controls

A key role of the WAC and wider site management controls, from an engineering perspective, is to provide confidence that containers and wastes will be disposed consistent with the concept. Relevant aspects include the following.

- Controls will ensure that wastes are only accepted using approved containers, and disposed to the relevant module (noting that, for example, modules for future LLW and for ILW that requires to be disposed in shielded modules will have their own criteria that will differ from those currently in place). Approved containers will be demonstrated to meet engineering demands such as:
    - supporting the multi-barrier containment concept (i.e. helping to reduce contaminant releases);
    - ensuring appropriate distribution of loads on the base;
    - ensuring safe stacking of containers from an operational perspective; and
    - supporting the required loads above the containers (including those associated with implementation of closure engineering, amongst other aspects).
- Requirements to minimise voidage will be continued, in the interest of minimising future settlements, and ensuring future containers are associated with lower potential voidage than existing older disposals.
- The WAC will ensure the range and quantities of chemicals disposed in the waste and their chemical condition are consistent with requirements for long-term performance of the repository.

The ESC and associated optimisation and engineering design processes set requirements that are reflected in both the WAC and the RMS[48]. These in turn take account of ESC requirements and assumptions. The relationship between the RMS and the design and optimisation processes is described further in Subsection 2.7.

8.5 Dose Management

Doses to workers and the local population as a result of site operations and future plans are minimised consistent with the LLWR site licence, ensuring the principles of ALARP and ALARA are applied. This includes design and optimisation for disposals. Examples of ongoing considerations follow.

- There may be requirements to modify some aspects of working practices or designs in the future, if it is identified that future LLW may present higher average dose rates than for past operational LLW (i.e. there is a higher proportion of containers with

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[48] See Subsection 2.7.

doses close to the current dose limit for acceptance). For example, potentially the outer vault walls (outside the 1 m vault wall drains) or landforms for future vaults could be designed to suitable heights to provide additional protection to off-site groups; although doses will be low, this approach could be very cost-effective, and thus still ALARA.

- In addition, a combination of controls on dose rates for any ILW that is accepted to the site - in particular for shielded module operation - and optimised working practices and shielding for disposal processes will be required. Initial work on this has already been factored in to the concept designs in Subsection 5.4 and reference [69] and the ILW inventory assumptions in reference [4].
- More broadly the principles of ALARP and ALARA will continue to be applied in developing the shielded module design for relevant ILW if disposed to the site.

8.6 Approach to Monitoring Engineering Installation and Post-installation Performance

The approach taken to the installation of engineering components and subsequent performance monitoring over both short and longer terms, is essential to building confidence in performance. Indeed, amongst the key factors typically considered in options assessment processes are the ability to understand, monitor and therefore model future performance.

Asset management and inspection arrangements will be a key part of engineering maintenance and monitoring plans through the PoA and into the period of active institutional control. This will include environmental monitoring, and leachate and groundwater monitoring. Further examples, focussing on the cap,[49] include:

- the cap constructability trial;
- plans to monitor the surcharge process before cap construction;
- monitoring of settlements during and after cap construction;
- gas monitoring to inform venting decisions; and
- the potential for long-term monitoring of the geomembrane evolution through sample exhumation and testing.

Approaches used during installation of an engineering component will be specific to the design and function of that component. An example for the first strip of the cap is set out in reference [29] [33] [34]. The long-term monitoring strategy is reported specifically in reference [8].

A key further aspect is the ability to remediate. If non-conformities in cap performance, for example, are observed during the remainder of the PoA, the operator will have the ability to

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[49] Based on Section 3. Intended as indicative rather than comprehensive.

remediate. Further information on the nature of potential activities during the PoA is summarised in reference [17].

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