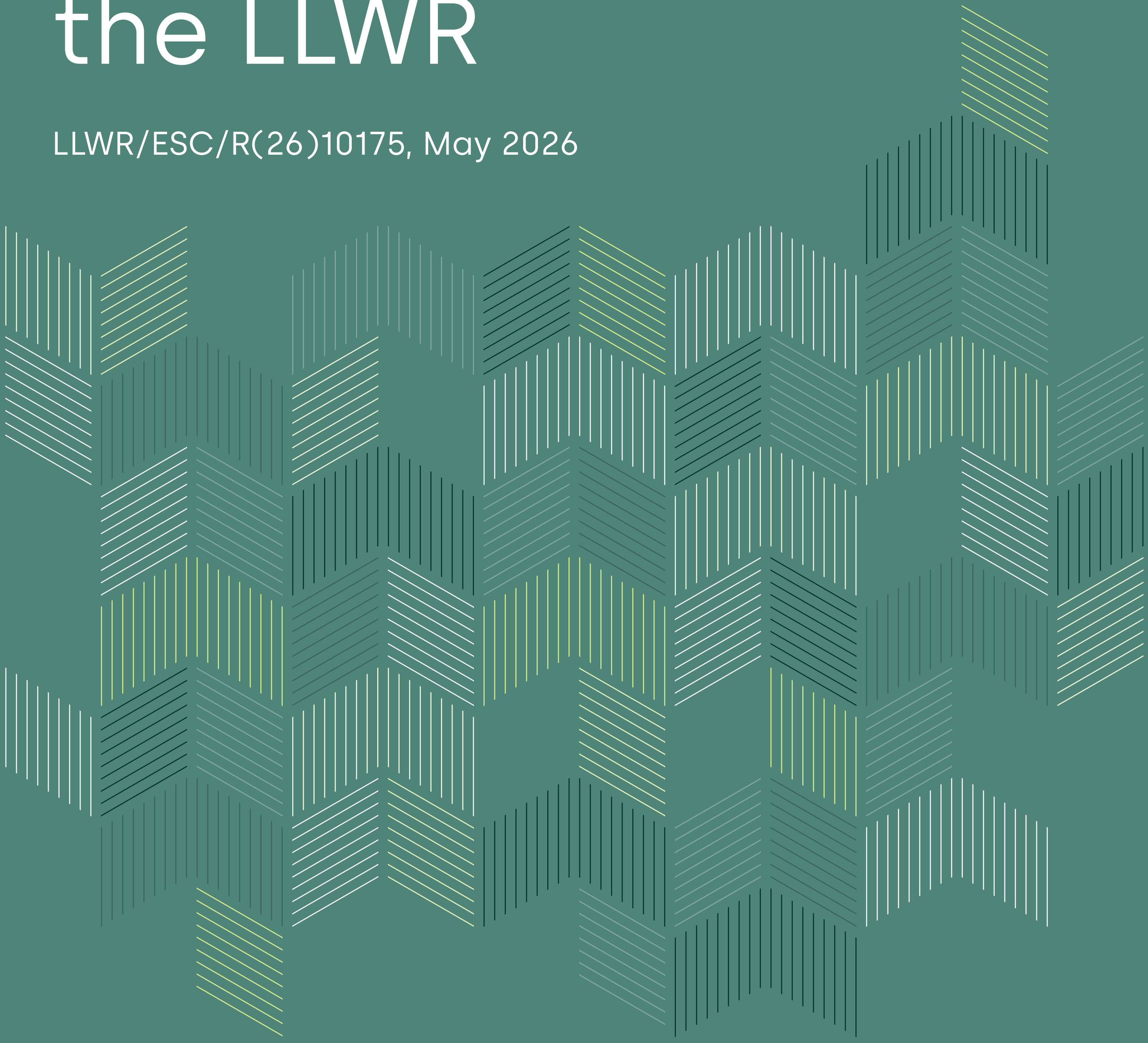
Nuclear Waste
Services

OPTIMISATION AND SITE DEVELOPMENT PLAN

2026 Environmental Safety Case for the LLWR

LLWR/ESC/R(26)10175, May 2026



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Preface

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

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

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

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

The 2026 ESC consists of documents at two levels:

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

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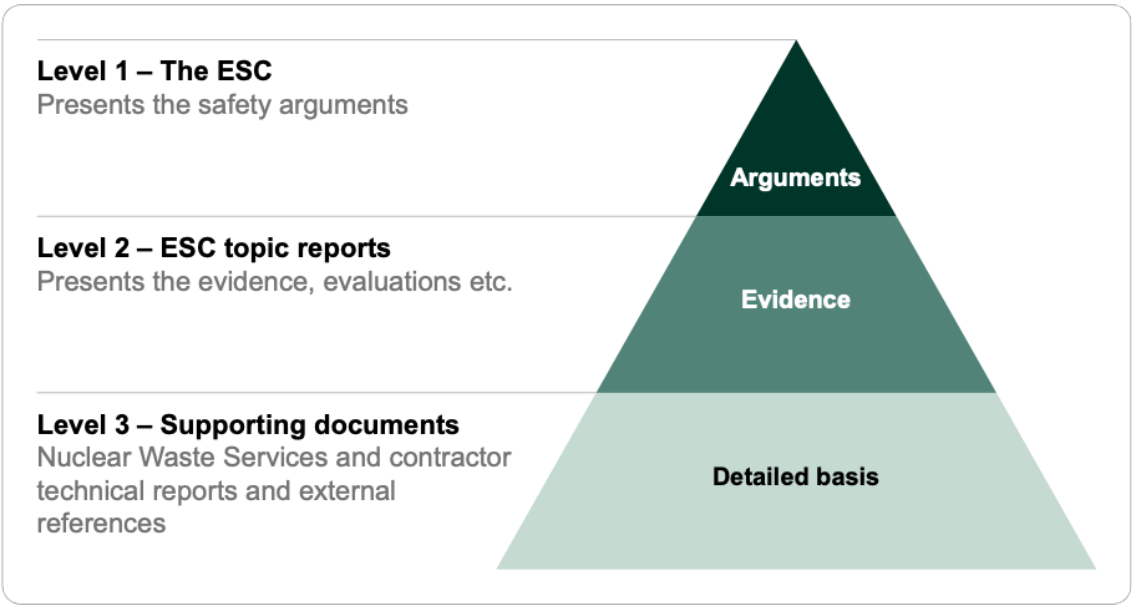
[1] In government policy, LLW is defined as radioactive waste having a radioactive content not exceeding four gigabecquerels per tonne (GBq t^{-1}) of alpha or 12 GBq t^{-1} of beta/gamma activity.

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



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

Engineering Design [5]	Presents the engineering design of the current facility and proposed changes as further disposal vaults are built and the disposal facility is closed
Near Field [6]	Describes our understanding of the chemical and physical evolution of the engineered disposal system
Hydrogeology [7]	Describes our understanding of the geology and hydrogeology of the site
Site Evolution [8]	Describes our understanding of how the site will evolve, with a focus on coastal erosion
Monitoring [9]	Presents our programme of environmental monitoring supporting the ESC
Optimisation and Site Development Plan	
Optimisation and Site Development Plan (this report)	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

Overview

Optimisation is the process by which our preferred approach to design, construction, operation, closure and post-closure arrangements for the LLWR is identified and justified. It draws on over-riding environmental safety management principles for the control of near-surface waste disposal, and examines the alternative ways in which they can be addressed, consistent with the environmental setting, history and anticipated future role of the facility. Options are analysed and compared, based on the principle of ensuring that radiological risks to members of the public are as low as reasonably achievable (ALARA), both during the period of authorisation (PoA) and afterwards.

Development of the ESC for the LLWR is a forward-looking, iterative process, ongoing through the life of the facility. It involves progressive development with focused improvement of data, understanding, design options and assessments. Decisions taken regarding the development and operation of the LLWR to meet environmental safety objectives are captured in the Site Development Plan (SDP). The SDP integrates the outcomes of optimisation studies to provide an optimised plan for the site, underpinning relevant sections of the site's Environmental Safety Strategy. It also provides context and guidance for ongoing optimisation and design work aligned with the developments that are described by the plan. In doing so it provides a summary of the optimised disposal model and plans for its implementation.

The aim in presenting the outcomes of optimisation is to make visible the key underpinning evidence and associated logic that has led us to put forward a preferred set of controls for future management of the LLWR. The logic begins by consideration of the type of controls that are available over the current and future environmental hazards presented by near-surface radioactive waste disposal, including:

- controls over waste inventory;
    - what, if anything, should be done about the existing disposals?
    - what controls are appropriate over the acceptance of wastes for disposal in future?
    - what conditioning is appropriate for wastes consigned for disposal?
- controls over design and operation;
    - what control functions are required of the different components of pre- and post-closure engineering, and how are those controls most effectively implemented in terms of:
        - design specification;
        - timing of construction/implementation?

    - what controls are required in order to ensure that radiological impacts are ALARA with respect to:
        - waste emplacement;
        - operational discharges?
- what active controls will be needed and for how long during closure of the facility?

Scope

This document describes the process and outcomes of LLWR-focussed studies relating to the types of control listed above, which together have informed decision making relating to future development and operation of the LLWR. The optimised control measures then form a key part of the implementation of the Environmental Safety Strategy for the facility, through execution of the SDP. Thus, for example, the broad strategic objective of ensuring isolation and containment of the source is translated into the specific design and operational principles that we will follow in future development of the facility over different timescales, through an appropriate combination of active and passive controls.

The relevant optimisation studies address four main areas:

- management controls and interventions relating to past disposals;
- management and engineering controls over future waste disposals to the LLWR, including waste acceptance, treatment and packaging, and methods for waste emplacement;
- active management controls over environmental safety performance, including implications for discharges during the PoA as well as post-closure arrangements for the LLWR site; and
- passive engineering controls over the environmental safety performance of the LLWR during the PoA and beyond, taking account of the functional role of engineering features in overall safety strategy, as well as their design and timing of implementation.

Previous iterations of the ESC were solely focussed on LLW. However, the NDA has asked us to explore options for disposing of Intermediate Level Waste (ILW) at the LLWR site, in line with UK Government Policy to consider alternative options for the management of ILW. The UK Government policy advocates engagement with regulators on the potential to use the LLWR to dispose of less hazardous ILW. In accordance with Government policy, we are considering the disposal of less hazardous ILW as part of the scope of the 2026 ESC. This work is a means by which we intend to engage with the regulator to explore the potential to dispose ILW at the LLWR site. However, it does not indicate that a decision to dispose ILW has been made.

On that basis, the role of the LLWR is wider than considered in the 2011 ESC. Our SDP also includes designs for ILW disposal at the LLWR, optimised at a level of detail consistent with the status of current decision-making processes.

Our approach presents firm optimisation arguments underpinning a robust design for the ESC. It also identifies where details of options can be beneficially kept flexible for future studies. Examples include designs and timeframes for gas venting through the final cap, and details of the approach to ILW disposal, should it be taken forward for the LLWR vaults.

The SDP recognises the need for ongoing flexibility and hence discusses the monitoring, assessment, design and related activities that will need to be undertaken in order to enable future decisions to continue to be suitably optimised.

Process

A major review of the LLWR design and wider aspects of optimisation and controls was undertaken for the 2011 ESC. This was an iterative, evidence-based process including stakeholder engagement. It identified an updated, optimised concept for the closure engineering and future vaults. Together with wider strategic influences such as the outcomes of NDA programmes on integrated waste management, the outcomes and process for the 2011 ESC provide the framework for ongoing design optimisation at the LLWR.

Through the work for the 2011 ESC and since, we have examined a range of aspects of the engineering design that would be employed in future development of the site. There are uncertainties associated with providing definitive estimates of long-term engineering performance at the system level, so the main emphasis in comparing engineering options for the purpose of design optimisation was whether there is a preference from the perspective of establishing confidence in demonstrating environmental safety. Having made such a comparison, we then assessed whether that preference would be materially affected by wider considerations.

The SDP also takes account of specific engineering options studies considering the potential for legacy trench waste retrievals, and the hydrological management of the trenches. Wider aspects of optimisation and controls cover operations, disposals and active institutional control.

Our process for optimisation of the LLWR disposal model follows the broad approach established in advance of the 2011 ESC. It is flexible, to ensure its application is proportionate to the challenges associated with different studies. Approaches have ranged from full, nested multi-criteria assessments for related engineering components with subsequent integration and reconciliation of outcomes, to direct logical arguments on the basis of evidence. In each case evidence is drawn from a range of sources to ensure necessary coverage of the criteria that are important when differentiating options. The priority assigned to confidence in environmental safety means that key inputs to options studies typically include the understanding gained through studies such as engineering performance assessments, and conceptual model development and assessments for different impact pathways. An integrated multi-disciplinary team underpins the execution of optimisation studies, supported by stakeholder engagement and ensuring independent challenge.

Optimisation outcomes identified are described below. For brevity the focus is on the key logic and main options arising from the relevant studies.

Optimised pre- and post-closure engineering concept

Our optimised concept for closure engineering and the provision of additional vault disposal capacity is based on providing the following controls.

- Minimisation of infiltration into the wastes via the use of a thick, multi-layer, single dome cap. A composite Bentonite Enhanced Sand (BES) and geomembrane layer is the key infiltration barrier.[2]
- Minimisation of water contact with wastes as the cap begins to degrade by the use of extensive drainage features at the 1 m level in the future vaults, with drainage arrangements at the 1 m level also backfitted to existing vaults. This will ensure that water will not contact wastes above this height for a prolonged period after closure.
- Over-topping waters will then be directed to drainage blankets under future vault bases to maximise access to the drainage capacity offered by the underlying geology. This is to preferentially direct any leachate to deeper systems. The cut-off wall will assist this aim, as well as minimising the potential for lateral releases of contaminated waters.
- Future vault bases will focus on supporting waste disposal operations, and management of leachate prior to installation of the closure engineering. A single composite BES and geomembrane liner will lie under the future vault concrete base slabs. This is in contrast to the double liner constructed for Vault 9, which was a response to the design intent for ensuring long-term storage that applied at the time.

The final cap also offers further controls.

- It will ensure isolation and containment of the wastes from the surface environment, and reduce direct radiation doses from the wastes.
- Together with the supporting profile fill, the final cap will provide a barrier reducing the probability of human intrusion into the wastes. The profile fill will also provide the cap geometry, and reduce strains in the cap that might otherwise arise from settlements. 1 m of fill has been added since the 2011 ESC to address potential settlements associated with enhanced voidage identified for Vault 8 wastes.

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[2] In this document, and indeed throughout our work on optimisation of the LLWR, usage of terms relating to the concept of minimisation by default reflect the wider context of ALARA (i.e. minimisation of impacts with wider factors being taken into account).

- The final cap will provide for the management of bulk, and therefore trace gases.

The closure engineering design is mature, reflecting an approach that has been developed over several decades, and consistent with good practice (for example, taking account of learning from landfill disposal and international facilities). Optimisation and design work for the capping programme has served to further review and confirm the 2011 ESC outcomes.

The optimised concept is summarised in Figure E1.

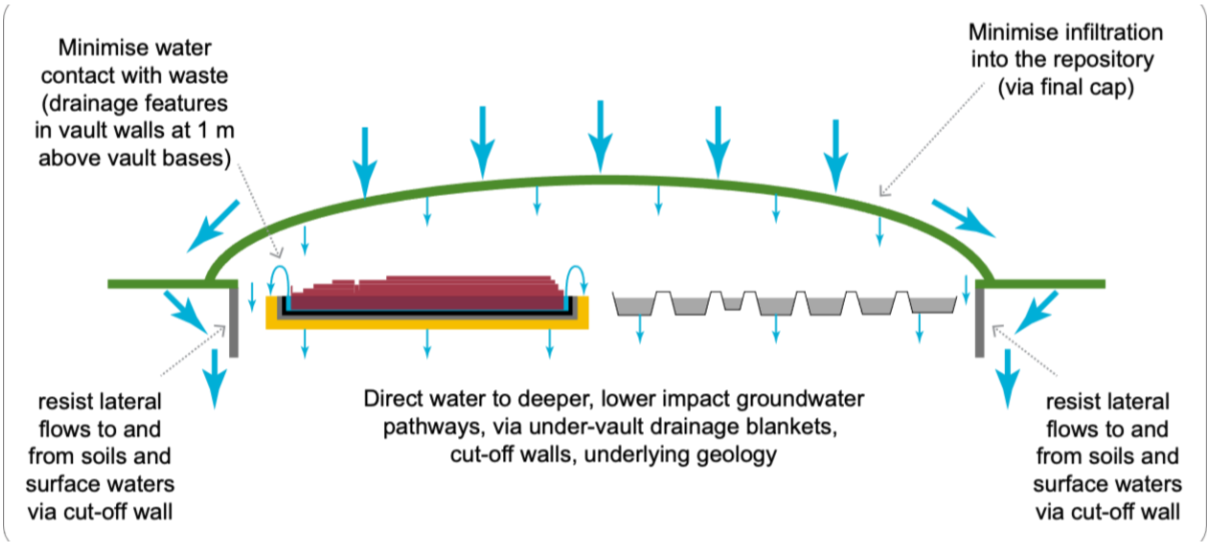

Figure E1: Schematic illustration of the optimised closure concept. The schematic focuses on water flows. It reflects evolution of the cap to a point where infiltration has increased sufficient for the vaults to saturate to the 1 m level, resulting in flows to passive drainage arrangements including the underlying vault drainage blankets.

Vault design and closure for different waste categories

Existing and Committed LLW

Since the 2011 ESC, a major programme of optimisation and design has taken forward the approach to closure of Vault 8 and the adjacent trenches, leading to the approval for construction of designs for relevant sections of the final cap, cut-off wall and profile fill.

As part of this, the understanding of the strength of containers in Vault 8 changed. It is now recognised that the placement of the closure engineering on top of the existing stacks would exceed their load bearing capacity, as would moving over them with plant to place additional containers to achieve higher stacking, therefore higher stacking is no longer planned. Options studies also identified that the stacks should be surcharged - that is, pre-loaded - to ensure that any deformations occur before placement of the final cap. This is necessary to ensure a stable formation for placement of the final cap and to maximise confidence in its longevity. This accepts that the contribution of the containers to the multi-barrier concept will be reduced as a result.

Existing disposals to Vault 9 to date have used the same container type as in Vault 8, and consignors are committed to the existing container until a new design is available (see Future LLW below). Disposals in Vault 9 and Vault 9a using this container will also be subject to surcharge for similar reasons as for Vault 8. Alternatives such as creating disposal corridors with roofs that would support closure loads, or the use of overpacks, were not favoured as they would delay the capping and vault sealing programme for relevant wastes and would involve materials and energy use as well as costs that were argued to be disproportionate.

For Vaults 9 and 9a, a practicable approach for existing and committed wastes was identified, based on early protection of the wastes through an extension of the final cap seal, with later surcharge combined with the process for final capping of Vaults 9 and 9a. This later surcharge approach will avoid the need to control material slopes and wider construction activities that would otherwise occur immediately adjacent to operational areas of the vaults.

Future LLW

Future LLW disposals to Vault 9 and the future vaults will transition to the use of a new container, once available. We assume these will be strengthened HHISOs that are able to accept closure loads without structural damage. Optimisation of the strengthened container design will consider the vault bases together with the container design as an integrated system.

Protection is required for the lids of the containers in uppermost stack positions. The lids are not load-bearing and would otherwise be damaged by closure loads. Use of steel and reinforced concrete Container Protection Units spanning the lids of the uppermost containers was identified as a proportionate response.

Studies have also considered the protection of disposals from environmental effects such as precipitation and wind-blown chloride. Uncertainties in inventory projections for future wastes mean there is also uncertainty in timeframes for strip capping of different vaults. A maximum target time period of 10 years between receipt and protection has been identified for future waste disposals, but future containers may not be covered by the final cap within this timeframe. Therefore, we have identified the use of interim storage warehouses, which would be standard, passively vented, and of industrial type construction. Simpler alternatives (e.g. tarpaulins or other membranes) were considered likely to be ineffective, and more complex options such as climate-controlled stores disproportionate to the hazard.

The warehouses will protect future disposals prior to their onward movement to final disposal positions before being covered by the final cap. They will be removed prior to final closure.

Potential for ILW Disposals

Since the 2011 ESC, the scope of the ESC has been broadened to consider the potential for ILW disposals in the vaults. We have identified optimised approaches for the disposal of different categories of ILW within the framework of the existing vault concept, should ILW disposal be taken forward.

- *ILW that can be managed as LLW* will be disposed within small mild steel containers that are similar to HHISOs, ensuring consistency with the existing concept. The smaller size recognises transport requirements for ILW and the likely need for transport overpacks (we assume use of Standard Waste Transport Containers). We have assumed that containers in the uppermost stack positions will, as for Future LLW, require Container Protection Units to protect container lids from closure loads. Similarly the interim storage warehouses approach will apply.
- *ILW that cannot be managed as LLW* for dose management reasons will be disposed in similar containers, but within reinforced concrete corridor-and-roof structures to manage doses during the period of operations; these are termed 'Shielded Modules'. These will provide shielding without presenting costs that are disproportionate to the benefits of vault ILW disposal. They require thicker bases for stability*;* rather than back-fitting to Vault 9, they will be located in the areas currently allocated for the future vaults.

Modular approach

A range of optimised approaches for the different waste categories is presented. This logically leads to a modular approach for the vaults. For Vaults 9 and 9a, different areas of the vaults will house existing and committed LLW, and future LLW, potentially together with any ILW that can be managed as LLW.

For the future vaults, discrete disposal modules will be used for future LLW and any ILW wastes. These modules might be constructed on the same base slab or utilise separate slab units. The future vaults will be delivered in a flexible manner, allowing for the sizes of modules to be altered in response to updates in disposal projections.

Management of legacy trench disposals

Review of Position on Trench Retrievals

In work both for the 2011 ESC, and in recent options reviews, we have considered a wide variety of actions identified as having the potential to achieve reduction in the radiological risk associated with disposals to the trenches. In doing so the potential reductions were set against the wider implications that would be associated with option implementation.

The emphasis in the options analysis has been on actions that would ‘target’ the retrieval of wastes from, or the implementation of other types of remedial action on, specific areas of the trenches. These are where localised high concentrations of key radionuclides are present that play a significant role in determining overall impacts from the facility.

Together, our original options assessments, and the recent reviews, demonstrate that the achievable scale of risk reduction (below what is already a low risk by comparison with the regulatory guidance level) is small compared with the costs and disruption that would necessarily be associated with targeted retrieval or remediation. We do not therefore propose to adopt any such actions within our SDP, and this has formed the basis for assumptions adopted in the ESC.

Hydrological Management

Optimisation studies have been undertaken since the 2011 ESC, following the recognition that water balance data suggested that the existing interim cap over the trenches was not performing as intended. It was identified that a larger fraction of precipitation than originally expected was entering the trenches. It was agreed that action needed to be taken to improve the cap over all of the trenches, as its condition was not considered consistent with good practice.

It was further identified that it would not be logical to upgrade the interim cap for the northern strip of the trenches as that would delay final capping. For the remaining areas that will not be covered by the first strip of the final cap, a new interim cap is currently in construction, as a result of the options studies. The cap is being emplaced over the existing geomembrane so that it is not necessary to excavate down to levels that could lead to interactions with the existing wastes.

Of the range of options considered for the new interim cap, a geosynthetic clay liner (GCL) was selected as providing an excellent barrier for an interim cap, whilst being comparatively simple to construct and to remove. Perforation of the existing geomembrane is required as part of the upgrade scheme, as well as removal of the GCL before final capping. These approaches will enhance predictability of long-term hydrological performance, and avoid the focussing of flows to the perimeter of the cap, with associated slip-plane hazards which could lead to risks to constructability and longer-term performance of the final cap.

Controls during repository operations

Wider aspects of optimisation associated with operations include the use of an optimised operational leachate management system; an optimised monitoring strategy; and approaches to ensuring wider environmental impacts arising from repository operations are minimised. Approaches such as construction quality management and assurance, and monitoring of engineering component construction and subsequent performance, are essential aspects of confidence in performance, as well as supporting ongoing optimisation.

The repository is managed in line with the ESC and thus optimised outcomes. This includes ensuring relevant controls are in place to adherence with the concept and related requirements. These are reflected in our approaches including Waste Acceptance Criteria (WAC), radiological capacity and emplacement strategy controls.

Controls during the Active Institutional Control period

It is not appropriate to define detailed plans for monitoring and management during the closure phase at this stage, for a site that we expect to remain in continuing operation for many decades and long-term direct management control thereafter. However, assessment calculations demonstrate that intrusion hazards associated with shorter-lived radionuclides are expected to fall substantially over the first 100 years following repository closure and much less rapidly thereafter, and we consider such a period to be an appropriate baseline figure for the assumed length of active control over the site in our assessment calculations. During active institutional control, there is the potential to allow some access to the site for amenity reasons, but controls will ensure that certain activities (e.g. construction on the cap) are prevented.

We consider that the most effective way of ensuring some control over use of the site persists for as long as practicable is to ensure that relevant information is identified and managed in an appropriate way such that knowledge is retained regarding the nature of hazards associated with the disposals that have taken place. We believe long-term information management would be assisted by close involvement of the local community in making decisions on beneficial future use of the site, as well as legal arrangements such as covenants and long-term leases to restrict the use of the land. However, our ESC does not rely on the provision of those arrangements beyond the end of active institutional control.

We do not anticipate the installation of engineered controls at the site to protect the LLWR in the long-term from the expected effects of coastal erosion, and we have not taken credit for such actions as part of the ESC. From the perspective of achieving risks that are ALARA, we believe there is appropriate evidence from the results of our safety assessments to indicate that such measures (which would imply a long-term burden for maintenance and re-building) would not be proportionate to the risks. Moreover, it would be impracticable to construct defences that could effectively prevent the repository being disrupted through the twin processes of erosion and sea-level rise. We also recognise that it would be inappropriate for the ESC to make any safety arguments that rely on such long-term provisions after the active institutional control period, noting that coastal evolution processes will continue for thousands of years.

Summary of disposal model optimisation studies since the 2011 ESC

Optimisation of the LLWR disposal model[3] has continued within the overall framework of the approach and concept set out in the 2011 ESC. A range of iterative and inter-linked options studies have together delivered the outcomes described above. Key studies are highlighted in Table E1 and together provide a summary of the main areas of development since the

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[3] The term 'disposal model' encompasses the engineering and waste disposal arrangements, and associated assumptions, that underpin the ESC and its assessments.

2011 ESC. For brevity the summary is specifically focussed on disposal model optimisation. It does not present a complete picture of all disposal model optimisation studies, but rather focusses on key examples to illustrate overall progress.

Table E1: Summary of Disposal Model Optimisation Studies since the 2011 ESC

Disposal Model Area	Studies
Closure of Vault 8 and the adjacent trenches, and the capping programme	Optimisation studies for the Repository Development programme covering: • iterations of optimisation on the approach to Vault 8 closure (leading to decisions including, for example, the surcharge of Vault 8 wastes); • the design of the final cap; • the approach to the cut-off wall; • further confirmation and development of approaches to other parts of the concept (e.g. profile fill, drainage material, ullage void management). Further options studies also include: • consideration of the use of the ‘remaining disposal area’ in Vault 8 for disposals; • consideration of options for the protection of containers from environmental effects prior to capping, for Vault 8 disposals; • a specific options study considering the application of learning from the EPA to the approach to selection of the geomembrane for the final cap; • ongoing consideration of potential options for gas venting.
Management of legacy trench disposals	Optimisation studies considering approaches to the trench wastes prior to final capping include: • a series of studies on the hydrological management of the trenches, concluding with optimisation and design work for the repository development and capping programme, leading to the upgrades to the trench cap that are currently being constructed; and • review of the options and arguments for trench management including the potential for retrievals.

Disposal Model Area	Studies
Vault 9 and future vault optimisation	Optimisation of existing and future disposals in Vault 9 and the future vaults, including, for example: • the approach to different categories of existing and future LLW disposals in Vault 9 and the future vaults; • the approach to disposal of any ILW that may be consigned to the vaults; • the approach to the protection of containers from environmental effects prior to capping, for Vault 9 and future vault disposals.
Leachate management	Studies on approach to leachate and wider water management, including operational approaches, and options during and after installation of closure engineering.
Key supporting studies	Other areas of optimisation, addressed more fully in other ESC documents, include (as examples): • optimisation of the approach to institutional control (see also the *ESC Implementation* and *Waste Management Plan* documents); • the approach to monitoring of the repository and its releases across the Period of Authorisation, including long-term monitoring of engineering performance (see also the *Monitoring* and *Engineering Design* documents).

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1 Introduction

1.1 Objectives

This document presents the approach to optimisation of the UK's Low-level Radioactive Waste Repository (LLWR), including existing and future disposal system engineering, and the approach to facility closure. It outlines the processes used to identify optimisation outcomes, and the associated logic and rationale. This includes setting out, in broad terms, the design and optimisation history of the facility.

The principle of optimisation is a fundamental element of international approaches to protection against radiological hazards, including radioactive wastes. It is reflected in guidance from bodies such as the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP) [19, 20, 21, 22]. To use the ICRP definition, optimisation is defined as *‘determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, as low as reasonably achievable, economic and societal factors being taken into account’* [21]. Correspondingly, optimisation is a key framing principle in national legislation and regulation. It is therefore recognised as a key part of the NDA's remit as described in their Strategy [23].

Similarly, optimisation is an important component of regulatory frameworks, including the Environment Agency's overall approach to radiological substances regulation (e.g. reference [24]). Optimisation is an over-arching principle in the ‘*Guidance on Requirements for Release from Radioactive Substances Regulation*’ for nuclear sites (the GRR; [25]) and in the environment agencies' ‘*Guidance on Requirements for Authorisation*’ for near-surface disposal facilities on land (the GRA; [26]).

In the GRA, optimisation is a specific radiological requirement for authorisation[4]. In this respect, it is recognised as *‘a continuing, forward-looking and iterative process aimed at maximising the margin of benefit over harm’* with the aim of *‘questioning whether everything reasonable has been done to reduce risks’* (GRA paragraph 4.4.3). In identifying the need for balance between the detriment associated with radiological risk and other benefits and detriments (economic, human, societal, political, etc.), it is further recognised that *‘The result of optimisation provides a radiological risk at a suitably low level, but not necessarily the option with the lowest possible radiological risk’* (GRA paragraph 4.4.4).

The approach to optimisation in the GRA is framed by Requirement 8.

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[4] Under the Environmental Permitting (England and Wales) Regulations 2016, which post-date publication of the GRA, waste disposal arrangements falling under RSA90 are now authorised through an environmental Permit.

Box 1.1: GRA Requirements most relevant to this report

Requirement R8: Optimisation

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

The GRA provisions can be seen to be part of the broader framework provided by the GRR that covers all aspects of the waste management life cycle, including the following GRR requirements.

Box 1.2: GRR Requirements most relevant to this report

Requirement R1. Optimisation of waste management options

Operators should use a proportionate process to select options, for managing radioactive waste arising from decommissioning and clean-up, that are optimised. This process shall ensure that the radiological risks to individual members of the public and the population as a whole are kept as low as reasonably achievable (ALARA) taking account of economic and social factors. The process should also consider the need to manage radiological risks to other living organisms and to manage the non-radiological hazards associated with radioactive waste.

Requirement R13. Optimisation of on-site disposals

Operators shall, through a process of optimisation, ensure that the radiological risks to individual members of the public and the population as a whole, from the on-site disposal of radioactive waste, are kept as low as reasonably achievable (ALARA) taking into account economic and social factors. Radiological risks shall be optimised throughout the period of radioactive substances regulation and afterwards, as far as can be judged at the time when relevant actions are taken. The process should also consider the need to manage radiological risks to other living organisms and to manage the non-radiological hazards associated with radioactive waste.

The framing of Requirement 13 within the GRR highlights its broad application across options including in-situ or re-use categories of on-site disposals for decommissioning sites, but the aims and intent remain valid for engineered repositories.

Optimisation in the context of radioactive waste management therefore focusses on demonstrating that impacts via relevant pathways are controlled to be As Low As

Reasonably Achievable (ALARA). This is typically achieved through BAT (Best Available Techniques) studies, utilising proportionate options assessment processes.

Insufficient consideration of optimisation was one of the main criticisms by the Environment Agency following their review [27] of the 2002 Safety Cases [28, 29] produced by the previous operator, BNFL. This was addressed in the 2011 ESC [30, 31] and the optimisation approach set out in the 2011 ESC has since provided the basis for further optimisation and design.

The objectives of this report are to demonstrate that the repository, including the approach to managing existing and future disposals and associated engineering, together with supporting management and operational approaches, are optimised. In doing so it summarises the wider context for UK waste-cycle optimisation as a framework for LLWR operations and disposals, and then describes the approach to optimisation of the LLWR within that remit.[5] As part of this a summary of the optimisation approach and concept established for the 2011 ESC is provided, together with the outcomes and rationale for optimisation studies since then.

This report therefore presents the optimised 'disposal model' that provides the basis for the ESC. The supporting rationale is also presented. The outcomes and logic then underpin the Environmental Safety Strategy presented in the ESC '*Main Report*' [1]. The Site Development Plan (SDP), identified to implement the Environmental Safety Strategy, on the basis of the optimisation studies, is also presented in this document.

The engineering design aspects of the disposal model arising from these processes are presented in more detail in the '*Engineering Design*' report [5]. The understanding of the evolution of the engineering is described in the '*Engineering Performance Assessment*' report [12]. Other controls of relevance to the disposal model e.g. Waste Acceptance Criteria (WAC) are presented in the '*Implementation*' report [17].

1.2 Scope

The central role of an Environmental Safety Strategy lies at the heart of expectations regarding the demonstration of consistency with regulatory principles and requirements (GRA [26], paragraph 7.2.2). A comprehensive account of the Environmental Safety Strategy for the LLWR is therefore a core element of the overall ESC [1]. We consider that such a strategy encompasses both the way in which environmental safety is achieved and the means by which it is demonstrated. Hence, the Environmental Safety Strategy for the LLWR establishes first a set of over-riding safety objectives, consistent with the declared goal of providing a route for the environmentally safe disposal of LLW. It also defines a process by which those safety objectives are translated into specific actions (the 'development plan' for

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[5] The Waste Management Plan (WMP) [10] provides further details of wider optimisation beyond the disposal model. The term 'disposal model' encompasses the engineering and waste disposal arrangements, and associated assumptions, that underpin the ESC and its assessments.

future management and use of the facility), the management framework within which those actions are implemented, and the characterisation, monitoring and analysis undertaken to provide assurance that objectives are being met.

The key strategic environmental safety objectives are identified as:

- Control of the source – i.e. managing the total inventory and concentration of radionuclides being disposed, as well as the wasteforms in which they are disposed and the manner of their emplacement.
- Isolation of the source from disturbance – i.e. providing optimised protection against the threats of disturbance by natural processes (erosion, water infiltration) and human activities.
- Containment of the source – i.e. ensuring that the wasteform, packaging, emplacement arrangements and repository engineering act together to minimise the likelihood that contaminants will be released from the facility, for as long as practicable.
- Management of residual releases – i.e. seeking to control any releases that may occur in such a way that their impacts are minimised. This includes releases to groundwater but also impacts through other pathways including airborne releases and external irradiation.

Consistent with overall safety management principles, discussed in the GRA [26], the emphasis during the PoA is on aiming for passive safety so far as is reasonably practicable, but with some necessary active engineered systems and human actions. After the end of the PoA, the ESC has to rely entirely on features of the system that do not depend on human intervention or active engineered measures.

Within this system, optimisation is the process by which our approach to design, construction, operation, closure and post-closure arrangements for the LLWR is identified and justified. It takes the over-riding safety objectives and examines alternative ways in which they can be addressed, refining the broad strategic goals into a preferred set of control measures that address environmental safety management. These preferred approaches provide the foundation of our SDP for the LLWR. The high-level optimisation arguments underpinning the SDP inform relevant aspects of the Environmental Safety Strategy for the facility. Execution of the SDP ensures the Environmental Safety Strategy is implemented, including providing a framework for ongoing optimisation.

The SDP therefore integrates the outcomes of optimisation studies to provide an optimised plan for the site, underpinning relevant sections of the site's Environmental Safety Strategy. It also provides context and guidance for ongoing optimisation and design work aligned with the developments that are described by the plan. In doing so it provides a summary of the optimised disposal model and plans for its implementation.

The GRA acknowledges (paragraph 4.4.4) that *‘Optimisation decisions are constrained by the circumstances prevailing at the time’.* This reflects recognition that demonstrating radiological doses and risks are ALARA is a continuing and iterative process through the lifecycle of a disposal facility. Because the LLWR is an operating facility with a substantial history of operations since the 1950s, decisions regarding its future management, design and operation are framed, and to a certain extent also constrained, by past actions. The logic and evidence developed in support of decisions regarding the future of the facility therefore start from an understanding of decisions that were taken in the past and the considerations that related to those decisions when they were taken (GRA, paragraph 6.3.67).

Not all aspects of past decisions are considered in detail in this report, although the overall framing of future plans is an integral part of what is presented here. In particular, the '*Site History and Description*' report [3] and the '*Implementation*' report [17] provide accounts of some of the background to the current status of the facility. While the main outcomes of the previous optimisation work for the 2011 ESC are outlined in this document, reference is also made to the 2011 ESC reports (see reference [31] and underpinning references) for full details.

The outcomes of optimisation are reflected in the design taken forward in the '*Engineering Design*' report [5]. In turn, therefore, they also underpin the assessments presented for the ESC [14, 13]. The relationships between the key engineering-focussed ESC level 2 documents are shown in Figure 1.1.

The overall principles and approach applied to optimisation of the LLWR that are set out in this document apply in general to all aspects of the LLWR site operation and design that are of relevance to the ESC (in particular in its role as a Site-wide Environmental Safety Case or SWESC). However, the primary focus of this document is on optimisation of the disposal model at the LLWR.

There are other sources of contamination at the site, for example due to its history as a Royal Ordnance Factory site before its current radioactive waste disposal use, and as a result of plutonium-related operations. These aspects are primarily of relevance to the wider WMP [10] and SWESC as opposed to the component of the SWESC that is specifically focussed on the disposal facility itself. Therefore, whilst the optimisation process used is consistent with the general approach laid out in subsequent sections of this document, the outcomes of optimisation of the management of wider site contamination are presented in the WMP.

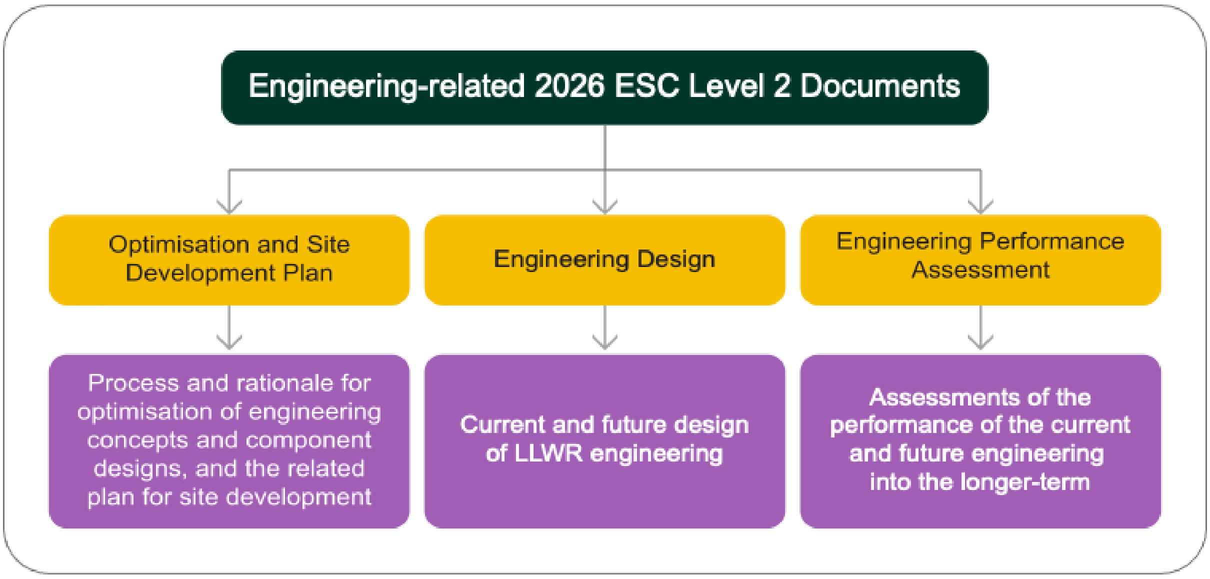

Figure 1.1: Relationship between key engineering-related 2026 ESC Level 2 documents. This diagram focusses on the presentation of information and is not indicative of the interactions of the processes involved in optimisation, design and performance assessment.[6]

1.3 Structure

The remainder of the report is structured as follows.

- Section 2 describes the optimisation framework for the LLWR provided by the wider UK waste management strategies and approaches. It also describes aspects of good practice processes and wider approaches that are relevant to the LLWR.
- Section 3 outlines the basis for optimisation of the LLWR, including past optimisation studies and the process for continuing optimisation priorities.
- Section 4 provides an overview of the site history and status, and ongoing optimisation priorities, in order to underpin subsequent sections on the optimisation of the site.
- Section 5 describes the optimisation process outcomes for existing and future disposal arrangements for the vaults, and for the facility closure engineering as a whole. This is complemented by Section 6 which describes the outcomes of optimisation processes for the interim management of the trench wastes. The optimised approach identified for the 2011 ESC is identified in each case, followed by the outcomes of subsequent optimisation studies, within the framework of the 2011 ESC outcomes.

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[6] An overview of processes and interactions is provided in Section 2 of the Engineering Design document [5].

- Section 7 presents a complementary discussion on the optimisation of monitoring and wider controls on the repository.
- Section 8 provides a summary of the optimisation studies undertaken for the LLWR disposal facility since the 2011 ESC.
- Section 9 presents the SDP arising from and defined by the optimisation outcomes.

2 Framework for Optimisation of the LLWR

2.1 Overview

Optimisation of the LLWR is undertaken consistent with national strategy, and the related integrated consideration of life-cycle waste management and disposal programmes across the UK. Regulatory and good practice guidance then informs on how optimisation should be demonstrated at the LLWR within that wider framework.

This section describes key aspects of that wider framework that are relevant to optimisation of the LLWR disposal model. It underpins subsequent sections which provide specific details of the optimisation process for the LLWR, and then its application to key features and associated engineering and controls at the LLWR site (Sections 3 to 7).

2.2 Role of the LLWR

The UK Government and devolved administrations have published a *UK Strategy for the Management of Solid Low Level Radioactive Waste from the Nuclear Industry* [32]. This document has since underpinned LLW-related aspects of the subsequent *NDA Radioactive Waste Strategy* published in 2019 [33], and in turn the overall *NDA Strategy* [23].[7]

The strategy has been prepared in response to relevant Government policies on LLW, the most recent version of which is the '*UK policy framework for managing radioactive substances and nuclear decommissioning*', published in 2024 [34]. The NDA has also developed programmes and projects on the theme of integrated waste management to underpin delivery and implementation of the UK Strategy.

With respect to the role of the LLWR, the UK Strategy underlines that:

- systematic implementation of the waste hierarchy at waste producer sites is expected to (continue to) reduce the volumes of LLW that need to be disposed at the LLWR.[8] Where wastes cannot be prevented from arising, the UK Strategy seeks to optimise the segregation of radioactive waste so that as much as practicable is handled as very low level waste (VLLW) or exempt waste, and to increase opportunities for reuse and recycling of waste materials;
- disposal needs to be retained as an option for some wastes that are not amenable to being managed at higher levels in the waste hierarchy;

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[7] Relevant provisions of the 2025 draft NDA strategy under update after a consultation period at the time of writing, also retain consistency with these underpinning documents.

[8] Compared to the volumes that would otherwise arise without waste treatment and diversion; volumes of wastes overall are projected to increase as decommissioning of UK legacy nuclear facilities progresses [4].

- capacity for receiving waste at the LLWR site, from both a volumetric and radiological perspective, is finite;
- consistent with the Policy requirement for a risk-informed approach to ensure safety and protection of the environment [34], waste consignors will be expected to make appropriate use of alternative waste management routes to support volume reduction as well as fit-for-purpose disposal facilities that reflect the lower hazard associated with VLLW;
- a key NDA priority, driven by the requirement to use public money efficiently, is to make the best use of existing LLW management assets. The strategy seeks to ensure the proportionate use of LLWR by only disposing of wastes that cannot be managed via other routes, to ensure capacity for the long term.

Previously, a Strategic Environmental Assessment (SEA), conducted to support development of the UK Strategy, concluded that best use of the LLWR is preferred over other options for the provision of LLW disposal capacity [32], and UK policy and strategy developments since then have continued to support that outcome. Best use of the LLWR was assumed to involve rigorous application of the waste hierarchy across NDA sites and disposing only those wastes that require the level of safety and security offered by engineered disposal.[9]

With respect to the provision of disposal capacity, the conclusions of the original SEA (and hence the strategy that it still informs) were nevertheless contingent on the identified key assumption that all alternative strategic options (i.e. variants based either on continued use or replacement of the LLWR) would be capable of meeting regulatory requirements and, specifically, that *'LLWR Ltd will be able to make an acceptable Environmental Safety Case for the LLWR'* [32]. Hence the identified candidate strategies were not differentiated in terms of their implications for health and safety, except with respect to the additional hazards that would be associated with retrieval, handling and transfer of wastes from the LLWR to a hypothetical replacement facility. The ability to make an acceptable ESC for the LLWR was then satisfied by the development of the 2011 ESC and the review and permitting process that followed.

A more recent development of framing aspects of UK LLW policy and strategy [23, 34], and thus NDA and IWMP plans, concerns the adoption of risk-based approaches to disposal. The intent is to focus on the hazard presented by wastes in deciding on optimal treatment

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[9] 'Best use' of the LLWR (in the context of its role as a component of the UK Strategy for LLW management) is not the same as optimisation with respect to the control of radiological risks. Nevertheless, operational considerations associated with managing the capacity of the facility are important in achieving the necessary balance between radiological detriment and other benefits and detriments (Subsection 1.1). Factors relevant to LLWR's role in implementing UK Strategy through the waste hierarchy are therefore highlighted in Sections 5 to 7 as part of the wider discussion of issues relevant to the optimisation of risks associated with future waste disposal plans.

and disposal routes, rather than being artificially constrained by existing LLW and Intermediate Level Waste (ILW) categorisation approaches.

The NDA has therefore asked us to explore options for the disposal of ILW at the LLWR site, in line with UK Government Policy [34] to consider alternative options for the management of ILW. The UK Government policy advocates engagement with regulators on the potential to use the LLWR to dispose of less hazardous ILW. In accordance with Government policy, we are considering the disposal of less hazardous ILW as part of the scope of the 2026 ESC. This work is a means by which we intend to engage with the regulator to explore the potential to dispose ILW at the LLWR site. However, it does not indicate that a decision to dispose ILW has been made.

On that basis, the role of the LLWR is wider than considered in the 2011 ESC. This document therefore also covers designs for ILW disposal at the LLWR, as well as LLW, optimised at a level of detail consistent with the status of current decision-making processes. An optimised approach to relevant categories of ILW disposal is presented, sufficient to underpin ESC assessments and arguments. However, it is recognised that further optimisation and design work would be required to develop the approaches presented into a formal, detailed design.

2.3 Wider UK Strategy and Optimisation Frameworks

As highlighted in Sections 1 and 2.2, the wider framework of national policy and strategy processes ensures the principle of optimisation is applied across the waste management life-cycle. Whilst this document is focussed specifically on the remit of the ESC, this wider context is relevant in establishing the boundaries of optimisation at the LLWR, including recognition of the role of decisions at the LLWR as part of wider life-cycle waste management optimisation. This integrated approach also supports the consistent consideration of wider factors, such as the impacts on consignors, within LLWR options processes, with associated information exchange and iteration.[10]

The Energy Act 2004 (as amended [35]) mandates that the NDA implements optimisation for all strategies and related activities associated with the management of radioactive wastes. This priority is similarly reflected in the UK Government policy and strategy (e.g. reference [34]) and therefore the NDA strategy (e.g. reference [23]).

Optimisation is therefore applied throughout all the different hierarchies of UK strategy and implementation. The approach is responsive and iterative; optimisation of the LLWR is framed by wider strategy, but practicalities and requirements associated with the LLWR, its disposals and consignors, in turn inform iterations of over-arching strategy. NDA strategy highlights the importance of LLWR and its capacity as a national asset and recognises that

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[10] An example is optimisation of the approach to containers for LLWR disposals; the containers need to provide engineering functions at the repository, but in establishing proportionality, options also need to take into account wider factors such as industry-wide costs and the impacts on consignors of different potential options.

optimised disposal frameworks for relevant waste categories are essential to enabling effective progress in decommissioning of the UK's legacy facilities, as well as supporting wider UK waste producers.

The guiding themes and requirements of UK Strategy and Policy [34] frame the approach to integrated waste management for the UK's LLW. NDA's projects and programmes in this area have involved partners including:

- all nuclear industry and defence sector waste producers, power generators, medical and nuclear services companies;
- organisations providing waste treatment and disposal services;
- NWS (in its disposal role);
- regulators; and
- local and national government.

These programmes have ensured collaboration and information sharing to optimise waste management practices, and to deliver the safe, secure, environmentally responsible and cost-effective treatment and disposal of LLW in the UK, in accordance with the national strategy.

Perhaps the most instructive example of these programmes concerns the response to the original priorities of the national LLW strategy in terms of LLWR capacity. At the time of the development of the 2011 ESC, there were concerns that the capacity of the LLWR would be exceeded and that this would impede legacy facility decommissioning and associated hazard reduction, if the existing waste management practice − predominantly, at the time, disposal of all LLW and VLLW arisings to the LLWR with limited treatment − did not change. This is reflected in the 2011 ESC's consideration of the potential extension of the repository capacity up to Vault 20, and in the identification of priorities for protection of LLWR capacity which remain a key part of UK strategy.

A programme of national strategic options assessments, engagements and pro-active co-working across organisational boundaries followed, to enhance the optimised application of the waste hierarchy across the UK, whilst addressing NDA strategic objectives. These objectives included:

- recognising the priority of enhanced sorting, segregation and characterisation to minimise volumes sentenced as LLW;
- implementing enhanced potential for diversion of lower activity LLW wastes to other facilities, and
- implementing waste treatment processes to reduce volumes.

Changes to site permits by the Environment Agency have also contributed to this process, enabling NWS (and its forerunner organisation LLW Repository Ltd) to co-ordinate the diversion and treatment of wastes as well as disposal to the repository. Together, these have led to substantial reductions to current and future estimated volumes for disposal at the LLWR, as reported in the *Disposal Facility Inventory* report [4]. Indeed, in contrast to the 2011 ESC position on the potential need for additional vaults, current projections only require disposals up to Vault 12[11].

Strategic options processes consistent with the optimisation principle provided key contributions to the approaches that led to this change, and provide continuing guidance to the industry. An example is the 'National Strategic BAT' studies for key waste categories. These are national options studies implemented through a process that included significant engagement across the industry and its regulators, and have been actively reviewed and maintained since their inception. The studies are used to inform national strategy, and to develop national consensus on optimised good practice for key LLW waste categories. They also provide a starting point and framework for individual consignor BAT studies for relevant wastes. They are actively maintained by NWS on behalf of the NDA via continued engagement and collaboration with the relevant stakeholders. Reference [36] provides an overview of the process and key associated studies.

An important aim of these processes is to ensure that an 'optimisation mindset' is established across the industry. The management approach and culture of NWS and related organisations therefore reflect the priority of optimisation. Correspondingly related principles and objectives are embedded in the culture of the NWS as an organisation. Further details of management approaches are provided in the *Management and Dialogue* report [2].

2.4 General Guidance on Demonstration of BAT

The primary vehicle in England for demonstrating optimisation in the context of radioactive waste management is through undertaking actions underpinned by a BAT study. As well as the GRA [26] and the GRR [25], our approach to BAT takes into account wider regulatory guidance on optimisation (e.g. reference [24]), and UK nuclear industry guidance (e.g. reference [37]). None of these sources of guidance are prescriptive in terms of how an optimisation assessment should be undertaken, but they establish expectations regarding process and fitness for purpose that are intended to support building consensus in a proposed solution.

The interpretation of BAT (or, more broadly, optimisation) in the context of radioactive waste management has tended to follow a fairly broad remit, reflecting the desire to minimise, so far as is practicable, the release of radioactivity to the environment while also taking into account a wider range of factors, including cost-effectiveness, technological status and feasibility, operational safety, wider environmental considerations (including non-radiological impacts, and aspects such as energy and other resource use) and socio-economic factors (e.g. reference [24]). This broad balance between potentially conflicting objectives is

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[11] The current design, however, retains provision for disposals up to Vault 14 to ensure flexibility and to accommodate uncertainties in arising projections.

particularly relevant in the context of activities on nuclear licensed sites, where there is an over-riding legal requirement on site licensees to demonstrate that the risks associated with operations have been reduced to levels that are as low as reasonably practicable (ALARP). For studies focussing on optimisation of disposal facilities from the perspective of minimising impacts via environmental pathways, however, regulatory guidance, good practice resources and practical experience at the LLWR concur that a well-planned optimisation study covering all the relevant factors should be sufficient to demonstrate ALARA and ALARP together within the combined BAT case (e.g. references [38], [39]).[12]

As described in reference [24], it is generally recognised that approaches to *the demonstration of optimisation may vary*, but that *in all cases the overall assessment process can be described very simply as*: *asking if there is anything further that can be done to reduce doses to people.* The guidance then makes clear that options to reduce doses to people (we interpret as including via environmental pathways) should be implemented provided they reflect the principle of proportionality, taking into account wider factors including any associated detriments. This is further developed in the GRA [26], paragraph 6.3.58), that states: *Although reducing radiological risk is important, it should not be given a weight out of proportion to other considerations. In other words, the best way forward is not necessarily the one that offers the lowest radiological risk.*

In the design optimisation work supporting the 2011 ESC (e.g. reference [40]) given the particular context of a long-term ESC for solid waste disposal, the above steps were interpreted as follows.

- The main emphasis in comparing engineering options was whether there is a clear preference from the perspective of establishing confidence in the environmental safety performance of LLWR.
- It was then necessary to determine whether that preference may be materially affected by wider considerations.

In practice, it was recognised that the choice between options that are differentiated in terms of confidence in environmental safety performance is likely to be challenged only where there is a strong (and contrary) differentiation in terms of other important factors. Alternatively, that options which cannot readily be discriminated in terms of providing confidence in environmental safety may then be differentiated on the basis of other considerations.

There are no definitive methods for demonstrating proportional outcomes in optimisation. Guidance from the Environment Agency [24] considers that '*sound judgment and a clear, logical argument*' can often be sufficient to make a successful case. This approach was

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[12] In this document, and indeed throughout our work on optimisation of the LLWR, usage of terms relating to the concept of minimisation by default reflect the wider context of ALARA (i.e. minimisation of impacts with wider factors being taken into account).

embedded in the process followed for the 2011 ESC and therefore the studies that have followed. Nevertheless, an important reference point (consistent with the adoption of a tiered approach to risk management) is clearly the magnitude of radiological detriment associated with any given management option.

Although a consistent overall approach has been applied across optimisation studies for the LLWR disposal model, it is necessarily the case that the specifics of its application need to be tailored to each study. While the same basic principles apply generally, individual processes reflect (for example) whether the study is more strategic in nature, or focussed on detailed optimisation of a specific aspect of the system. In addition, it is important to identify criteria or factors that represent the key areas of differentiation between options as a main focus. This may include recognising where other criteria are important in principle, but do not specifically discriminate between options.

The optimisation work for the 2011 ESC identified an optimised pre- and post-closure engineering concept for the LLW (summarised in Section 5). In doing so, it identified key areas of logic and associated criteria and differentials relevant to optimisation of the LLWR disposal model. This has provided a process and conceptual framework for subsequent optimisation studies, assisting consistency and allowing a refined focus on the key options and differentiators associated with a particular challenge.

2.5 Regulatory and Wider Stakeholder Engagement

A core aspect of good practice and guidance for optimisation is engagement with regulators and stakeholders. The broader ESC approach to engagement is described in the *Management and Dialogue* report [2].

In addition to regulators, relevant stakeholder constituencies include planning authority representatives, local stakeholders or other groups, and industry stakeholders such as consignors and treatment facility providers. Consistent with good practice, one important area of input from stakeholders concerns views on the relative importance (or weighting) of differentiating criteria.

Our process recognises that regulators cannot directly contribute to decisions arising from optimisation processes. However, regulatory engagement in optimisation programmes is an essential part of our approach. Participation is particularly important from the perspective of demonstrating the process and its logic, providing a mechanism for challenge and queries, and helping clarity on matters of interpretation of regulation.

Approaches to stakeholder and regulatory engagement have varied depending on the nature of optimisation programmes. For major studies including for example the pre- and post-closure concept optimisation studies for the 2011 ESC (Subsection 5.2), and the recent process for capping and closure of Vault 8 and the adjacent trenches (Subsections 5.3 and 5.4), regulators were explicitly involved in scoping and assessment stages. For the pre- and post-closure optimisation study, wider stakeholder groups were also involved in the options process.

For other studies, other approaches have been followed to ensure appropriate engagement. For example, specific regulatory review and input meetings have been arranged, or in other cases discussions during regular liaison meetings have been identified as a proportionate approach. A wider overview of the approach to engagement for the ESC is provided in reference [2].

3 Basis for LLWR Optimisation

3.1 Overview

In this section the control measures that need to be taken into account in determining an optimised safety strategy are identified, and the approach taken in informing decisions between options described. This includes the approach to:

- identifying the overall optimised concept for ongoing disposals and closure;
- managing past disposals; and
- ongoing optimisation within the context of the wider concept.

3.2 Principles of Options Assessment for Optimisation of the LLWR

Regulatory guidance relating to the principle of optimisation highlights that optimisation reflects a balanced approach to risk within the context of ALARA. It also acknowledges that measures taken today cannot guarantee a particular outcome in future, and that the question of whether sufficient measures have been taken is *'inherently a matter of judgement'* (GRA [26], paragraph 4.1.3).

The need to demonstrate that an appropriate balance has been achieved between radiological risk and other possible detriments, or benefits, in the determination of management controls over waste disposal lies at the heart of the optimisation process for the LLWR. As a general rule, and particularly in relation to the definition of management strategy, this implies the need to examine what feasible options are available for a particular aspect of control. These options then need to be compared in terms of the balance they represent between radiological risk and other factors.

In comparing options for the LLWR, our focus has been to make visible the key underpinning evidence and logic that has led us to put forward the proposed set of controls for future management of the LLWR. Our optimisation process is intentionally flexible to allow its application to focus on the differing nature of controls at a proportionate level of detail.

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

This approach is particularly suited to optimisation assessments of a complex system such as the LLWR and allows greater insights to be gained than a quantitative approach in which option performance against each attribute is numerically evaluated. This is because significant uncertainties arise when considering long-term environmental management and judgements are required that can be challenging to address efficiently in quantitative options processes. In addition, many of the relevant attributes do not lend themselves to quantification and so expert judgement is thus required to assign them a quantitative metric.[13]

In any case, it is the logic and arguments underpinning the analysis which are the key outcomes, and it is more direct and transparent to present these qualitative assessments and associated arguments directly.

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

3.3 Optimisation and Controls for the LLWR

The essential nature of optimisation, whether in design, construction, operation, closure or post-closure management of the LLWR, or in the determination of waste acceptance controls, can be expressed as the identification of a preferred set of control measures consistent with the goal of achieving ALARA with respect to the management of radiological impacts. An effectively designed and executed optimisation process informs the development of plans and programmes for the lifetime management of the facility, by establishing the actions that need to be taken to ensure an appropriate level of both active and passive control over the hazards presented by the wastes. These control measures are then enacted through, for example, inventory and WAC controls, operational procedures and institutional controls, and the functions provided by optimised designs of engineering components.

Optimisation is an iterative process which *involves 'continually questioning whether everything reasonable has been done to reduce risks'* (GRA [26], paragraph 4.4.3). Given the strategic role assigned to the LLWR and the current status of the facility (i.e. understanding why the facility is the way it is), the requirement for the ESC is therefore to determine a vision for the controls that need to be put in place now and in the future. The optimised controls, both active and passive, that are established then effectively become the functional expression of the Environmental Safety Strategy for the facility, implemented in the SDP (Section 9).

In broad terms, the controls that are available over the current and future environmental hazards presented by radioactive disposal can be classified as:

- controls over waste inventory;
    - what, if anything, should be done about the existing disposals?

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[13] Quantitative outputs, for example from assessment and underpinning models, are however key in informing these judgements and demonstrating they address the associated uncertainties; see also Subsection 3.5.5.

  - what controls are appropriate over the acceptance of wastes for disposal in future?
  - what conditioning is appropriate for wastes consigned for disposal?
- controls over design and operation;
  - what control functions are required of the different components of pre- and post-closure engineering, and how are those controls most effectively implemented in terms of:
    - design specification;
    - timing of construction/implementation?
  - what controls are required in order to ensure that radiological impacts are ALARA with respect to:
    - waste emplacement;
    - operational discharges?
- what active controls will be needed and for how long during closure of the facility?

All these factors are framed by the underlying strategic role assigned to the facility (Subsection 2.2), which is to provide, over the foreseeable future, the necessary national capacity for the disposal of LLW that is not amenable to being managed at higher levels in the waste hierarchy and requires the protection of vault disposal. Moreover, given that this strategy is itself contingent on being able to make an acceptable environmental safety case for disposal, the optimisation of control measures necessarily relates to the operation of the LLWR as a final disposal facility.

The relevant option assessment studies and their outcomes are grouped together as follows:

- passive engineering controls over the environmental safety performance of the LLWR during the PoA and beyond, taking account of the functional role of engineering features in overall safety strategy, as well as their design and timing of implementation (Section 5);
- management controls and interventions relating to past disposals (Subsection 5.4.4, and Section 6);
- management and engineering controls over future waste disposals to the LLWR, including waste acceptance, treatment and packaging, and methods for waste emplacement (Subsection 7.2);
- active management controls over environmental safety performance, including implications for discharges during the PoA as well as post-closure arrangements for the LLWR site (Subsection 7.3).

Inevitably there is a degree of overlap and dependency between the management actions and controls relating to different aspects of the facility. There are also certain aspects of control where flexibility is appropriate, in order to enable options to be kept open in future. These are highlighted as they arise in the discussion of individual factors. An overall synthesis of the outcomes, interactions and contingencies is provided in the SDP, summarised in Section 7.

3.4 Hierarchies of Optimisation for the LLWR

The disposal model for the LLWR reflects the outcomes of optimisation considering relevant threats and controls as described above. Components of the disposal model work together as part of the overall concept, as well as providing functions on an individual basis, consistent with their role within the disposal model, and aligned with the provision of the required controls. Options are therefore identified and assessed in a manner that can be expressed as hierarchical, although there are inevitably interactions and feedback between different levels that blur distinctions.

From the perspective of engineering controls, for example:

- The overall optimised concept provides the over-arching approach to the pre- and post-closure engineering and associated arrangements. Optimisation at this level identifies how the engineering will deliver key contributions to the overall SDP and therefore the Environmental Safety Strategy[14].
- Optimisation of key components of the LLWR is framed by the overall concept[15]. The requirement for consistency with the overall concept provides a starting point and set of constraints for these more detailed studies. Nevertheless, studies have included checks to ensure that changes in understanding or options for specific aspects do not present a challenge to the overall concept. This means that ongoing studies have served to provide a continual review of the validity of the overall concept, and have confirmed it is robust.

A hierarchical approach can also be necessary within a specific study, to separate overall choices of categories of options from detailed variations between options. It has often proved important for a range of different types of study to combine 'top-down' objectives-led strategic options with 'bottom-up' identification and analysis of detailed options.

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[14] While there had been many previous iterations of design developments and concept development for key components, the present concept was in essence defined by work in advance of the 2011 ESC [30].

[15] As noted in Subsection 2.4, the current optimised concept is described in Subsection 5.2.

A key example concerns the work undertaken in advance of the 2011 ESC to identify the overall pre- and post-closure engineering concept (see Subsections 5.2 and 5.3). Figure 3.1 provides an illustration.[16]

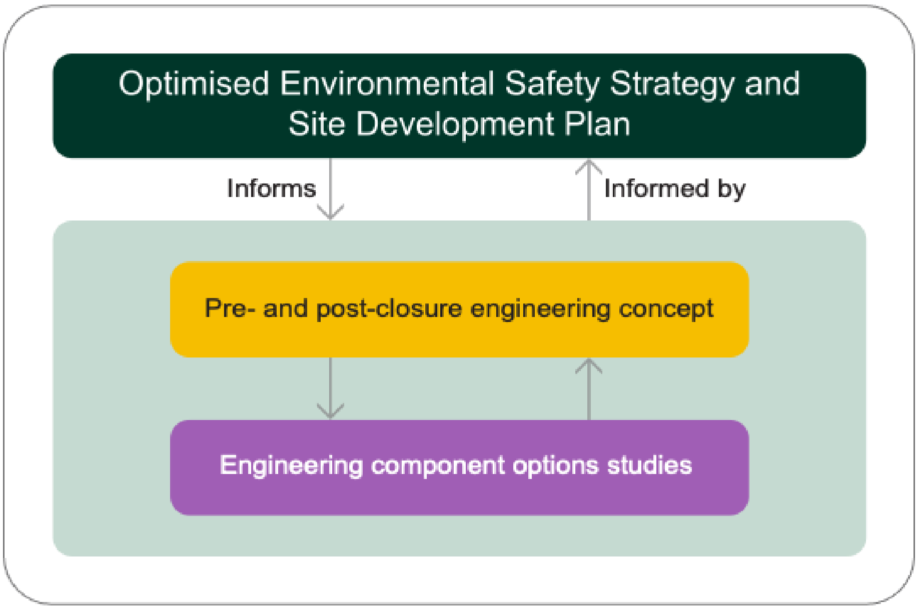

Figure 3.1: Illustration of hierarchies of optimisation and iteration. The figure focusses on engineering controls, but similar interactions apply to wider controls operations (such as WAC and leachate, monitoring) and subsequent active institutional control period approaches (including the length and nature of controls). The term 'pre- and post-closure engineering' refers to the design of future vaults and the design of closure engineering.

This was framed by the identification of broad categories of control measure options at the overall facility level. These were identified as approaches to address the different broad 'threats' to facility performance (Subsection 5.3). Here the threats identified reflected priorities such as isolation of the wastes from the environment, and wider aspects relevant to controlling impacts from key environmental pathways.

These broad strategic categories however depended on the identification of plausible engineering options for components that could deliver the controls. Therefore, detailed long lists of options that could plausibly offer meaningful contributions to relevant concept options were also identified. The long lists provided the necessary underpinning for the strategic options, and an audit tool to demonstrate they provided the required coverage. This integrated approach then provided the basis for the remainder of the study.

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[16] This hierarchy underpins the presentation of optimisation of relevant categories of engineering in the remainder of this document, and in particular Sections 5 and 6.

In addition, the ongoing nature of optimisation at the LLWR includes specific allowance for iteration and review when, for example, new information or changes to understanding become available. While optimisation work since 2011 ESC has not challenged the overall concept, new information has changed how it will be delivered.[17]

3.5 Optimisation Process Steps for the LLWR Disposal Model

3.5.1 Introduction

An overview of the steps generally applied to optimisation processes for the disposal model at the LLWR is provided here. This is intentionally generalised; the approach to optimisation at the LLWR is always within the framework, but there is flexibility to adopt a problem-specific approach within those constraints. This flexibility is important as it allows us to implement study-specific processes which are proportionate to the role and nature of a particular study.[18]

3.5.2 Summary of Key Process Stages

The process used for LLWR disposal model optimisation is illustrated in Figure 3.2, where it has been mapped to the Nuclear Industry Code of Practice (NICOP) on BAT, now referred to as a Good Practice Guide or GPG [37].[19]

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[17] Examples include the approach to Vault 8 stacking and closure given changes in understanding of the response of the container stacks to closure loads (Subsection 5.3), and the approach to trench hydrological management (Subsection 6.2)

[18] The principle of using optimisation processes that are proportionate to the hazard involved is a key part of good practice guidance, including the GRA (e.g. Paragraph 4.4.5).

[19] The guidance was in development at the time of the optimisation work undertaken ahead of the 2011 ESC. The mapping shows consistency in approach and intent and has been used to inform ongoing studies.

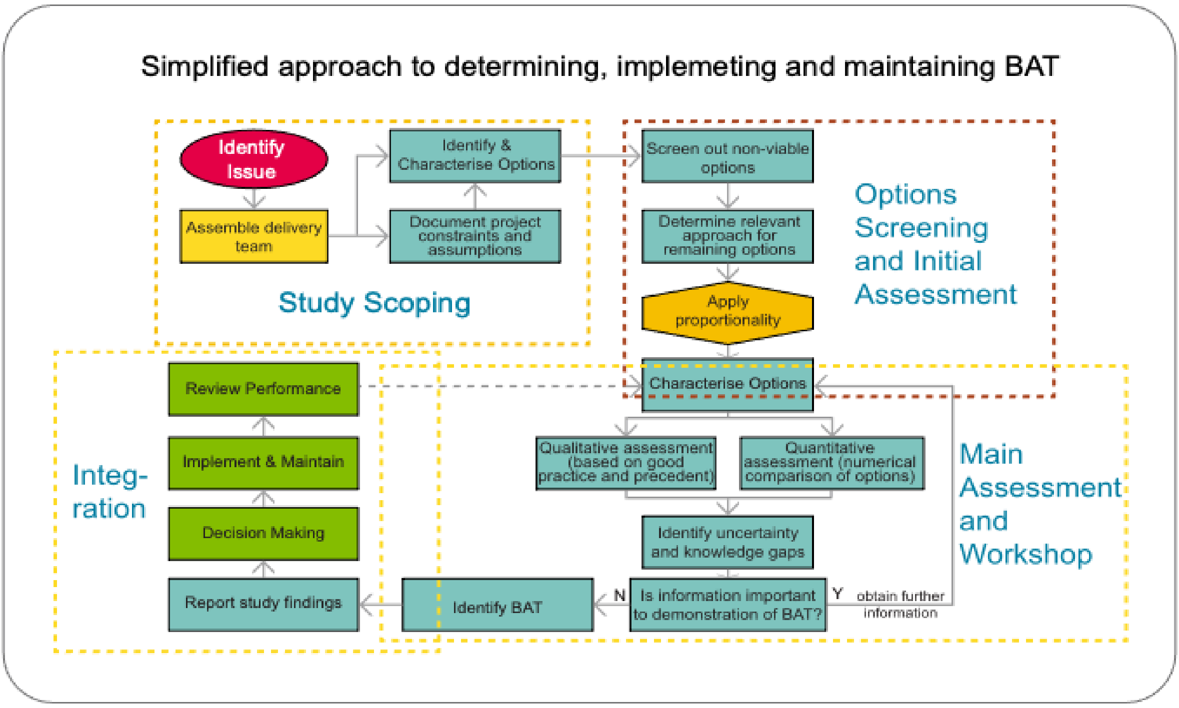

Figure 3.2: **Schematic of the approach to the BAT study, mapped to the 'Code of Practice' process**

3.5.3 Study Scoping (Problem Definition)

This phase focusses on defining the scope of the optimisation study itself, in order to agree the approach with appropriate stakeholders. Typically, this phase has included the preparation of a report covering key aspects, and then discussion of them in a scoping workshop.

The scoping phase includes discussion of the:

- role and objectives of the optimisation study, often framed as 'key questions' that the study needs to answer;
- relationships to existing studies, including framing concept options studies or previous iterations of optimisation for the specific aspect of the disposal model;
- links with sources of requirements including regulatory and good practice guidance, and also aspects such as planning requirements and the RMS;[20]
- nature of the options that need to be considered, and how they can be structured;
- approach to options screening or down selection, and relevant screening criteria;

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[20] See Subsection 3.8 for additional details.

- methods and criteria for the main phase of the options assessment;[21]
- audience and associated approach to stakeholder engagement; and
- the nature of outcomes required, including how reporting and engagements will support ongoing NWS and NDA decision processes.

Where regulators or other stakeholders are not involved directly in scoping, they are consulted through routine liaison fora, including seeking comment where views on interpretation of regulation are relevant to the study.

3.5.4 Options Screening and Initial Assessment

Initial long lists of options are developed during the scoping phases of optimisation studies. These are then developed and expanded in options screening and initial assessment phases. The aim in each case is to identify any option that, on its own or in combination with others, could plausibly provide a meaningful contribution given the objectives of the study (in particular, but not limited to, relating to environmental or health and safety protection). The intent is to be as comprehensive as wide-ranging as practical whilst acknowledging basic requirements and constraints.

Screening workshops are then typically held whereby the long list of options for the study in question is reviewed, further developed, and then systematically compared with screening criteria.

The overall aim of this step is to ensure the long list of options is sufficiently comprehensive, and then to discard options that can clearly be shown to have significant disadvantages such that they cannot plausibly be part of the final outcome.

3.5.5 Main Assessment and Workshop

This is the main options assessment stage and is broken down as follows.

Initial work on options development and assessment

The detailed options retained post-screening are worked up into an appropriate set of options for assessment, with grouping as appropriate for each study.

For the majority of studies, significant work on options assessment is undertaken prior to assessment workshops, often including proformas with options descriptions and performance details, and in most cases an analysis of advantages and disadvantages. Studies typically also involve the specific commissioning of work to develop options and to generate information to allow options to be assessed.

Whilst for simpler assessments, an analysis of options against criteria can be undertaken in a workshop environment, assessments for the LLWR disposal model are often complex, with inter-linked options, and subject to uncertainties. On this basis, for such more complex studies, a draft assessment of options is typically undertaken in advance, for structured

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[21] Criteria are discussed explicitly in Subsection 3.6.2.

review at the workshops by appropriate experts. This review then underpins the update and finalisation of the assessments, with additional information gathering and iteration where required.

The form of assessments differs according to the nature of the options being assessed. For complex studies focussed at the concept level, options are explored in a hierarchical 'decision tree' type approach, considering decisions stepwise in order to address interactions between repository components.[22] For other studies focussing specifically on individual components, simpler more 'standard' options processes are typically sufficient.

Options assessments against criteria are often presented using matrices, in a MCDA[23] format, appropriately underpinned by detailed analyses of the performance of options on the basis of available evidence. In addition, the nature of some assessments allows direct logical arguments to be made, where the arguments are clear. A third approach involves listing differentiating 'strengths and weaknesses' and then mapping them to criteria to demonstrate coverage. Each approach is consistent with recognised good practice, including ensuring the proportionality of the process.

In these assessments we primarily use qualitative approaches to 'scoring', to identify differentiators. The use of qualitative rather than quantitative scoring is a response to the strategic and over-arching nature of some assessments, and the uncertainties that apply to options for facilities involving legacy disposals and projections of long-term performance. Using a quantitative scoring approach would often prove challenging in the face of uncertainties, and could obscure the logic and analysis that is in any case the primary output of MCDA approaches.[24]

Main Assessment Workshop

The main assessment workshops generally involve a range of experts including the optimisation project team, key stakeholders and decision makers from NWS (and fore-running organisations), and technical experts from outside the immediate project team. For a subset workshops to date, ‘active observer’ participants from one or both of the Environment Agency and the ESC’s independent Peer Review Group have also attended. The combination of participants depends upon the nature of the study and workshops. Where

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[22] Specific examples include the work to define the pre- and post-closure engineering concept (Subsection 5.2), studies for the Vault 8 closure and capping programme (Subsections 5.3 and 5.4.1 to 5.4.4), and studies for the optimisation of Vault 9 and the future vaults given the outcomes of Vault 8 studies (Subsections 5.4.5 to 5.4.7).

[23] Multi-criteria Decision Analysis; the term MADA, or Multi-attribute Decision Analysis, is also often used for the same process.

[24] For example, studies on vault design and the final cap, prior to the optimisation work for the 2011 ESC, used quantitative scoring approaches which arguably did not assist in providing confidence in the final outcomes, in part due to uncertainties (the outcomes of those studies are summarised together in [31]). On that basis, studies for the 2011 ESC utilised a qualitative approach for identifying options differentiators and logic. For clarity, the focus here is on the options assessments; quantitative inputs (such as the outcomes of assessment models, and detailed modelling work) provided key underpinning.

regulatory or peer review group observers are not present, alternative fora are instead used to inform on and discuss the process and outcomes.

The aim of the main assessment workshops is to identify an optimised BAT outcome and rationale. Discussions also ensure that the outcomes are presented in a format that maximises support to subsequent decision processes, as well as following technical work such as ongoing options design.

The main assessment workshops generally focus on structured review of the key arguments from the draft assessment, with feedback and challenge from facilitated discussions between the experts present. The assessments, including matrices or tables, are either explicitly reviewed and updates made, or the workshop discussions are used to underpin subsequent updates.

The final BAT reports document the process and the audit trail.[25] They articulate the arguments underpinning the selection of the preferred BAT option or options, and the implications of alternatives, to clearly inform those responsible for making subsequent decisions.

BAT outcomes including 'reconciliation'

Often, BAT studies conclude with the reporting of the BAT outcomes, which in addition to standard NWS report checking and approvals, include providing workshop participants with an opportunity to check that that document faithfully reflected workshop discussions.

Specific studies require a further step. For more complex assessments[26], options assessments for aspects of the disposal model involving several engineering components can require parallel working for the different components, despite where interactions mean that the outcomes need to be linked. Making progress independently is necessary in such situations to simplify assessments and make progress in the face of complexity. However, interdependencies between such studies then mean that an extra step of 'reconciliation' or integration can be required. In such cases, the outcomes of the linked studies are considered together within one or more further iterations of assessment, to align the overall outcomes into a consistent strategy, with update of the individual assessments consistent with the overall outcome.

3.5.6 Integration

An important concept in BAT studies is that the options process supports but does not 'make' decisions. Decision making on the basis of BAT outcomes, and associated integration into plans and programmes, is made subsequently through internal NWS and NDA processes.

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[25] Summaries of key BAT studies, and associated report references, are provided in Sections 5 to 7.

[26] For example, those undertaken for Vault 8 closure where options for profile fill, void fill, and the final cap - amongst other aspects - were considered independently at first, to reduce the total number of combinations of options to a manageable level; despite final outcomes needing to consider the options on an integrated basis (see Section 5),

This recognises the requirements of formal governance and sanctioning steps in making the relevant commitments. As part of this, such processes ensure the BAT outcomes are considered alongside wider aspects such as other site programmes and priorities, and funding profiles.

A core part of the optimisation approach to the ESC, therefore, is to make sure that outcomes are articulated in a manner that clearly communicates the logic for the BAT outcomes, and also the implications of pursuing alternatives.

Note that if more than one option is potentially BAT (e.g. two very similar options for a particular engineering component cannot be differentiated in performance), it is appropriate to recognise that flexibility within the BAT outcome to be taken forward for decision making. The priority is to focus on demonstrating BAT at the appropriate level. Similarly, this means that some details of a preferred option can be left open if they are not a key part of the BAT argument. This flexibility allows subsequent steps such as commercial processes to make final choices within the overall envelope of BAT outcomes. It also ensures that subsequent options development steps are not unnecessarily constrained by over-specifying details at this stage.

Consistent with optimisation as a continuing and iterative process, decisions will typically lead to further work. For example, a decision to pursue an optimised overall engineering concept may lead to relevant engineering component options being taken forward for ongoing optimisation and design.

3.6 Key Themes for Process Implementation

3.6.1 Uncertainties

For optimisation processes to be successful, as far as practical, significant uncertainties should be identified and addressed, to the extent that allows decisions to be confidently made. However, it is unavoidable that some uncertainties will remain for optimisation of the LLWR. Uncertainties are inherent in designing for engineering performance over a period of many centuries. There is also inventory uncertainty and variability associated with both the existing wastes, and projections of future arisings.

We have identified and documented uncertainties and, where possible, undertaken work to resolve these uncertainties so that optimised solutions can be identified with confidence. This includes understanding the uncertainties and their distributions so far as is practicable, and associated biases. The aim is to identify outcomes that are robust to any remaining uncertainty.

Some uncertainties are irreducible or otherwise difficult to characterise fully. For such situations, our optimisation process recognises robustness with respect to uncertainty as important. In some cases, a single, specific option may provide the required performance coverage across all plausible outcomes within the uncertainty envelope. Wider option flexibility - such as the flexibility to accommodate changes in design as understanding evolves - is a further way in which such robustness can be demonstrated.

3.6.2 Assessment Criteria

Options assessment processes for disposal model optimisation have included the use of screening criteria to reduce the initial long lists of options, and then assessment criteria (or attributes) for the main assessment of differentiators.

To ensure consistency and traceability of logic, similar criteria sets have been used across similar categories of options assessments. For example, assessments considering the pre- and post-closure engineering, including those for the 2011 ESC through to the more recent work on Vault 8 closure and capping (Section 5) considered the same criteria.

Typical screening criteria are as follows.

- An option is not capable of being legally implemented within required timeframes.
- Health and safety, environmental, cost or other disadvantages are clearly disproportionate to the potential advantages of the option.
- The option has significant negative disadvantages against a key technical requirement that will clearly outweigh any advantages that may be gained.

Any option failing any of the above arguments was 'screened out' of relevant assessments, with the logic appropriately recorded.

For the main assessment phase, a more detailed criteria set is required, although the assessments were typically presented via combined high-level criteria groups with the detailed list as an *aide-memoire*. The primary set used is listed in reference [41].

This criteria set was originally agreed for the work for the 2011 ESC [40]. It was formulated prior to the release of the NDA Value Framework [42], which includes a stakeholder-informed criteria set which is often also used, with appropriate screening and interpretation, to support BAT assessments. To ensure consistency with earlier optimisation studies, we have continued to use the original LLWR criteria set for engineering optimisation studies, rather than changing to the NDA Value Framework. However, to demonstrate consistency and coverage, the LLWR criteria set has been audited against and mapped to the NDA Value Framework [41].

3.6.3 Relative Importance of Differentiators Against Criteria

A key principle of good practice guidance in options assessments is that the relative importance of criteria to a decision should be understood. In practice, this means that the importance of differentiators aligned with relevant criteria needs to be established. The relative importance of criteria is referred to as 'weighting'[27] in the MCDA process. Weights

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[27] Technically, the phrase 'weighting' is often used to express the relative importance of criteria in general, and 'swing-weighting' builds into this the relative importance of differentiators against those criteria.

are normally identified in part by establishing requirements and constraints arising from legislation, regulation and good practice, and by eliciting views on values from stakeholders that can be reflected in the MCDA approach.[28]

An important consideration for weighting is that the approach needs to reflect ALARA. Specifically, priority needs to be given to criteria reflecting confidence in environmental and human safety in managing radiological hazards, to ensure that safety is prioritised, whilst also recognising any disproportionality arguments from the perspective of wider practicability concerns.

As our disposal model options assessments typically use qualitative assessments of options in identifying differentiators against criteria (Subsection 3.5.5), evaluations of the relative importance of differentiators are also qualitative. A key aspect is the prioritisation of differentiators relating to confidence in environmental and human safety. Options offering relevant advantages are favoured unless there are clear disproportionality arguments aligned with other criteria.

The focus on 'confidence' is key here. A robust outcome will not rely solely on assessments of doses or risks for options once constructed. Confidence will also be contingent on aspects such as confidence in implementation, the ability to demonstrate that the resulting measures meet design requirements, the ability to monitor subsequent performance, and the ability to make reliable projections of option performance into the longer term.

3.6.4 Review and Challenge

An important aspect of good practice in options assessments is the use of challenge to ensure that 'group-think' does not lead to options being missed or biases being introduced into the assessment. Approaches for the LLWR therefore include, wherever practical, experts from outside the immediate project team to provide review and challenge in order to minimise this possibility. Demonstrably independent challenge is then also ensured through the involvement of the Independent Peer Review Group or regulatory representatives, either as workshop observers or through alternative consultation routes.

3.6.5 Iteration

Iteration is a key principle of regulatory and good practice guidance for optimisation and is a key part of our process. This is also reflected in our use of the ESC to provide 'a tool for site management', and in turn the need for the facility to be managed consistent with the provisions of the current ESC. Developments of understanding can lead to a need to check

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[28] Discussions on criteria and their relative importance were key topics of stakeholder engagements within the optimisation processes ahead of the 2011 ESC. The outcomes of those discussions have continued to provide a framework for weighting since, given the use of the 2011 ESC concept and process to frame ongoing discussions. In addition, the Value Framework set of criteria [42] has been developed through significant stakeholder engagement across the industry, and review and mapping to those criteria has reinforced the LLWR approach on priorities and differentiators.

or review the outcomes of past optimisation processes. In turn, the outcomes of optimisation processes inform the wider ESC.

Iteration occurs at a number of levels.

- **Iteration within individual studies is often required**. For example, for successive BAT studies for Vault 8 closure described in Subsection 5.3, scoping, screening and assessment processes were revisited in an iterative fashion as information gaps or new information requirements were uncovered, and also to ensure alignment of outcomes across different engineering components.
- **Review of approaches can be necessary if there are changes to over-arching requirements such as national or site strategy, or legislation or the regulatory regime**. An example here is the optimisation work undertaken to explore the potential for ILW disposal at the site, reflecting the potential for a change in national strategy for relevant categories of waste. Approaches to potential ILW disposal will be consistent with the existing LLWR concept but require specific updates and developments, as set out in Section 5.
- **BAT or optimisation studies may need to be re-visited if new information is obtained that challenges or otherwise requires update of the outcomes of previous studies**. Examples include changes to the understanding of container performance under load and the implications for Vault 8 closure (Subsection 5.3) and the studies for interim trench hydrological management, where iterations of investigation and optimisation studies led to the current Southern Trenches Interim Membrane (STIM) programme (Subsection 6.2). In addition, changes to detailed aspects of understanding could arise through subsequent design phases.

3.6.6 Ongoing Optimisation during Design Phases

Optimisation does not cease once a specific optimisation study has been concluded. This includes detailed development of designs and specifications. It is important that the rationale for the optimised design is appreciated by the teams responsible all the way through to construction. This includes ensuring that the need for iteration is flagged if changes (e.g. to projections of performance, or potential design improvements) are identified during relevant processes.[29]

3.7 Wider Aspects of Confidence in Options for Optimisation

In this subsection, broad aspects of ensuring confidence in options are considered, that apply across the optimisation process and are not specific to any one step.

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[29] An example is the design work for the capping programme which has continued within the optimisation framework set out by the main Vault 8 closure BAT studies, including recognising the potential for further optimisation of choices of the geomembrane (Subsections 5.2 and 5.3).

3.7.1 Ability to Predict and Assess Performance

Confidence in constructability, and in performance once constructed, is a core consideration for LLWR options processes.[30] Options that could, in principle, perform well but for which construction could prove challenging, or for which the outcomes are uncertain or unpredictable - for example, where solutions are novel and with limited provenance - are typically not favoured.

Given the challenges in understanding likely performance over the longer term, this aspect typically tends to favour simpler solutions, for which performance after construction can be predicted and demonstrated with more confidence.

3.7.2 Benchmarking and International Good Practice

An important input into options processes concerns the application of learning from experience (LfE) relevant systems in the UK and elsewhere. This includes learning from radioactive waste disposal facilities for similar waste categories, and also appropriate experience from engineering for hazardous waste facilities. LfE contributes to:

- building confidence in processes and approaches to optimisation;
- creating and auditing options lists, at both strategic and detailed levels, to ensure nothing is missed; and
- assisting in ensuring performance and wider factors are addressed in evaluating evidence for the assessment of options.

As an example, the pre- and post-closure engineering optimisation work undertaken ahead of the 2011 ESC explicitly considered international good practice in informing options development. Options for engineering, concepts and retrievals explicitly built on reviews of international facilities undertaken for the 2008 'Schedule 9' submissions ([43, 44]). Previous reviews (e.g. reference [45]) were also part of the audit trail. International resources such as those produced by the IAEA [46, 47, 48, 49, 50] were also reviewed. In addition, reviews of international good practice and learning from the non-radiological disposal sector were developed for the 'modular vaults' process in the mid-2000s (reference [51]). This range of resources, together with the use of an interdisciplinary project team for optimisation studies with experience of a range of programmes and industries, ensured that those optimisation studies were very well founded in LfE and good practice.

Clearly these studies are now out of date, although it is notable that the engineering concepts for surface facilities for relevant wastes (El Cabril, La Manche etc) have not changed notably. However, we and forerunner organisations have long recognised the value of LfE and have implemented ongoing programmes for engagement on national and international levels to continually exchange ideas and knowledge and feed good practice

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[30] The importance of ensuring high standards in construction management and CQA is recognised as fundamental in engineering and construction practice, as discussed in the *Engineering Design* report [5].

into the LLWR engineering and optimisation programme. The *Engineering Design* report [5] summarises ongoing LfE processes for engineering components that continue to support our optimisation process.

Complementary LfE processes are operated across NWS's ESC, NSC and engineering functions. A wider discussion on LfE and relationship management processes is provided in the *Management and Dialogue* report [2].

3.7.3 Integrated Teams

Optimisation requires inputs from a range of disciplines. The use of an integrated, multi-disciplinary team, including independent review and input, is essential to ensure the full range of inputs and expertise, and to make sure nothing important is missed.

We therefore use integrated core teams for optimisation that work within an integrated and consistent approach. These core teams are supplemented by additional expertise and independent experts as required for individual studies.

3.7.4 Role of Safety Assessments in Supporting Optimisation

A key aspect of demonstrating ALARA, and thus BAT and optimisation, is to show that impacts arising from relevant pathways will be minimised (wider factors also being taken into account). Understanding of the implications of options for impacts is therefore important in options assessments.

However, this does not mean that options assessments have necessarily been informed by direct calculations of impacts such as doses or risks for the different options. This is because the understanding gained from underpinning information and assessments is typically sufficient to understand the performance implications of options for pathways, without necessarily needing an assessment calculation for every option.[31]

In addition:

- Whilst we aim for a 'cautiously realistic' approach in assessment calculations in the ESC [1], these calculations necessarily incorporate biases and cautious representations of uncertainty when making simplifying assumptions to make progress in calculations. This means that comparing options via assessment calculations can, often, lead to a comparison of the assumptions made in addressing uncertainties, rather than being a direct comparison of the performance of options themselves. Moreover, making judgements on assessments where cautious assumptions are used can, in turn, lead to over-cautious outcomes in decision-making.

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[31] For example, groundwater flow models were used to assess the depth of the cut-off wall required for the 2011 ESC, to ensure protection of the wastes and under-vault drainage blankets from lateral inflows. This information was sufficient to make the required judgements without an associated impact calculation.

- Sometimes assessment calculations can entirely neglect a feature which is still assigned importance in optimisation choices. An example in ESC calculations is the contribution to containment provided by vault containers for the groundwater pathway. Safety arguments reflect the value of the role of the containers in contributing to the multi-barrier concept. Our groundwater safety assessment calculations however neglect their contribution. Therefore, the calculations cannot be used simply to differentiate options for containment.

Our focus, therefore, is on using the understanding gained from assessments and supporting modelling and information, to inform a balanced assessment of options. This includes exploring uncertainties and addressing known biases, in order to identify overall arguments for confidence in performance.

3.8 Relationship with Engineering Design, Engineering Performance Assessment, and Requirements Management System Processes

Overview

Subsection 2.7 of the *Engineering Design* report [5] describes the relationship between the optimisation, engineering design, EPA [12] and Requirements Management System (RMS) [52, 53] processes, with supporting diagrams. To briefly summarise, the engineering design is a function of:

- existing arrangements that are already in place, both for legacy wastes and ongoing vault disposals;
- the pre- and post-closure design (that is, plans for future vaults and closure engineering) identified through the optimisation processes described in this document;
- the RMS, which captures requirements arising from optimisation, the EPA and the wider ESC, and ongoing iterations of these activities which capture updates to understanding arising from those processes and from practical experience of developing and implementing detailed designs; and
- detailed design processes, framed by the optimisation approach and concepts, with iteration as required.

The EPA [12] provides a systematic assessment of the projected performance of the engineered barriers over time; learning from the EPA is then fed back into the design and optimisation processes as appropriate. In general, the relationships between design, optimisation and the EPA are iterative and ongoing.

Requirements Management and the optimisation process

The discussion that follows supplements the overview presented in the *Engineering Design* report [5], and provides a high-level summary of the role of requirements management within the optimisation process.

The formal RMS was created between the 2011 ESC and the current submission. It was therefore not in place for a number of the optimisation studies reported in this document, such as the pre- and post-closure optimisation work that identified the overall concept defining the optimised disposal model (see Subsection 5.2). However, the outcomes of those studies were captured in the RMS when it was first populated. Then, the RMS was used to provide requirements for studies such as those for the repository development and capping programme and the future vault optimisation studies, summarised in Subsections 5.3 and 5.4 respectively.[32] The RMS was updated during the execution of several of the key repository development studies, for example for the final cap. We will update the RMS with the outcomes of the remainder of repository development work. It will also be updated with the outcomes of subsequent studies and ongoing design and optimisation programmes.

In addition to the optimisation studies, RMS entries informed the development of capping programme documents such as CQA plans and Design Justification Reports (see the *Engineering Design* report [5] and supporting references). We will develop 'verification and validation' plans that confirm requirements have been met when engineering components are constructed.

While the formal RMS was not in place for earlier optimisation studies, the importance of requirements and associated design and optimisation aims and objectives, assumptions and constraints was recognised within our structured and systematic optimisation process. Clarity in these areas is essential for optimisation and design work to progress effectively. Scoping phases of studies[33] therefore ensured that requirements (in effect, if not in name) were formally identified, reviewed and tested through document and workshop reviews with relevant experts. This process included regulatory engagement to ensure the clarity of key requirements, their focus and coverage, and to invite challenge and feedback to maximise confidence in the process. The most important aspects were typically reflected in 'key questions' that needed to be addressed by a study, with the subsequent answers to these questions then describing how requirements have been met by study outcomes.

The outcomes of the pre-RMS studies - in particular the pre- and post-closure concept optimisation work - in turn informed scoping steps in subsequent component-specific studies (i.e. those summarised in Subsection 5.3). These later studies together, with the process of formally populating the RMS, also provided an additional opportunity to review and confirm the relevant requirements. Component-specific studies have typically continued to use the 'key questions' (or an equivalent 'key issues' or similar) approach; highlighting key RMS requirements and in turn showing how they had been addressed.

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[32] In practice, some of the key options studies that first utilised formal RMS requirements were developed in parallel with the process of RMS population and documentation.

[33] Subsection 3.5.3 provides an overview of the scoping process; see also Subsection 5.2.1 and reference [40][for a relevant example of its application.

Where options processes considered engineered components whose performance are linked and required an integrated outcome, these were addressed by an alignment or 'reconciliation' step as part of the optimisation process (Subsection 3.5.5). This part of the process ensured that key questions (or requirements) that require more than one component to work together to address them, were assessed within an integrated approach. It also ensured that any potential conflicts in design aims, performance or wider aspects of the options assessment were taken into account. This continues to be an important aspect of our options process for ongoing optimisation aided by the formal RMS.

Table 3.1 captures the key categories of requirements in the RMS [52, 53] and indicates how equivalent aspects were addressed in optimisation studies before the RMS was formally populated. The RMS entries arise from a range of sources, including WAC, engineering design considerations, good practice guidance and requirements, specifications for materials, the near-field understanding of evolution of disposals, amongst others. Whilst the overall set of requirements covers these wider considerations within an integrated approach, the focus of this Table is specifically on aspects related to engineering optimisation.

Table 3.1: Categories of RMS entries and coverage in pre-RMS optimisation studies

Requirement category	Description	Coverage in pre-RMS studies
High-level external requirements	Requirements imposed by external organisations such as the NDA and regulators. Not specific to any one design.	Overall requirements were identified, reviewed and confirmed through scoping phases of studies including structured expert workshops. The main study defining requirements at this level was the pre- and post-closure concept optimisation study (Subsection 5.2; [31, 40]) including its stakeholder engagements. This also took account of pre-existing ESC documents, and previous options study outcomes and engagements (e.g. [28, 43]). In addition to generic requirements for near-surface disposal, optimisation-relevant objectives were framed as the need to identify controls to address threats to repository performance, aligned with assessment pathways.[34]
System requirements	Qualitative and quantitative requirements that define the total repository system and its management. Not specific to any one design.	

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[34] See Subsections 3.3, 3.4 and 5.2.1.

Requirement category	Description	Coverage in pre-RMS studies
Sub-system requirements	Specific requirements for each of the major structures, systems and components (SSCs) and activities of the LLWR, including engineering functions related to safety. Sub-system requirements contain both external and internal requirements. Not specific to any one design for components (although aligned with overall concept strategy options).	For engineered components already constructed, a range of baseline requirements for continued operation apply (e.g. disposals to existing vaults and associated WAC). The outcomes of optimisation studies (e.g. for the pre- and post-closure concept) then further inform on requirements. This included, for example, continuing optimisation and design of the future vaults and closure engineering, as the concept provided an updated understanding of design objectives at the sub-system level. This further informed on requirements for ongoing optimisation and design.
Component specifications	Specific requirements for engineering component design and optimisation (to deliver the sub-system requirements and approach).	Reflect requirements to deliver confidence in performance on the basis of the role of the engineered component within the optimised concept option. The outcomes of such options studies are therefore a key source of requirements.

4 Facility History and Description

Decisions taken now and in the future regarding the development and operation of the LLWR are framed, and to some extent may also be constrained, by past actions.

A detailed account of the past development of the LLWR, and the present status of the site, is provided in the '*Site History and Description*' report [3]. Full details of the current and planned engineering for the repository are described in the '*Engineering Design*' report [5].

In what follows, relevant aspects of existing features of the facility and its history are discussed, together with anticipated future developments and uses, in order to provide context for the optimisation considerations addressed by the ESC programme.

4.1 Site

Construction of the LLWR began in 1940 as a Royal Ordnance Factory (ROF). Ownership subsequently passed to United Kingdom Atomic Energy Authority, which was granted planning consent in 1957 for the disposal of waste in the northern 40 ha of the site. The first Certificate of Authorisation for disposal of LLW was granted in 1958 under the terms of the Atomic Energy Act 1954, and disposal operations commenced in 1959. Ownership and responsibility for the site was transferred to British Nuclear Fuels Ltd (BNFL) when the company was formed in 1971, and the site became a part of the NDA's estate when the organisation was established as a non-departmental Government body in 2005.

Land ownership and the proximity of the LLWR site to Sellafield were undoubtedly important factors in its identification as a suitable site for LLW disposal. In addition, it was judged that the clay, which exists at a shallow depth on the site, would provide an effective barrier to the downward transport of radionuclides into the Triassic sandstone aquifer. Leachate could therefore be collected in the trench drains and subject to controlled discharge (originally to the Drigg Stream, but since 1991 via the Marine Pipeline).

It could be argued that the original approach of loose tipping and leachate collection (see below) placed the emphasis of safety arguments on controlled gradual release and dilution, rather than extended long-term containment.[35] As such, siting considerations did not differ significantly from those associated with general practice for landfills. In any case, the long-term evolution of the site does not appear to have been a significant consideration in earlier decision making relating to disposals.

Taking into account the increased emphasis on isolation and containment in international policy and practice for the disposal of solid radioactive wastes, and recognising the long-

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[35] Optimisation work over recent decades has substantially changed the emphasis of the concept - even for the legacy trench facilities - to containment, via the use of approaches such as the multi-layer final cap, the cut-off wall, and the interim cap upgrades (Subsection 5.2).

lived component of the radioactive inventory at LLWR, the implications of site evolution have gained appropriate prominence in safety analyses over recent decades.

As set out in the '*Site Evolution*' report [8] and the associated assessments in the '*Assessment of Long-term Radiological Impacts*' report [14], disruption of the site through coastal processes is now expected to begin within several hundreds to a few thousand years, and then to be complete within a few thousand years. Whilst the ESC also assesses a 'what-if' scenario whereby the site is not eroded, this is considered very unlikely, and in this respect we note that GRA provision that *'unlikely circumstances should not have undue influence on design, construction or operation'* (GRA [26], paragraph 6.3.65).

The range of timeframes for the onset of disruption provides significant guidance to the optimisation process, and relevant aspects of and timeframes for performance. This means that phenomena that were not relevant to the original selection of the LLWR site therefore play a central role in framing the ESC and related optimisation decisions.

4.2 Trench Disposals

For the first few decades of operations, disposals were solely by tumble tipping drummed, bagged and loose wastes into excavated trenches. There are seven disposal trenches in total and disposals to Trench 7 were completed in 1995.

Future actions relating to the control of hazards associated with authorised trench disposals are a relevant factor in optimisation of the overall disposal facility, to ensure that radiological impacts are ALARA. Ongoing considerations include possible interventions and factors relating to the design of hydrological management arrangements and the closure engineering for the site (Section 6). As background to examination of these issues, it is relevant first to consider the basis for past actions.

Loose tipping of waste was a widespread and internationally accepted practice when the trenches were first commissioned. The approach was considered to be efficient in terms of space utilisation, radiation exposures of the workforce and the time taken for disposal operations [54]. It was also a flexible system that allowed trenches to be formed in a phased manner in response to the demand for disposal space. No records have been identified relating to the consideration of alternative approaches to disposal in the original development of the facility.

The boulder clay on the site was expected to provide a low hydraulic conductivity base to limit the vertical migration of leachate through the trenches. In addition, a slight fall was incorporated in the base of each trench to cause leachate to be collected by an interceptor drain at the southern end of the disposal area. Experience in operations led to progressive improvements in detailed design, construction and operation. While maintaining consistency with overall design principles, such improvements included:

- variation of plan area and depth to optimise the available disposal capacity;

- construction of firebreaks and covering waste with soil at the end of each day's disposal operations to minimise the risks of fire;
- installation of perforated drainage pipes along the trench bases to promote the flow of leachate to the interceptor drain;
- engineering the base of trenches by rotovation and mixing with sodium bentonite to a depth of 0.5 m, at locations where the basal clay layer was absent.

A review of the leachate management system for the site was undertaken as part of a general review of the disposal facility in the 1980s [55]. This determined that the monitored discharge of leachate through the Marine Pipeline to offshore diffusers, rather than to the Drigg Stream, was the preferred (ALARA) approach to the control of public exposures from site operations.

Post-emplacement engineering has also been undertaken to mitigate the impacts of trench disposals. A low-permeability, cement-bentonite slurry cut-off wall was installed from the north-west corner of Trench 3 (the western-most trench) to the southern end of Trench 7 (the eastern-most trench) between 1989 and 1995 [5]. This was undertaken as an operational measure in order to limit the potential for lateral migration of leachate from the trenches to the adjacent railway cutting. In combination with the interim cap (see below), the cut-off wall was also intended to support the minimisation of leachate production by controlling the lateral migration of meteoric water into the trenches from the surrounding land.

An interim cap, extending over the top of the cut-off wall, was completed over Trenches 1 to 6 in 1989 and was subsequently extended to cover Trench 7 following the completion of trench disposal operations in 1995. The purpose of this interim cap was to:

- isolate the waste from the near-surface environment, limiting the possibility of disturbance and protecting the waste during the initial phases of waste settlement;
- control the release of gas from the trench disposal area;
- limit the infiltration of meteoric water into the disposal area and hence the volume of leachate generated.

In association with these post-emplacement actions, the decision was also made as part of the wider review to phase out the disposal of loose wastes in favour of the orderly emplacement of compacted, containerised and grouted wastes in engineered concrete vaults. Vault operations commenced in 1988, but the phasing out of trench disposals was not completed until 1995.

Since the installation of the interim cap, monitoring work identified that it is not performing as originally intended (see Subsection 6.2). Iterations of optimisation led to the recognition that an upgrade to the interim cap is required for the parts of the trenches that will not be covered by the first strip of the final cap. At the time of writing, this upgrade is in progress.

Iterations of the optimisation and design process for the final cap (Subsection 5.4) have recognised that there is the potential for ongoing biodegradation and compression movements within the wastes. Surcharge of the trench wastes has therefore been part of closure plans for many years, to express any available settlements at the time of final cap implementation. This will ensure a stable formation for cap placement, as well as contributing to minimising risks associated with cap stability post-emplacement.

Optimisation considerations associated with the future control of hazards from the trench wastes, during the PoA and beyond, have therefore included (Section 6):

- the possible need to replace or refurbish existing engineered controls, including the interim cap;
- the possibility of remedial actions to provide additional containment or to recover some or all of the trench waste inventory;
- the implications of waste settlement and trench leachate management for the design and scheduling of future site engineering and closure measures.

4.3 Vault 8

The adverse visual impact created by the tumble tipping of wastes into trenches was highlighted, as part of a wider review of radioactive waste management in the UK, in a report of the House of Commons Environment Select Committee in 1986 [56]. As part of its review of site operations in the mid-1980s [55], BNFL sought to identify a disposal system to supersede the trenches that would improve management practices, enhance containment and mitigate the visual impact of operations. Options for facility design, waste packaging and site closure were considered in a series of qualitative and quantitative studies [54].

In addition to the development of the cut-off wall and interim cap for those parts of the facility where disposal operations had been completed, the decision was made to move to an engineered concrete vault disposal concept. The new disposal vault was identified as Vault 8 in order to maintain continuity of numbering from Trench 7. It was designed to fit into the available space in the northwest corner of site. The design incorporated a secant pile wall to provide structural stability along the shared boundary with the adjacent Trench 3 while minimising wasted space that could otherwise be used for disposal capacity.

The vault has surface water drains to collect rainwater from the surface of the reinforced concrete base slab, while an under-slab drainage blanket and perimeter drains collect groundwater from beneath and around the vault. The ultimate barrier to downward migration of leachate is the same as for the trenches – the low conductivity of the naturally-occurring boulder clay layer beneath the vault base.[36] Where this could not be assured (e.g. where the top of the natural clay dipped below the vault formation level or where it was assessed to be less than 1 m thick), bentonite was mixed with the local soils to a depth of 300 mm to achieve an in situ permeability of 10^{-10} m s^{-1} or less [5]. The concrete slab has a jointed

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[36] Passive leachate management will continue post-closure, with arrangements being back-fitted such that Vault 8 waters drain into the sub-vault drainage blankets associated with future vaults.

construction and in between the joints some cracking can be observed, but this is consistent with performance expectations.

At the time that the vaults were first proposed, a single-dome multi-layer final cap was also assumed (see references [57] and [58] for further details). Closure plans up to and including the design used for the 2002 Post-closure Safety Case (PCSC) [59] recognised the need to address long-term passive leachate management and the designs included a deep vertical drain system at the south of the site to which waters would be directed after over-topping the vaults. This was subsequently updated in the mid-2000s to include a line of deep disposal borehole drains between the trenches and vaults, associated with the 'valley' between the twin domes of the cap that were also assumed at that time. The latter design for the cap and the drainage, and the evolution of the approach through the optimisation work for the 2011 ESC including the current position, are described in Section 5.

Although the designs for Vault 8 first considered loosed-tipped waste as for the trenches, containment of the disposed radionuclides within the vault was enhanced by introduction of the containerised wasteform to reduce the potential for interaction between the wastes and waters passing through the facility. In terms of long-term safety, the functional requirements assigned to the wasteform also included keeping the residual voidage low, in order to minimise the potential for settlement of the final cap; void-filling is the primary engineering function provided by the container grout.[37] In addition, an aim was to distribute the load on the base slab as uniformly as practicable to minimise differential settlement [60] as well as wider impacts on the slab and the underlying mineral layers. The grouting of the wastes within the final container primarily takes place at the LLWR Grouting Facility, which also started operations in the mid-1990s. All wastes are subject to waste receipt monitoring.

In determining the preferred wasteform, high-force compaction was judged to be consistent with good practice in other national programmes. It was recognised as being capable of providing the desired low product voidage as well as efficiency in the use of disposal capacity within the facility. Apart from compaction, no records have been identified relating to the consideration of other approaches to primary waste treatment at the time that the original vault design was developed.[38]

The half-height ISO (HHISO) waste container was selected as the standard container, being sufficiently large to minimise the number of waste handling operations and consistent with practical limits on weight during movements on the site. The container could also be readily demonstrated to be consistent with transport regulations during shipment from consignors. A mild steel container was also considered to be more cost-effective, as well as being more efficient, than concrete in making use of the available space for disposal.

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[37] Other functions, such as chemical conditioning of waters and providing a substrate for sorption, are also valued by the ESC (see e.g. references [94, 11]).

[38] Changes to waste disposal and treatment practices since the 2011 ESC have primarily impacted Vault 9 to date (Subsection 4.4).

A low-viscosity grout formulation was designed with the aim of providing efficient flow properties during filling, to be self-levelling and to set sufficiently quickly in order to limit the need for temporary buffer storage prior to final emplacement. The top layer of grout across the surface of the waste container contents was originally considered to help the distribution of load throughout the wasteform (although studies since the 2011 ESC have identified that this layer is not present in all disposals, and 'ullage' voidage at the top of many Vault 8 consignments has been identified, due to incomplete grouting and, or waste settlement; see reference [61]).

As well as the standard half-height ISO container, a small number of additional designs were developed. These include a third-height ISO container for use with very dense wastes (such as metal plates) enabling the handling weight limit for relevant plant to be met while maintaining efficient filling of the container. A nominal 10 m^3 ISO container, with reduced length and width, was also introduced for easier handling and use in smaller areas at waste producers' sites.

The majority of waste emplacements to Vault 8 prior to 1995 needed to be retrieved, in a campaign that commenced in 1994, for upgrading (via Sellafield's WAMAC supercompactor and the LLWR Grouting Facility) to meet improved standards for aspects including compaction and void-filling. Nevertheless, not all of the resulting re-worked containers completely met requirements for control of void space. In some cases (where full-height ISO containers were used for non-compacted wastes) the contents were removed and processed (via WAMAC) prior to re-packaging. Others were deemed unsuitable for processing of the contents and such containers were typically repositioned at the top of the container stacks, in order to minimise loads on them.

Vault 8 has also received small arisings of large items of waste (such as uranium hexafluoride cylinders and the heat exchangers from the Windscale Advanced Gas-cooled Reactor) that were judged at the time to be impracticable to size-reduce into standard containers. Such items have mostly been grouted in situ using mobile grouting facilities; however, not all large items disposed to Vault 8 in this way were grouted internally.

2011 ESC assumptions on higher stacking of containers in Vault 8

In response to the pressing concern regarding capacity at the time of the development of the 2011 ESC, inventory projections assumed that higher stacking of waste containers above those already in place in Vault 8 would be undertaken [30]. Engineering assumptions were based on information and judgements available at the time. It was recognised explicitly that further substantiation of the approach would be required before higher stacking could be fully confirmed as optimised and viable. Nevertheless, higher stacking was assumed for Vault 8 − and other vaults − to ensure that the ESC presented the maximum envelope of potential disposals, on the basis of contemporary inventory projections. The primary optimisation argument was that, if proven to be achievable, disposals above the current level of containers would make use of the disposal volume under the cap (without deliberately engineering the cap shape for that purpose), consistent with maximising the use of the facility as a national asset. In addition, disposals under the cap would significantly reduce the requirement for import of 'clean' profile fill material.

As can be seen in the discussions that follow, subsequent work after the 2011 ESC that looked to fully substantiate higher stacking, instead showed these initial judgements were optimistic, and robust and fully underpinned analyses led to a reversal of the approach.

Vault 8 developments since the 2011 ESC

Work since the 2011 ESC has substantially revised some key aspects of the understanding of the existing Vault 8 disposals. In particular, the Vault 8 Container Issues project of 2013 [61] identified that many disposals, in particular older containers, were likely to be associated with much higher levels of potential voidage than previously appreciated (see Subsection 5.3.3).[39] The understanding of voidage and potential settlements that may arise is important for the understanding of future evolution of the cap. In addition, the work on voidage demonstrated that the contents of the containers do not, in general, represent a fully grouted matrix spanning the HHISOs, and so cannot be relied upon to provide a monolith extending throughout the internal container volume that could otherwise enhance the overall load-bearing capacity of the containers. This is consistent with the stated main aim of the grout as a void-filling medium, but some of the early engineering judgements assumed an effective load-distributing matrix for the majority of containers.

Optimisation and design work for closure of Vault 8 and the adjacent trenches via the first strip of the final cap was underpinned by container strength testing and associated finite element analyses (Subsection 5.3.3.2). The outcomes identified that the containers would not be strong enough, on the basis of container structures alone, to support the loads associated with implementation of the final cap. It was these analyses that led to higher stacking being discounted (Subsection 5.4.4).[40]

The changed understanding of total potential voidage and container performance led to additional changes to the closure approach compared to 2011 ESC assumptions. These included an extra 1 m of profile fill to distribute any strains that might otherwise affect the final cap due to settlements, and the decision to surcharge Vault 8 wastes (see Subsection 5.3.3.2).

Disposals of containers to Vault 8 are now complete, with the remaining disposal volume to the north of the vault having been filled with waste containers. Treated Radwaste Store drums and bagged VLLW wastes have recently been placed in remaining volumes on an

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[39] This was further explored and confirmed by the subsequent 'Stored Waste Assessment' [95].

[40] It is notable that the approach involving no higher-stacking, and accepting container deformation during closure, is in essence a return to the original Vault 8 container concept e.g. as assumed in the 2002 PCSC [28].

opportunistic basis.[41] The vault is now being prepared for closure and the remaining bags of VLLW will be placed as part of the closure programme.

Part of this closure process will involve implementing updates to the leachate management approach. The updates are required for the following reasons:

- to allow a change from active pumped leachate management arrangements to passive gravity-fed arrangements;
- to provide the capability to continue to manage and monitor Vault 8 leachate once the first strip of the final cap has been installed and Vault 8 closed;
- to ensure that the arrangements for the closure of Vault 8 are consistent with long-term (i.e., post-closure) leachate management plan.

Optimisation considerations and outcomes associated with the future control of hazards from Vault 8 wastes, during the PoA and beyond, are described in Subsections 5.2 to 5.4, and in particular in Subsection 5.4.4, including:

- the consistency of the vault design with overall strategy for pre- and post-closure engineering of the LLWR;
- the approach to cap installation, including surcharge.

4.4 Vault 9

The 2002 PCSC [28] was originally expected to establish a basis for the continued authorisation of disposal operations at the LLWR. The safety case was supported by a SDP [60] that set out expectations for the development of future vaults and final closure of the facility within what was formerly understood to be the ‘consented area’ for disposals (dating back to the original 1957 planning consent). It was anticipated that development would take place on a phased basis, following a broadly similar design philosophy to that adopted for Vault 8, but with an increased height of container stacking, achieved by increasing the depth of the vault base slabs. It was also expected that, subject to the detailed geology of the area, more use would need to be made of engineered clay as the foundation for future vaults because of their greater depth.

These plans were not put into effect, for two main reasons. Firstly, Cumbria County Council established that the concept of a ‘consented area’ had no meaning in the context of current and future use of the LLWR site, and that future developments would require planning permission from the Planning Authority via the appropriate procedures. In addition, the Environment Agency, in its review of the 2002 Safety Cases and the subsequent decision on

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[41] That is, volumes that are accessible for such disposals from the north of the facility, below the required minimum depth of profile fill - see Subsection 5.4 - that are not to be occupied by disposal containers for geometrical reasons.

disposal authorisation, considered that the safety cases had failed to make *'an adequate or robust argument for continued disposals of LLW'* [27].

As a result, in its Decision Document [62] at the time, the Environment Agency determined that the continued disposal of LLW to Vault 8 would be authorised (subject to existing annual solid waste disposal limits) until its capacity was reached, but that any further consignments to the facility would be for the purpose of temporary storage only. Disposals to the proposed Vault 9 (and any future vaults) would not be authorised until the appropriate planning permission had been received, confidence had been established in estimates of the radiological capacity of the site, and the Environment Agency was satisfied that a sufficiently robust safety case had been made.

In the light of these decisions taken by the regulators and planning authorities, a detailed analysis and associated rationale was developed for a preferred 'Modular Vault' design [51], to be adopted in the construction of Vault 9 and to serve as a baseline for any future vaults. Long-term environmental impacts were considered through qualitative judgements comparing different designs with the outputs of the 2002 PCSC. Information on cost and wider socio-economic impacts was also developed to aid this process, and the options assessment process was undertaken with the involvement of stakeholder representatives, including members of the West Cumbria Site Stakeholder Group. The implementation of a comprehensive double-liner system for the vault base and walls was judged to be preferred because it [51]:

> *' … better satisfies the design principles, as defined in the applicable UK regulations and Best International Practice (i.e. containment) and will therefore be more acceptable to the regulators and other stakeholders. It was also the clear preference of the stakeholder elected representatives.'*

The options study specifically prioritised containment and operational requirements in the absence of a disposal authorisation. However, flexibility was retained to convert the storage system to a disposal vault.

The options study therefore identified that a concrete-lined approach would continue to be the basis of the Vault 9 concept, The concrete elements of the base provide a stable running surface for container placement. It has a jointed construction; as for Vault 8, between the joints some (very limited) cracking is to be expected but this is not inconsistent with performance. In addition, to maximise containment, long-term water retention was to be ensured by employing a double set of composite Bentonite Enhanced Sand (BES) and geomembrane layers underlying the concrete base; these composites were also designed to extend into the walls.

The options study also recognised that, in the longer term after the cessation of active leachate management measures, extended leachate containment within the vault would lead to increased contact times with the waste and corresponding increased concentrations of radionuclides. In order to mitigate the risk of releasing this concentrated leachate to surface or near-surface systems (i.e. after over-topping of the vault walls), the closure design also incorporated a vertical drain system and a substantial cut-off wall, both of which would be constructed at a later stage in site operations. However, it was also highlighted that the preferred option also offered scope for flexibility, enabling the containment strategy to be adapted in future, if required.

Temporary planning permission for Vault 9 was granted in January 2008, on the basis that it would be used for storage only. This did not preclude the possibility of subsequently achieving planning permission for the vault to be converted to use for disposal.

Construction of Vault 9 according to the Modular Vault design commenced in September 2008 and was completed in July 2010. An important element of the work undertaken (as reported in the 2011 ESC [31], and underpinning references including reference [51]) was to revisit the evidence and rationale that underpinned the preferred safety strategy for long-term passive leachate management. Specifically, the apparent attractiveness to community stakeholders (and the assumed attractiveness to the Environment Agency) of the preferred Modular Vault design was embodied in its description as *'containment of leachate for as long as practicable'* [51]. On further examination, however, the confidence that could be attached to this description, and the extent to which it could be described as an optimised strategy for disposal, was called into question [31].

The 2011 ESC [31] identified a significant change to the ongoing approach to future management and closure of Vault 9, and to the design and management of future vaults. This included changing from a maximum containment approach to one involving minimising aqueous releases by minimising water contact with wastes. For future vaults (see Subsection 5.4.6) this included drainage features in vault walls at the 1 m level, running along the walls associated with long axis of the vaults, with those drainage features then being connected to under-vault drainage blankets. Walls had already been largely constructed for Vault 9 at the time of the relevant optimisation processes. Therefore, for Vault 9 arrangements will be 'back-fitted' to achieve a consistent outcome, with slots or other features between relevant vault walls at the 1 m level, to subsequently access under-vault drainage blankets associated with the future vaults. These changes are discussed in detail in Subsection 5.4.5.

In terms of drainage arrangements during the PoA, leachate is currently actively pumped from Vault 9. Future developments will include the construction of a gravity-based passive drainage system including a deeper leachate gravity drain [63].[42]

The Environment Agency's review of the 2011 ESC led to the decision in principle to permit Vault 9 for disposals [62]. This in turn underpinned an updated planning application that included provisions for disposal, which was accepted [64]. Disposals to Vault 9 are ongoing as a result.

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[42] This new passive system will be focused on operations and will be separate from the post-closure passive drainage provisions, which will include arrangements being back-fitted such that Vault 9 waters drain into the sub-vault drainage blankets associated with future vaults.

No detailed review was undertaken of wasteforms prior to the granting of planning permission for Vault 9. However, in line with development of the NDA's UK Strategy for management of LLW [32], NWS and its forerunner LLW Repository Ltd (through its integrated waste management projects and programmes) has been pro-actively working with waste consignors and waste treatment providers, and regulatory bodies to implement waste management routes that have increased opportunities for reuse and recycling, together with diversion from LLWR for appropriate waste disposals (see also Subsection 2.3).

This has led to a major change in the volumes of waste being received at the LLWR, as a result of diversion to other disposal facilities, and volume reduction of wastes consigned to the LLWR [4]. Treatments include incineration and metal melting. In addition to reducing volumes for disposal, this has led to changes in the proportions and forms of materials being disposed.

These changes led to a significant reduction in the volumetric rate of disposals to Vault 9 (and indeed to projections for future vaults). However, for Vault 9, this is offset in part by the decision not to higher-stack containers above the existing stacks in Vault 8, which has led to those containers that might otherwise have been placed in Vault 8 higher-stack positions instead being disposed to Vault 9.

5 Pre- and Post-closure Engineering

5.1 Introduction

The following subsections describe optimisation of the pre- and post-closure engineering. This covers future vault designs, the approach to closure of existing and future vaults, and long-term leachate management arrangements.

While the closure engineering description also includes closure of the trenches, optimisation of related aspects such as the potential for retrievals and interim hydrological management are considered separately, in Section 6.

5.2 Optimised Pre- and Post-closure Engineering Concept

Here, the optimised pre- and post-closure engineering concept is summarised, together with key aspects of the associated options process and rationale.

The concept was identified through a wide-ranging, systematic optimisation process undertaken in the years prior to submission of the 2011 ESC. The following summary is based on Section 5 of reference [31]; reference [40] provides full details.

5.2.1 Key Features of the Process

The process followed the approach set out in Subsection 3.5. The implementation of individual steps is not set out in detail here, however key aspects included the following.

- On the basis of agreed scoping outcomes, the process involved a review of the overall concept to ongoing disposals and closure, constrained only by the presence of existing facilities. This included a full range of concept options.[43] The identification of concepts, and associated engineering component options, was framed by recognition of threats to performance (see Subsection 1.2) and the control measures available.
- This 'top down' approach to concept options, considering overall responses to threats via overall concepts and controls, was complemented by a 'bottom-up' approach. This started from the perspective of identifying detailed categories of engineering options that could meaningfully contribute to addressing threats. The two resulting options sets were audited against one another, combined and then screened to remove concepts that did not meet basic requirements (e.g. confidence in containment).
- Reviews of international good practice and benchmarking studies (see Subsection 3.7) were used to support the initial options process.

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[43] Subsection 5.2.2 includes examples.

- Significant pre-work, via a combined multi-disciplinary team, was implemented to develop detailed proformas describing key components, main alternative options and associated variants, and their compatibility with key overall concepts. Assessments identified key advantages and disadvantages mapped to criteria. Technical analyses were developed so support the assessment process, ranging from hydrogeological models through to scoping engineering concept diagrams and designs, and interpretations of assessment pathway models.
- The final workshop was held over two days and involved a systematic process stepping through key alternatives for concepts aligned to component options and assessing options in the context of differentiators against criteria given the underpinning information, with iteration.
- The assessment of concepts was primarily structured into assessments of overall options for isolation, containment and infiltration reduction. The initial focus was therefore on approaches to capping and other potential methods for provision of the relevant controls. This led to an agreed preference from participants that a final repository cap, similar to the design developed over many iterations over previous years, remained an optimised response and basis of the closure concept (as articulated further in Subsection 5.2.2).
- Options for engineering components 'below' the cap were then explored in an integrated and systematic manner. An integration, reconciliation and review process concluded the workshop to ensure an agreed outcome.

Significant stakeholder engagement was implemented throughout, from the scoping phase to the final workshop. The Environment Agency, the Office for Nuclear Regulation (then the Nuclear Installations Inspectorate), county, borough, and parish councils, the NDA, the independent Peer Review Group, and representatives of the local stakeholder group were included in the process.

5.2.2 Concept and Key Rationale

The outcomes of the pre- and post-closure engineering optimisation work for the 2011 ESC served to underpin the basic logic that had already been at the heart of the design for decades, i.e. the use of a multi-layer repository cap, with passive drainage of any infiltrating waters. Alternative concepts were reviewed through the process but not favoured.[44] It was

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[44] Example options and high-level arguments include the following. Use of a minimal (e.g. thin grass) cap would present concerns from lack of controls over isolation and containment. However monolithic concrete options for one or both of the cap or vault systems were also not favoured. Concrete will still eventually saturate in Cumbrian conditions, leading to leachate generation; at the same time concrete will not provide for effective passive drainage within the vault. Moreover, a monolith will age and crack leading to inconsistent performance and preferential flow pathways; a concrete cap and support will be more susceptible to damage through settlements compared to a composite-based cap supported by profile fill; and will involve significant energy use compared to the use of inert natural materials.

recognised that the cap layers had been subject to many iterations of design and assessment, and the process participants considered that the existing cap layer design remained robust.[45]

There were, however, some important changes to other aspects of the facility design, in particular relating to long-term passive leachate management for the existing and future vaults.

Previous design approach for long-term leachate management

The concept that was in place prior to the 2011 ESC was developed during the 'modular vaults' process in the mid-2000s [51], that led to the Vault 9 concept as well as designs for long-term leachate management. As noted in Subsection 4.4, the Vault 9 design was informed by its then primary role as a storage facility, with the potential for later conversion for disposal.

The concept focussed on maximising containment during storage, with active pumping of contained leachate during the operational phase. As a result, the design included a double composite liner in the base, and a further single composite liner to the top of the side walls, to maximise waterproofing. It was recognised at the time that this approach would, if converted to disposal and then closed via the final cap, lead to the system retaining infiltration until the water level eventually reached the top of the vault.

This raised the question of how to manage over-topping waters. A series of circular vertical drains was therefore part of the design prior to the 2011 ESC, located in a line between the vaults and the trenches, to drain waters that may then over-top the vault, and any other leachate, to deeper systems. A deep cut-off wall was also part of the concept, illustrated in Figure 5.1.

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[45] This conclusion has been further supported by BAT studies and reviews since (e.g. Subsection 5.4.1), which have also endorsed the use of the same final cap layering approach with only minor amendments.

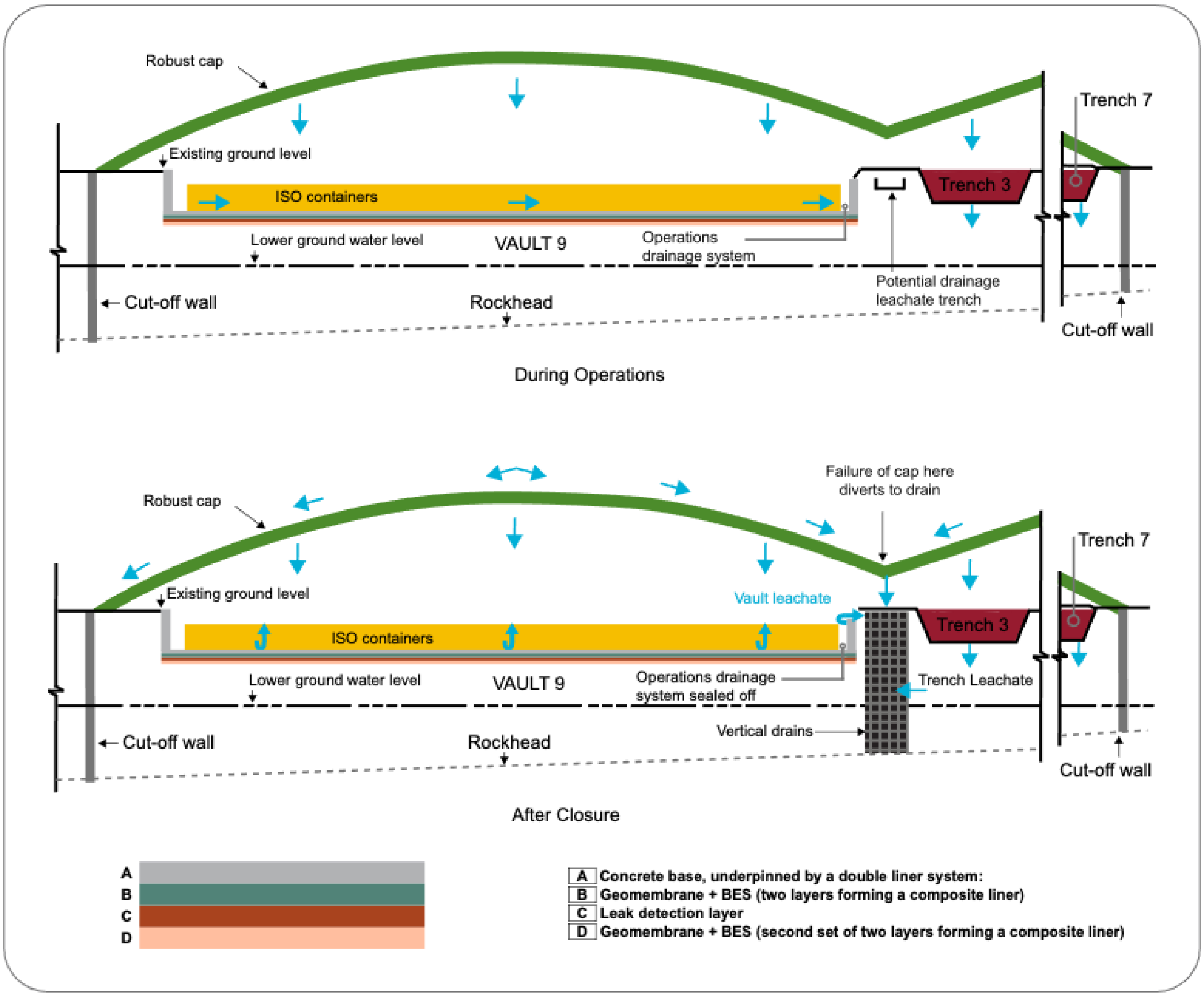

Figure 5.1: Section view for the preferred vault conceptual design in the Vault Single Option selection process [40, 51]

During the pre- and post-closure optimisation process for the 2011 ESC, concerns were expressed that the drains may not offer sufficient capacity as the cap degrades, due to their relatively narrow cross-section and potential liability to clogging. It was considered that clogging might occur as flows and associated materials from waste degradation would be focussed into a system of narrow drains, with the potential also for chemical changes.

Reviews of the concept also recognised that allowing waters to build up in the vaults prior to over-topping would maximise contact of water with wastes, with implications for leaching of contaminants. Then, if leachate was not drained effectively via the vertical drains, there would be the likelihood of discharge of the contaminated waters to near-surface systems.

The drains were located between the vaults and the trenches under the 'valley' feature formed between the dual-dome or 'gull-wing' design [51] (see Figure 5.1) that was assumed for the cap at the time. The two-dome approach had been identified to give flexibility in construction, e.g. allowing trenches and vaults to be capped at different times, and to reduce overall profile fill volumes and thus costs, amongst other reasons. This approach accepted that wastes over the trenches and the vaults near the interface would only be covered by limited depths of profile fill due to the cap gradients. The line between the two domes was recognised as a potential weakness due to erosive forces associated with water being shed into the 'gulley' and along drainage features, whilst they remain functioning, for a prolonged period. This was the main reason that the deep drains were located along the line of the join between the domes, to mitigate this known weakness

During the optimisation process for the 2011 ESC, it was considered that controls offered in relation to isolation and containment could be significantly enhanced by changing the cap geometry. In particular, reverting to a single-dome cap profile would allow the removal of the 'gulley' as a known weak point, and would also increase the depth of profile fill in relevant areas. The increase in depth of profile fill was identified as having benefits ranging from enhancing confidence in cap resilience to reducing the potential for impacts from certain categories of potential human intrusion.

It was also identified that adopting an appropriate strip-capping schedule, together with an appropriate sealing approach to the face of the cap, would provide the required flexibility in construction that had previously been one of the main drivers for the two-dome approach.

The removal of the weak point in the cap also then allowed a change in vertical drainage approach. Rather than using a single line of deep drains with risks of clogging, the benefit of reducing overall water contact with wastes and providing redundancy in drainage capacity, minimising the risk of near-surface discharges, was a key consideration in identifying alternatives.

Updated 2011 ESC pre- and post-closure engineering concept

The resulting optimised approach is illustrated in Figure 5.2.

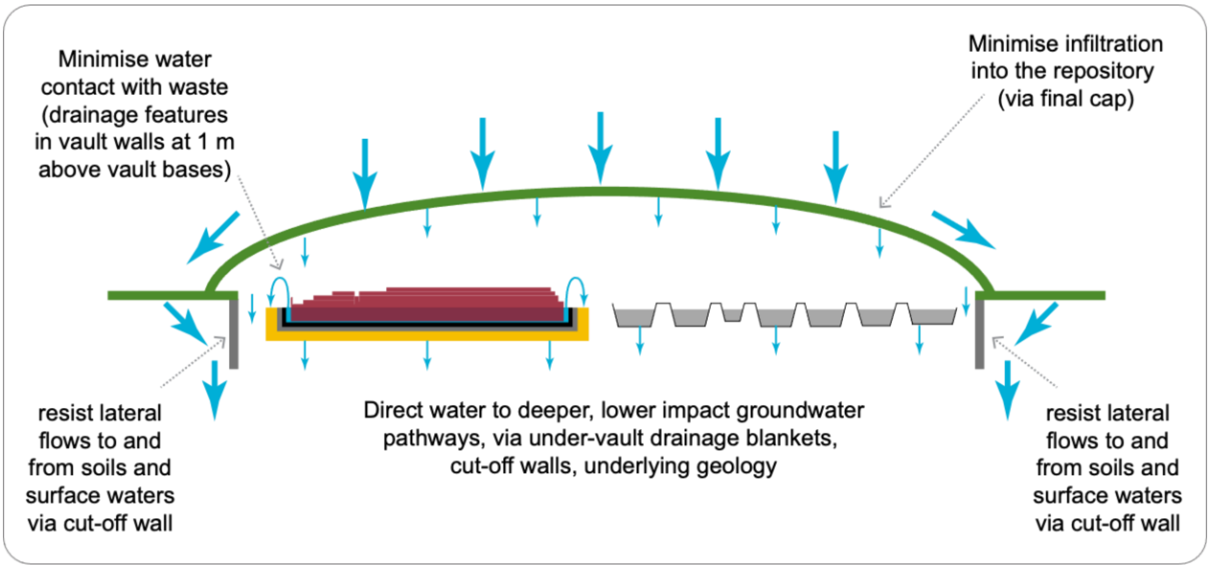

Figure 5.2: Schematic illustration of the optimised closure concept. The schematic focuses on water flows. It reflects evolution of the cap to a point where infiltration has increased sufficient for the vaults to saturate to the 1 m level, resulting in flows to passive drainage arrangements including the underlying vault drainage blankets.

The overall concept uses the multi-layer, single-dome final cap to provide isolation and containment of the wastes, and to manage bulk (and thus trace) gases. Specifically in terms of the groundwater pathway, the concept is focussed on minimising water contact with wastes (and thus minimising the concentration of contaminants in leachate) for as long as practicable, primarily through the use of the cap. A further key aspect of the concept is the preferential direction of any leachate that does arise, e.g. as the cap begins to degrade, to deeper (rather than surface) systems.

This concept is delivered by the following measures.

- The final cap includes layers encouraging evapotranspiration and drainage above a multi-barrier, composite system for reducing infiltration. The composite barrier is based on a geomembrane in intimate contact with a BES layer. In addition, the upper soil and rooting layers provided for evapotranspiration will help control hydrologically effective rainfall (HER). The drainage layers above the low-permeability layers serve to direct water to the perimeter and to minimise the head on the low-permeability layers, whilst their drainage performance lasts (noting layers in the upper part of the cap will eventually clog).
- Extensive drainage blankets will be constructed under the future vaults to maximise access to the drainage capacity offered by the underlying geology. Extensive drainage arrangements will also be constructed within vaults, providing sufficient redundancy in capacity to ensure waters can access the drainage blankets for a

prolonged period post-closure. Arrangements include: highly permeable inter-stack void fill; drains running along the length of future vault walls at the 1 m level; and passive drainage connections installed at closure at the 1 m level between Vaults 8 and 9 and the future vaults.

- The passive drainage system will collect waters at the 1 m level to minimise the risk of over-topping, and to minimise water contact with wastes and thus associated leachate generation; this ensures that only the bottom 1 m of container stacks become saturated when the cap begins to degrade, infiltration increases and the vault water level rises. The 1 m level, rather than for example basal drainage arrangements, was set to allow for operational management of waters, and to minimise the risk of clogging of the drains.
- It was identified that the drainage blankets would not be contiguous and would be separated by low-permeability material to avoid them providing a combined fast pathway that could concentrate leachate to the south of the site due to natural falls. However, those natural falls will be used to facilitate passive, gravity-based drainage from Vault 8 and 9 to the drainage blankets under future vaults. The future vaults will discharge to their own drainage blankets.
- The encircling cut-off wall will work with the drainage blankets to preferentially direct any leachate that does arise, as the cap begins to degrade, to deeper systems. The cut-off wall will also minimise lateral inflows into the disposal areas and associated drainage blankets. To assist in both functions, the low-permeability layers of the cap will be integrated into the cut-off wall.[46]

The process included iteration, and consideration and alignment of benefits and trade-offs associated with between options. The process used was hierarchical; the starting point was options for the overall concept and the associated choice of approach to capping.

As an example of this hierarchical method, the choice of a single dome approach for the final cap led to a move away from deep drains between the vaults and the trenches. This was because this location was proposed to address the potential weakness associated with potential erosion of the valley between domes in the previously proposed gull-wing cap, Moreover the move to a concept with the defined aim of minimising water contact with waste for as long as practicable informed the selection of passive leachate management options. This led to preference for under-vault drainage blankets and extensive connections in vault walls at the 1 m level. In turn, ensuring these drainage blankets would remain unsaturated for a prolonged period was reflected in requirements for cut-off wall options, in particular in setting its depth.

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[46] As noted in Subsection 5.4.3, hydrogeological modelling was used to optimise the proposed depth of the cut-off wall, to ensure that it provides the required functions including minimising in-flows into the wastes and the drainage blankets and their interface with the underlying geology. This led to a reduction in the required depth of the cut-off wall compared to previous assumptions.

This options process was undertaken in parallel with the construction of Vault 9. The preference for water control via the walls to the 1 m level was identified after the construction of the concrete elements of the outer vault walls, but before the installation of the geomembrane and BES. This accounts for those walls extending to the original design height but the geomembrane and BES being capped at the lower 1 m level.

A further consequence is that the level of containment in the design for Vault 9 is not required for future vaults. Future vaults need to provide for water management during operations but do not need to maximise containment into the longer term. This is because the post closure the priority for the vaults and the passive drainage system is to maximise the preferential direction of leachate to the drainage capacity provided by the geology underlying the vaults. Leachate flow through the vault bases as they degrade post-closure is consistent with this. The future vault design therefore includes a single composite liner for water management during the PoA, rather than the double composite implemented for Vault 9.

The system also allows for gas management in recognition that bulk gases would need to be managed to avoid pressure build-ups that could challenge cap integrity. On the basis of available modelling at the time, the position for the 2011 ESC was that gas evolution would potentially mainly occur during the PoA, and thus the gas vent, which had been part of the cap design for several decades, would be closed at the end of the PoA. However, the optimisation work for the 2011 ESC also considered the uncertainties associated with projections of gas evolution and explicitly kept open the possibility that the gas vent could be kept open after closure. It was recognised then, as now, that experience of monitoring the waste form evolution and gas production over the time period between now and final closure would present the best evidence base for a final decision[47].

Finally, the position on coastal erosion was considered in the work for the 2011 ESC [30, 31], and has been further endorsed since. In summary, we note that facility disruption through coastal erosion is expected, and also that we cannot place reliance on human actions beyond the PoA to prevent it. Indeed, no options have been identified that could plausibly protect the facility into the longer term.[48] Our approach is therefore to use constraints on future disposals via WAC (including controls on inventory and container types) to ensure that related impacts are consistent with regulatory targets.

The controls offered by the cap and profile fill, vault engineering and passive drainage systems, working with the cut-off wall were overall agreed to represent an optimised response to the 'threats' to performance outlined in Subsection 5.3.

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[47] The topic of gas venting in ongoing optimisation and design is considered further in Subsection 5.4.1.

[48] This includes the decision that bulk disposal of durable (e.g. stainless steel) containers to the vaults will not be allowed (see reference [89]). This is primarily for amenity reasons as such disposals could persist on the beach after site disruption.

5.2.3 Subsequent Reviews of the Concept

The concept has been used as a starting point and framework for ongoing optimisation. However, consistent with the principle of iteration, there is a commitment to revisit the concept if any studies or information identify a change in understanding sufficient to require the original concept to be re-assessed.

This has not proved necessary because optimisation work undertaken since the 2011 ESC has served to reinforce the arguments for the overall concept. The robustness of the concept has therefore been further underpinned.

5.2.4 Concept Summary

An overview of the current concept and the approach to its optimisation is provided in Box 5.1.

Box 5.1: Summary: Pre- and Post-closure Engineering Concept and Optimisation Approach

A summary of the concept and optimisation approach follows.

- Ahead of the 2011 ESC, a structured, stakeholder informed optimisation (that is, BAT) process, in line with regulatory and good practice guidance, was employed to provide a comprehensive review of the pre- and post-closure engineering concept.
- The study considered a wide range of alternative concept options and associated engineering approaches. Its outcomes confirmed the previous position that the concept should be based around the use of a thick, multi-layer final cap, to provide isolation and containment, including reducing doses from the wastes, providing a barrier to intrusion, minimising infiltration, and providing bulk gas management features. Other options were considered but either did not provide the required confidence in isolation and containment (e.g. thinner or no cap options), or were associated with a reduced level of confidence in long-term performance (including, for example, monolithic systems, the use of geomembrane only, or clay or BES only, systems rather as a composite, or reliance on other categories of synthetic low-permeability layers for which long-term performance is uncertain).
- The main changes for the 2011 ESC optimisation work concerned the approach to long-term leachate management from the vaults, post-closure. A concept option involving minimising water contact with wastes, whilst maximising the preferential directing of any leachate that does arise as the cap begins to fail to deeper, rather than shallower systems, was considered to be consistent with the principles of ALARA. Leachate directed to deeper systems will primarily discharge to the sea-bed, which is preferable to direct releases to the surface environment in the vicinity of the site.
- Rather than using the previously proposed systems of deep drains, the design of which was based on allowing over-topping of vaults, and which were considered to

be at risk from clogging, under-vault drainage blankets for future vaults will be constructed. These will be connected to the existing and future vaults by lateral drainage arrangements at the 1 m level in order to reduce water contact with wastes. This approach will also enhance confidence in performance, compared to options such as the previous localised deep-drain approach, by providing redundancy in drainage to ensure resilience to clogging processes, whilst maximising the interface with the drainage capacity provided by the underlying geology.

- The drainage arrangements will be complemented by the use of a fully encircling cut-off wall, to minimise flows into the wastes and drainage blankets from outside the facility, and to promote the direction of leachate arising from the wastes preferentially to deeper systems. As well as representing a standard and well-understood industry approach, the successful implementation and performance of the existing cut-off wall, together with the understanding of its likely future evolution, was considered to provide strong evidence that the cut-off wall will provide the required function for a prolonged period post-closure.
- The concept identified has provided a robust starting point and framework for subsequent optimisation studies.

5.3 Pre- and Post-closure Engineering Component Optimisation

5.3.1 Continuing Optimisation since the 2011 ESC

Optimisation and design of the pre- and post-closure engineering components is an ongoing process, within the overall framework of the concept established for the 2011 ESC. A range of studies have been implemented over recent years to take forward the optimisation and design of individual engineering components, whilst ensuring the overall design continues to be integrated and aligned.

The number of studies and the level and detail of optimisation involved represents a large volume of work, captured in a hierarchy of detailed reports. Several aspects have been subject to multiple iterations. It is not the aim of this report to exhaustively repeat the details of each of these studies and their contributions to overall optimisation; rather, the focus is on the optimised outcomes and key arguments. Nevertheless, an understanding of the key steps towards identifying the final optimisation status of components is provided to assist clarity of the overall approach and the associated depth of analysis that has been involved.

The discussion is set out as follows.

- Subsection 5.3.2 provides an overview of pre- and post-closure engineering optimisation studies undertaken since the 2011 ESC.

- Subsection 5.3.3 provides a discussion on key topics where understanding of key topics or wider priorities have changed as a result of the studies identified, including implications across the system that are not specific to one engineered component.

Each of the studies has been undertaken consistent with the overall optimisation philosophy and process set out in Section 2. Therefore, it is not necessary to provide detailed discussions of the individual processes used. The references provided for the studies present the range of modes of application of the generic process.

As elsewhere in this document, the presentation is consistent with the approach to the 2011 ESC, in that discussions on optimisation of the pre- and post-closure engineering focus on the vaults, the cap and the cut-off wall. This recognises that the greatest level of interaction is between these components. However, optimisation of the trenches has also been addressed within an overall integrated approach.[49]

5.3.2 Summary of Key Pre- and Post-closure Engineering Studies

Table provides a summary of optimisation studies since the 2011 ESC for the vaults and closure engineering.

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[49] The separate discussion of optimisation studies and arguments for the trenches (Section 6) is primarily for clarity of presentation.

Table 5.1: Overview of Key Pre- and Post-closure Optimisation Studies since the 2011 ESC

Topic Area	Key Studies	Commentary
Vault 8 Closure	Vault 8 Closure Plan [65]. Repository Development programme, summarised in [66] and [67]; including the specific 'design packages':[50] • Final Cap [66, 68]; • Surcharge and Profile Fill [67, 69]; • Void Fill [67, 70]; • Higher-stacking [67]; • Cut-off Wall [71].[51] Detailed optimisation is continuing through the capping programme and associated design development. In addition, a specific BAT study has been implemented for the approach to	These comprised successive, detailed studies on the overall approach to closure of Vault 8 (and the adjacent strip of the trenches). They included a full review of optimisation of the cap design and its layering structure, together with the cut-off wall, as part of an integrated system. The approach to void fill and profile fill, alongside consideration of surcharge of the trenches and, latterly, surcharge of Vault 8 was also addressed. The approach to higher stacking of containers in Vault 8 was considered, although as studies progressed, higher stacking was not taken forward (see Subsection 5.4). Together this was a major programme of optimisation and review, implemented by a multi-disciplinary team and with regulatory engagement. Significant engineering design, options development and substantiation work was involved, together with input from the ESC programme. Several iterations were required including a full 'reconciliation' process to align outcome, where the interactions between components were sufficiently strongly related that they could not be fully disaggregated. Implementation of the optimised outcomes into detailed design has continued since the conclusion of the above studies, and the first strip of the cap, and associated sections of the cut-off wall, void fill and profile fill, has been approved for construction. In addition, a specific study on the selection of the geomembrane for the final cap was undertaken. This recognised that learning gained from the EPA indicated an opportunity to

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[50] The Repository Development programme design package considering interim hydrological management of the trenches is discussed separately in Section 6.2.

[51] Other design packages were also relevant to optimisation in principle, but cover detailed aspects focussing on practical aspects of implementing designs and are not discussed here in detail; e.g. access routes, haul roads, monitoring of construction activities; see reference [66].

Topic Area	Key Studies	Commentary
	selecting the final cap geomembrane [72].	further optimise the approach to the geomembrane, reflecting additional analyses made available since the conclusion of the Repository Development programme.
Optimisation of Vault Disposals	Container Protection optimisation studies for Vault 8, Vault 9 and the future vaults [73, 74] Repository Development programme [66] and [67]. Optimisation of vault disposals for relevant waste categories [75].	Container protection - that is, consideration of the protection of containers from environmental effects such as precipitation and wind-blown chlorides - was considered in successive studies including those undertaken for the Repository Development programme. This was then taken forward by the more recent vault optimisation study [75]. However, this latter study had a broader remit. It considered the implications of the improved understanding of container performance under load[52] for disposals to Vault 9 and the future vaults, given that previous studies addressing this issue had only considered Vault 8. Moreover, the study considered the potential for ILW disposal to the vaults. As for other key studies this was a significant optimisation programme involving an integrated team.

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[52] See Subsections 5.3.3 and 5.4.

5.3.3 Updates to Key Aspects of Understanding and Context

Since the 2011 ESC, the understanding of key areas of repository engineering and wastes has changed. These changes have not challenged the overall concept but have led to developments in the manner in which it will be implemented. These major updates are summarised in the text that follows, in order to underpin subsequent discussions on the optimisation status of the different engineering components.

For the vaults, the main areas of development have included:

- responses to updates to the understanding of waste voidage in Vault 8 (Subsection 5.3.3.1);
- consideration of the implications of changes to the understanding of container performance under closure loads (Subsection 5.3.3.2);
- approaches for existing and future potential waste categories in Vault 9 and the future vaults, including the potential for modular approaches, and container protection (Subsection 5.3.3.3).

The discussions in the following subsections introduce these topics and the key aspects of the optimised response to them, in order to underpin the descriptions of the optimised status of system components in Subsection 5.4.

5.3.3.1 Implications of Voidage Associated with Existing Disposals to Vault 8

A study was undertaken of the existing disposals [61] in order to re-assess the levels of existing and total potential voidage associated with disposed containers. This was in part due to observations of enhanced 'ullage voidage', i.e. gaps at the tops of containers that might otherwise be expected to be effectively capped with grout. An assessment not just of the ullage voidage but of other forms of total potential voidage revealed much higher overall voidages than previously understood, including the voidage ranges presented in the 2011 ESC [61].

This led to the addition of an extra 1 m of profile fill (see also Subsection 5.4.2) to distribute strains that might otherwise arise from differential settlements that could arise from expression of this voidage after closure. This was added to the entirety of the cap, not least due to minimum and maximum gradients meaning that 'feathering out' the additional thickness over the trenches would be difficult. However, in addition, the increase in the minimum total depth of the cap and profile fill from 4 m to 5 m[53] was also recognised as being beneficial from the perspective of waste isolation and human intrusion.[54] On that basis, the extra 1 m was considered an optimal response.

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[53] This minimum applies over the vast majority of the wastes (see Subsection 5.4.2).

[54] The potential benefit of an extra 1 m pathlength for radon releases, especially over the trenches where profile fill will be predominately cohesive (Subsection 5.4.2), has since also been recognised in assessments for the 2026 ESC [14].

It was considered that the cap profile could be adapted to minimise any additional visual impacts of this extra barrier thickness to local residents. The use of granular material over the vaults was assessed to be consistent with the overall aim to maximise strain distribution to control settlement impacts on the low-permeability layers of the cap, and this was confirmed by subsequent options reviews for the profile fill (Subsection 5.4.2).

The associated cap resilience assessments recognised that the most substantial settlement risks were associated with the older containers near the vault walls at the north and west of Vault 8. These older containers are the most likely to be associated with higher levels of voidage, and the vault walls will act as a 'hard point' which enhances the potential for differential settlement within the system, as the walls will not settle with the wastes. Even with the subsequent decision to surcharge the Vault 8 disposals (see Subsection 5.3.3.2), the 1 m extra was considered to remain of value in ensuring confidence in cap resilience towards the edge of the vault.[55]

5.3.3.2 Implications of the Understanding of the Ability of Container Stacks to Resist Closure Loads

As described in Section 4, the initial design for Vault 8 was for loose tipped wastes. This was updated to the container-based disposal approach at an early stage. Until the 2011 ESC, however, only stacking to four-high of the HHISOs had been assumed, and allowance had been made for some expected damage to the containers upon loading during the closure process, in particular concerning the bases of older containers, considered to be mitigated in part by the use of a grouted waste form [59].

In the 2011 ESC [31], higher stacking of containers was assumed - that is, to eight containers high - above those currently placed in Vault 8, and also in other vaults. It was recognised at the time that this had not been subject to full optimisation and underpinning, and that this would be required if taken forward; however, initial engineering judgements ahead of the 2011 ESC were indicative of the potential for successful implementation of higher stacking. These judgements in part reflected assumptions at the time that for the majority of the containers, the grouted waste form would provide an effective, spanning matrix that would help distribute load through the containers rather than solely through the container corner elements. Such load distribution would effectively enhance the overall load bearing capacity of the containers.

The findings of the Vault 8 voidage studies in 2013 [61] provided an early challenge to those initial engineering judgements. They led to the updated understanding that the majority of containers in Vault 8 are associated with non-trivial potential voidage. This had the implication that only a minority of grouted waste forms could be relied upon to provide the assumed continuous load-distributing structure within the containers.

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[55] Such areas of the vault, associated with the greatest unmitigated potential for differential settlements, are termed 'sensitive locations' in the cap resilience assessments (e.g. reference [92]).

This was contrary to previous judgements which had, in part, taken into account observations of a small subset of containers that were cut open as part of grouting demonstration projects ahead of the 2011 ESC (see e.g. Figure 3.3 of reference [76]). Those specific examples suggested excellent encapsulation, which was shown not to be representative by the 2013 studies.

These concerns led to an early priority to re-assess the approach to higher stacking within a systematic options study, as part of a wider framework of optimisation focussed on closing Vault 8 and the adjacent sections of the trenches. Iterations of analysis (e.g. as reported in references [65, 66, 67]) led to an increasing focus on the evidence base for container properties and their likely response to closure loads.

The use of physical container testing was identified as being critical to confidence in container performance under load. However, as outlined in reference [67], the testing then undertaken, rather than enhancing confidence in higher stacking, served to challenge previous judgements on the ability of the containers to withstand the required loads. Together with supporting finite element models that proved able to replicate the observed deformations in the container from the physical testing (see Figure 5.3), the analysis indicated that during the closure process most, potentially all, containers in Vault 8 will be loaded beyond the ability of the load-bearing elements (that is, the corner elements) to withstand loads. Furthermore, to emplace higher-stacked containers in Vault 8, plant (appropriately supported by removable trackways) would need to move over the existing containers, and this would place loads on the stacks that would be equivalent to closure loads (noting these would involve moving rather than static loads). This would lead to stack deformations occurring underneath plant during the process of higher stacking, and no practicable options were identified to mitigate these risks. As a result, it was identified that higher stacking in Vault 8 would not be operationally safe. This re-assessment of container strengths also led to the decision that containers will currently not be stacked above five-high, for operational safety reasons, irrespective of the closure process.[56]

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[56] This was based on the analyses of TC-08 type HHISO containers and the potential for stack toppling if lower containers in the stack fail during placement operations. The TC-01 variants that are currently in general use are considered to be stronger and there is considered to be the potential, should finite element analysis, container testing and further optimisation work considering also interactions of the slab confirm, to stack them to seven-high in Vault 9, although they would still not be able to withstand closure loads. See also Subsection 5.4.5.

Figure 5.3: **Physical testing of containers, and corner element deflection analysis in finite-element models. The photograph and model outputs are indicative of the broader physical testing and finite-element analysis outcomes presented in [67] and supporting references.**

Irrespective of the final stacking height, a general concern is the risk that container deformations could occur during the placement of the low-permeability layers of the cap. This would be contrary to good construction management practice, which is to ensure such layers are founded on a stable formation. Options were considered to prevent or mitigate deformations, but none were considered to provide a practicable response [67]. This was in part related to the strong preference identified in successive studies not to move the existing four-high containers in Vault 8. This was on the basis of the large number of containers in place in the vault, which means moving them would be a very significant activity (requiring creation of more vault space first), together with concerns with potential container ages, structural stability (and thus the ability to move them) including the likely requirement for dilapidation assessments for every container.

Further, no practicable option was identified that would effectively span the disposals in a manner that would spread or reduce the load on the stacks. As the load cannot be avoided this means potential deformations will have to be addressed ahead of emplacement of the final cap.

Iterations of optimisation and analysis involving a full range of alternative options and evidence [66, 67] converged on the following position.

- Higher stacking of containers above the existing four-high and six-high stacks in Vault 8 cannot be achieved safely, and will no longer be pursued.
- To ensure a stable formation for placement of the final cap, it is important to first drive out container deformations. The optimisation work identified that this should be

implemented via a surcharge approach (indeed, no practicable alternative was identified). This includes "pre-loading" of the stacks, using material sufficient to replicate relevant closure loads. Surcharge can be achieved through locally raised areas of the profile fill, using a push-and-place approach working progressively across the vault, with associated observations and monitoring.

- In addition to maximising confidence in cap construction, surcharge will have the additional benefit of contributing to further enhancing confidence in long-term cap performance, by driving out voidage that could otherwise lead to settlements at a later stage.

The surcharging process will necessarily involve some degree of container damage. This will include damage to the upper container lids, which will not be of sufficient strength to resist closure loads. Some damage to other parts of the container structure (e.g., welds) is also anticipated as container corner posts and side walls buckle. However the damage will be limited as the gaps between stacks of containers will be filled with a permeable gravel-like infill, which provide lateral restraint and will help to limit associated stack movements and thus overall levels of damage.

In the ESC, the containers are recognised as forming part of the multi-barrier system. The contribution to the multi-barrier concept will be reduced, but not entirely removed, as a result of these deformations; while the containers will contribute less to containment, they will still act to reduce the release of contaminants. However, in our safety assessments for the groundwater pathway we do not take quantitative credit for the containment provided by the containers that will be surcharged [14]. Whilst their contribution to containment remains of value from the perspective of overall safety arguments, damage to containers will have no effect on assessed impacts from wastes in Vault 8.

5.3.3.3 Existing and Future Waste Categories in Vault 9 and the Future Vaults, Including the Modular Approach

The implications of the changed understanding of container performance for LLW led to different categories of LLW being considered in ongoing optimisation. In addition, the potential for ILW disposals implies a further set of categories need to be addressed. These are noted below, with optimised approaches to addressing these categories then being set out in Subsection 5.4.

- **Existing and committed LLW.** This includes disposals that have already been received at the LLWR, or disposals which are already committed to the existing container approach, given that a new container has not yet been designed. Optimisation studies for Vault 9 considered how these disposals could be managed, given the updated understanding of container performance arising from the Vault 8 studies.

- **Future LLW.** Relevant to Vault 9 and future vaults. This category recognises the opportunity to change the disposal model for future wastes, optimised to enhance containment and operational safety.
- **ILW that can be managed as LLW**. Should ILW disposals be pursued at the site, some categories of ILW suitable for near-surface disposal can be managed as if LLW as they do not require additional arrangements.
- **ILW that cannot be managed as LLW**. Some ILW disposals may require additional measures for vault disposal, for example to manage operational doses that may other arise to workers as a result of enhanced dose-rate components of the waste inventory.

The use of different optimised designs for these categories of wastes for Vault 9 and the future vaults leads to a modular approach to the vaults.

5.4 Optimisation Status of Closure Engineering and Vault Components

This subsection presents the status of the outcomes of pre- and post-closure engineering optimisation processes to date. The aims are to:

- summarise the key outcomes of options assessment processes;
- describe the main logic and rationale underpinning those outcomes;
- indicate any remaining information gaps and areas of uncertainty;
- identify key considerations for the ongoing design process; and
- provide references to the underpinning individual BAT reports that provide full details in each case.

In each case, only a brief overview of the design is provided, sufficient to underpin and illustrate optimisation arguments. The design is described in full in reference [5] and underpinning references.

5.4.1 Final Cap

5.4.1.1 Overview

The final cap for the LLWR has been subject to a long history of design development and optimisation. It is fundamental to the LLWR's closure design and provides a range of key safety functions. These include functions relating to:

- isolation of the wastes from the surface environment, including reducing direct irradiation doses to anyone who may work on or occupy the cap surface in the future;
- reducing the likelihood of, and impacts associated with, inadvertent intrusion into the wastes as a result of future human activities;

- minimising infiltration of water to the wastes (through promoting evapotranspiration, encouraging drainage of precipitation, and the action of the low-permeability geomembrane and BES layers).

As noted in Subsection 5.2, the use of a multi-layer, single-dome cap is central to the optimised closure concept for the LLWR. The material here provides details of its further optimisation since the 2011 ESC.

The most recent major iteration of review of the optimisation and design status of the final cap was held as part of the Repository Development programme [66, 68] The starting point and reference option for the study was the existing final cap design as set out in the 2011 ESC [5] and the subsequent 2015 Planning Application documentation [64]. The latter included an update to the geometry of the cap, including integrating the 1 m of profile fill added to the design since the 2011 ESC (see Subsection 5.4.2). Further, minor updates to the geometry were applied during the Repository Development and capping programme work to accommodate changes to landform in order to maximise the profile fill thickness above the six-high stacks in Vault 8, and the four-high stacks at the northern edge, as otherwise the profile fill here could have been below the target minimum for relevant containers. The final geometry is set out in references [77] and [78].

5.4.1.2 Main Optimisation Outcomes

The assessment for the Repository Development programme [66, 68] delivered a cap design with only relatively minor updates compared with the existing baseline option. The main layer features and materials were retained, and no strong reasons for significantly different alternative cap geometries found.[57]

The work reviewed the potential for removing or combining layers to simplify construction. Only one opportunity for simplification was identified – combining the gravel filter layer and the biointrusion layers into one. It was considered that a combined layer would be equally capable of providing the required filter, biointrusion and drainage properties that the individual layers would provide, whilst simplifying construction.

Additional changes included adding further man-made elements (e.g. geotextiles) to enhance confidence in construction, and the use of man-made drainage layers to assist natural layers in drainage of water (above the low-permeability layers) and of gas (below the low-permeability layers). These layers were also primarily added to enhance constructability, while including the use of man-made functional layers to complement the natural layers to maximise overall confidence in performance, for as long as the layers last.

Otherwise, the BAT review process largely confirmed previous design choices, but with an improved underpinning evidence set providing further confidence in the projected future performance of the system. This includes evidence providing enhanced confidence in the

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[57] Note however that details of the cap geometry, primarily relating to edge details, required gradients, and local constraints, continued to be addressed during ongoing design within the capping programme.

longevity of performance of the low-permeability layers, including the strain resilience of the geomembrane [12]. The resulting cap layer design is shown in Figure 5.4.

As the cap will be constructed via a programme of strip capping, the design includes a progressive sealing approach that will stabilise the 'leading edge' of each strip of the cap, provide protection of the vault wastes from environmental effects for the periods in between cap strips, and key into the upgraded STIM cap (Section 6). Each strip-cap seal will also include gas vents to manage bulk gases during the PoA (see reference [5] for further details). The seal will include a geomembrane, laid at suitable angles, protected above and below with appropriate engineering materials [5], and with drainage also provided. The cap seal is not part of the engineering that will be present at closure, by definition, but is an important part of the optimised system to provide interim protection of wastes between strips of the cap.

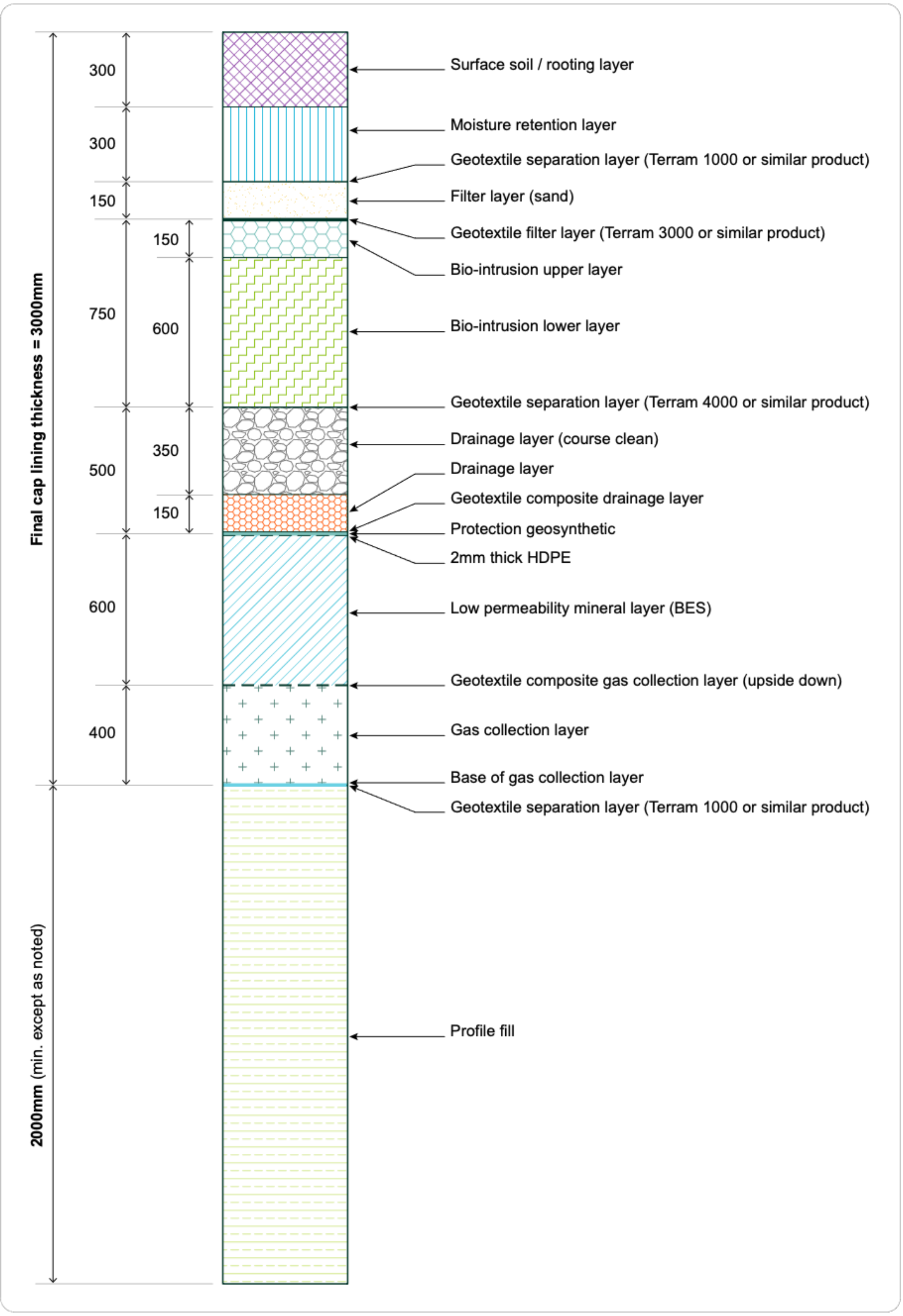

Figure 5.4: **Optimised final cap layer design (after reference [68]). Note that the profile fill is discussed separately in Subsection 5.4.2.**

Further optimisation: choices for the Final Cap geomembrane

Assessment of the performance of the optimised engineering design has been undertaken through the EPA [12]. The EPA has been developed alongside, and integrated with, the Repository Development and capping programmes over several years (see also Subsection 3.8). As part of this, the understanding of the aspects of the geomembrane evolution that contribute to confidence in long-term performance has progressively developed.

This led to a targeted optimisation study, which was undertaken to ensure that the understanding gained from the EPA was fed into the ongoing design and selection processes for the geomembrane. This included reviewing national and international approaches and the supporting literature to draw together an enhanced specification for the geomembrane consistent with maximising confidence in longevity[58]. It also included an outline testing programme both to make final choices between geomembranes that meet the enhanced specification and to subsequently provide further data and support choices for subsequent strips of the cap. The BAT study also provided input into the process for the ongoing optimisation of long-term monitoring including engineering evolution [9].

Further optimisation: Final Cap gas vent

The position of the final cap gas vent for the 2026 ESC is the same as for the 2011 ESC; in the reference case we assume a gas vent that is open during the operational phase and closed at the end of the PoA, but the potential for the vent to remain open is also assessed.[59] The final decision will only be made at the end of the PoA on the basis of time-series data of gas evolution of the wastes into successive strips of the final cap, and associated modelling and analysis work.

In past assessments, the underlying assumption was that it was most likely the gas vent could be safely closed without a risk of bulk gas build up and pressurisation that could subsequently damage the cap. However, more recent assessments [14, 6] have indicated that uncertainties in gas evolution suggest an increased probability that gas venting might indeed be required post-closure, given remaining uncertainties. That is, even if it is currently considered most likely that the cap would not require venting, the uncertainties may be sufficient that open venting will in any case be maintained post-closure.

The current gas vent design assumes a location around the apex of the cap, and is associated with strips of the cap that are unlikely to be constructed for several decades. Nevertheless, we have commenced work to consider optimisation of the venting approach, including consideration of options focussed on the PoA solely, and a related options set options should an open vent system be required after the PoA. This is largely to explore whether different approaches could reduce calculated impacts from the gas pathway without

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[58] The pre-existing specification was developed prior to the relevant assessments within the EPA process.

[59] Therefore, radiological capacities are calculated [17] for the case where the vent remains open, on the basis that remains a plausible final outcome.

increasing constructability or wider cap performance risks. The work will inform approaches and options as a near-term response to the latest understanding within the context of the overall longer-term timeframe for implementation. Arguments on safety in the 2026 ESC are not contingent on the outcomes of this work and so it is scheduled as a continuing ESC activity consistent with the principles of ongoing optimisation.

Examples of options identified to date for potential further consideration include:

- variations on the current gas vent design and location, including an alternative gas vent location along the southern boundary of the repository, or the use of both vent locations, to spread releases and to provide redundancy;
- increasing the pathlength for radon transport and thus decay via the use of strategically placed low-permeability mineral or geomembrane materials (or both) e.g. between areas of higher trench Ra-226 disposals and the finalised gas vent locations;
- enhancing the distribution of gases through multiple release locations, e.g. using small, engineered release points in the low-permeability layers (including 'flaps' in the geomembrane);
- engineering gas releases through other engineered features, in particular discharge over the cut-off wall, through the cut-off wall and cap tie-in, and into the geosphere;
- appropriate combinations of the above.

For the 2026 ESC, the aim is to demonstrate that options are available suitable to inform an ongoing optimisation programme for potential designs, taking account of the enhanced understanding of gas evolution and assessments reported in the ESC.

5.4.1.3 Final Cap Optimisation Summary

Box 5.2: Summary: Optimisation of the Final Cap since the 2011 ESC

This box provides key optimisation arguments for the optimisation of the final cap of the 2011 ESC.

- A structured, stakeholder informed optimisation (that is, BAT) process, in line with regulatory and good practice guidance, was employed to review and develop the optimisation outcomes for the final cap. The process aligned with that set out in Section 3.[60]
- A comprehensive review of cap geometry and layer options confirmed the previously defined basic design as representing an optimised approach. Specifically the use of a composite BES and 2 mm high-density polyethylene

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[60] This also applies for all the summary boxes for other components in this and following subsections. It is not included in those summary boxes to minimise repetition.

(HDPE) geomembrane liner was confirmed as consistent with maximising confidence in long-term performance. The BES in particular will offer self-healing properties and there is confidence it will provide very long-term performance even with cation exchange. The geomembrane will further lower the overall permeability of the composite while it lasts. The layers will work in combination to enhance the performance of one another; for example, the BES will act to seal defects within the geomembrane, and the geomembrane will protect the BES from damage and reduce the rate of its degradation by reducing infiltration into the BES layer.

- Layers above and below the composite will protect the low-permeability layers by managing gases and settlements, and are consistent with good practice for capping systems. Minor modifications were made to the layering structure to maximise confidence in constructability and as-constructed performance, including combining drainage and bio-intrusion layers, and adding in extra man-made layers.
- The outcomes of the EPA have been used to ensure that the approach to selection of the final cap geomembrane will be consistent with maximising confidence in longer-term performance.

5.4.2 Profile Fill

5.4.2.1 Overview

The profile fill provides a stable formation for the final cap, and provides strain distribution functions into the longer term, minimising the risk of settlements adversely affecting the cap. The profile will also assist in gas management by transporting gas from the wastes to the gas collection layers, and works with the cap to provide isolation of the wastes from humans and the environment. Its history of design and optimisation therefore largely mirrors that for the cap.

5.4.2.2 Main Optimisation Outcomes

Iterations of review and optimisation including the profile fill since the 2011 ESC (see Table) have led to the following outcomes [67, 69]. The profile fill shall now target a minimum thickness of 2 m (previously the minimum thickness was 1 m) over the wastes, such that the minimum total distance to the cap surface from the wastes will be increased to 5 m. In the absence of higher stacking, profile fill thicknesses away from the edges of the facility will be further enhanced. The rationale for this is set out in Subsection 5.3.3. As well as enhancing confidence in cap resilience, the extra 1 m is also recognised as beneficial for human intrusion assessments [14].

- The profile fill over the vaults will specifically be low-fines, inert, granular material. This is to:
  - help manage settlements by distributing strains that may otherwise occur in the cap, contributing to confidence in cap resilience;

    - minimise the potential for clogging of drainage features within and under the vaults; and
    - provide continuity with the granular material in the gas collection layer, to assist in bulk gas management.
- For the trenches, there is flexibility to use a wider range of materials, including site-won cohesive materials. This recognises that settlements present less of a potential challenge across the trenches, and the use of materials that might include fines above the wastes does not present an issue for trench drainage. The use of cohesive materials over the trenches, including the extra 1 m, is also of benefit in enhancing the travel time for radon releases from the trenches, and associated decay [14].
- The profile fill will be used as part of the surcharge approach, which will be used both for the trenches in general (Section 7) and for existing and committed wastes in the vaults (Subsections 5.4.4 to 5.4.6).

Box 5.3: Summary: Further Optimisation of the Profile Fill

This box provides key optimisation arguments for the further optimisation of the profile fill.

- Optimisation studies, aligned with cap resilience assessments, have demonstrated that an extra 1 m of profile fill is a proportionate approach to the observations of enhanced potential voidage, and therefore potential cap settlements if unmitigated, in Vault 8. The extra 1 m is also of benefit to the human intrusion and gas pathway assessments.
- Inert, low-fines, granular fill will be used above the vaults. This choice is consistent with maximising cap resilience and minimising risks of clogging of vault drainage features (as compared to, for example, cohesive materials).
- A wider range of materials, including site-won cohesive materials, will be used for the trenches, providing the required confidence in cap resilience whilst reducing the requirements for import of material.
- Progressive approaches to surcharge and profile fill will ensure surcharging objectives can be achieved without increasing total fill volumes beyond those required for profile fill placement alone.

5.4.3 Cut-off Wall

5.4.3.1 Overview

The main roles of the cut-off wall are:

- to work with the passive drainage arrangements to direct any leachate generated to deeper systems as the final cap begins to degrade; and

- to minimise lateral flows into the trenches, the vaults and sub-vault drainage.

To deliver these roles, the main requirement for the cut-off wall is that it should provide a permeability contrast with the surrounding geology.

The existing cut-off wall, which runs alongside the north and east sides of the trenches (Subsection 4.2), will be extended to encircle the entire facility 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 will be constructed to 2 m below the bottom of the vaults, to ensure it extends below the sub-vault drainage blanket. It will be a cement-bentonite slurry wall of similar mix to the existing cut-off wall. The cut-off wall will be integrated with the low-permeability elements of the final cap and will be constructed consistent with the strip capping schedule; the first section will therefore be constructed with the first strip of the cap, to be completed by 2037. Due to the edge gradients of the cap and the position of the low-permeability layers, the cut-off wall will be placed several metres from the cap perimeter, with the exact distance from the perimeter varying depending upon local gradients and land form.

5.4.3.2 Main Optimisation Outcomes

Options for the cut-off-wall were most recently reviewed for the Repository Development programme [71]. The associated optimisation process did not identify any need to change from the position identified in the 2011 ESC. Cut-off walls are used in many contexts and the LLWR cut-off wall will employ a commonly used, simple construction approach (a trench filled with a cement-bentonite slurry). This is also consistent with the approach to the existing cut-off wall, which was successfully constructed and achieved an appropriate permeability, confirmed by post-implementation sampling and testing. Its good condition has been further confirmed by inspections and monitoring since then [71]. The post-installation testing of the existing wall also provides a strong basis for the start-point of the permeability parameterisation of both existing and future sections of the wall.[61]

For the 2011 ESC, hydrogeological modelling (see reference [31] and supporting references) confirmed engineering judgements that 2 m below the vault bases is an optimal depth for the future cut-off wall. This 2 m depth is sufficient to protect the vaults and the drainage blankets from inflows (including those arising from cap runoff), and to direct any leachate to the underlying geology and away from surface systems. Therefore, deeper installations were considered to offer negligible additional benefit.

A 1 m thickness for the cut-off wall has been identified, consistent with the range assumed in the 2011 ESC[62]. As well as being the same thickness as the existing cut-off wall, that has been shown to perform well, it recognises that thinner cut-off walls could be at a greater risk

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[61] Described further in the '*Engineering Performance Assessment'* report [12].

[62] In the 2011 ESC, a range of 600 to 1500 mm was identified for the cut-off wall, with the intention that the width would be the subject to further optimisation. In the 2011 ESC assessment models, a default assumption of 800 mm was used [76].

of early wash-out and cation exchange, whereas thicker cut-off walls will not offer substantial additional confidence in the provision of a long-term permeability contrast. Thicker walls can also be more difficult to construct.

The optimised design will function for a prolonged period [12]. This confidence arises from the following arguments.

- 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 can be expected to be stable and will be confined by the geology on either side and unlikely to move or evolve significantly.
- Evolution of the cut-off wall will mainly be via cation exchange of the bentonite component of the mix, and the leaching of the cement and wash-out of bentonite and other materials with time. This may occur primarily in particular once the cap begins to degrade and there is potential for higher head gradients across the wall. However, such effects will be limited and even a fully cation-exchanged wall will still offer the required permeability contrast.

Given these arguments, a slurry wall will provide more than sufficient confidence in the required performance in the long term. This also reinforces the previous 2011 ESC optimisation decision not to include a vertical geomembrane in the design. This would be a redundant feature in that it would not add significantly to confidence in performance; indeed, it could introduce constructability challenges through complicating an otherwise comparatively simple slurry placement approach, which could enhance construction and therefore performance risks. Therefore, the current design does not include a geomembrane.

Box 5.4: Summary: Further Optimisation of the Cut-off Wall

This box provides key optimisation arguments for the further optimisation of the cut-off wall.

- Further optimisation studies have confirmed the approach to the cut-off wall identified in the concept work for the 2011 ESC, i.e. completing a cement-bentonite slurry wall to 2 m below the depth of the vault bases. This will provide the functions required without nugatory additional work and spend.
- The previous optimisation work identified a range of potential thicknesses of the cut-off wall; this has now been specified to be a thickness of 1 m, as this is consistent with the existing cut-off wall, and represents an appropriate balance between long-term performance (noting e.g. rates of washout and cation exchange) and confidence in construction.

5.4.4 Vault 8

5.4.4.1 Overview

A summary of the design of Vault 8 is provided in Subsection 4.3. A more comprehensive overview is presented in reference [5].

5.4.4.2 Main Optimisation Outcomes

The Repository Development programme (see reference [67] for details) built on previous options assessments (as described in Table 5.1). The main outcomes of these iterative studies are summarised in the text that follows. Key aspects of the rationale reflect the discussions in Subsections 5.3.3.1 and 5.3.3.2 which provide details.

- Consistent with optimisation decisions made in advance of the 2011 ESC long-term passive leachate management will be ensured by draining waters over-topping the 1 m level above the vault bases, by back-engineering connections that allow access to the drainage blankets underlying future vaults (Subsection 5.4.6).
- Void fill will be used to enhance stack stability, reduce voidage, and to provide preferential drainage pathways around the stacks, consistent with the aim of minimising water contact with wastes for as long as practicable, and ensuring further redundancy in drainage route provision. The BAT study for Repository Development programme [67, 69] confirmed the 2011 ESC position that inert, low-fined, granular material shall be used.
- Higher stacking of wastes above the existing containers in Vault 8 has been shown not to be practicable (see Subsection 5.3.3 for details). The surcharge approach will be used to express deformations in the containers in advance of cap placement.
- At the time of writing disposals to the 'remaining disposal volume' within Vault 8 (the small area of the base that was previously kept free from disposals to the north of the vaults, and the associated volume below the maximum height of disposals under the cap, plus the access ramp that is present in this area) are near completion. These disposals include a combination of HHISOs (already in place) and VLLW arising demolition of the empty Plutonium Contaminated Material (PCM) magazines for which placement will be completed prior to capping, taking forward the outcomes of [79].

Vault 8 will be closed, along with the adjacent strip of the trenches, via the emplacement of the final cap and cap seal, over the next few years.

Box 5.5: Summary: Further Optimisation of Vault 8

This box provides key optimisation arguments for the further optimisation of Vault 8 and its closure.

- Observations of enhanced voidage compared to the understanding at the time of the 2011 ESC, and the changed understanding of container deformations under load, meant that it was decided that higher stacking of wastes above the existing containers in Vault 8 will not be undertaken for operational safety reasons, and that surcharge should be employed. The latter approach was selected as it will ensure a stable formation of placement of the cap, at the expense of accepting some (limited) damage to the containment function of the stacks.

- Reviews have confirmed that the use of free-draining, inert, low-fines, granular void fill remains the preferred approach to provide preferential flow paths around the stacks. This approach will maximise the overall drainage capacity within the vault, minimise the risk of clogging, and will contribute to cap stability by minimising voids outside the stacks.

5.4.5 Vault 9

5.4.5.1 Overview

A summary of the design of Vault 9 is provided in Subsection 4.4. A more comprehensive overview is presented in reference [5].

5.4.5.2 Main Optimisation Outcomes

Key aspects of the optimisation status of Vault 9 are summarised in what follows. In each case reference [75] provides further details. It reports the process and outcomes for the optimisation programme for the vaults, involving an integrated project team and regulatory engagement, consistent with the process set out in Section 3.

Leachate Management Post-closure

Consistent with optimisation decisions made in advance of the 2011 ESC, long-term passive leachate management will be via routing to the drainage blankets of future vaults, using back-fitted slots at the 1 m level into relevant vault walls.

Existing and Committed LLW

For existing and committed LLW, it was recognised that the understanding of the load-bearing capacity of existing container categories identified for Vault 8 disposals (Subsection 5.3.3.2) also apply to equivalent ('existing and committed') wastes to be disposed in Vault 9 and Vault 9a. A range of options were considered for these wastes, focussing on ensuring that container deformations would not adversely affect the cap during construction. In addition to surcharge, options ranged from container overpacks to concrete roof-and-corridor systems to house the wastes. These options were all identified as approaches that would be able to support the cap without damaging the containers. Other options, such as re-packaging of wastes, were ruled out as they did not offer substantial benefits over these options but were associated with potential ALARP challenges.

Through the detailed assessment process, however, it was identified that overpacks and other forms of back-fitting container modifications would be very expensive, reduce the volumetric efficiency of vault disposals, and different versions of this approach would all involve, to variable extents, backfitting of structures to the existing containers. This would lead to close interactions of workers with the containers and wastes within, potentially including drilling into containers for most of the options, with associated safety and dose management concerns. These options were therefore not favoured in the assessment.

This category of dose management concerns would not apply to options involving the construction of roof-and-corridor (‘external structure’) systems.[63] Here, reinforced concrete roof-and-corridor structures would be created, within which containers would be placed, to support the cap and avoid loads on the containers. However, compared to the surcharge option, these approaches would:

- be much more expensive;
- reduce the volumetric efficiency of the vault;
- involve large volumes of materials, and the considerable energy use associated with the large amounts of concrete required; and would
- take several years to complete.

These activities would delay covering the existing and committed wastes with the final cap, and in turn the time for achieving the maximum protection of the wastes. This is contrary to the desire, expressed through successive options studies (e.g. references [73, 74]) to cap wastes as soon as practicable after receipt, recognising that a large proportion of the existing containers have already been in the open vault for a decade or more.

In the assessment, these significant detriments were balanced against the detriments associated with the surcharge approach, and accepting some damage to the containers, with the associated (limited) impact on the multi-barrier concept.[64]

Overall, the judgment of participants involved in the relevant workshops was that the detriments associated with the roof-and-corridors disposal approach were sufficient to clearly outweigh the detriments associated with surcharge, and surcharge was therefore selected as the proportionate approach.

On that basis, further optimisation of the approach identified the following preferred process. Relevant disposals will be stacked at the northern edge of Vaults 9 and 9a and will be closed via an extension of the cap seal over the relevant wastes as soon as practicable after Vault 8 closure. This will provide closure-levels of protection of the wastes as soon as is currently practicable. While other options were considered in the process for protection of this category of wastes (e.g. warehousing, etc; see also the discussions for future LLW wastes

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[63] These approaches were similar to the options subsequently considered for ILW that cannot be managed as LLW, described in Subsection 5.4.6.

[64] As noted in Subsection 3.7.4, this would not affect calculated impacts as the role of the container as a barrier is, cautiously, not represented in our assessment calculations.

below), this cap seal approach was considered to present both the best level of protection and the quickest plausible route to achieving that level of protection, of the options considered.

Surcharge will not occur immediately after emplacement of the cap seal over these wastes, but will be undertaken in a manner consistent with the implementation of the next strip of the cap over Vault 9. This is because surcharge is not needed until the final cap itself is about to be emplaced. Also, for operational safety and practical considerations associated with materials slope management arrangements, the required height of surcharge material could not be built up while disposals are still ongoing to the rest of the vault. The cap seal will be tied-in to appropriate retaining walls in Vaults 9 and 9a; Figure 5.5 provides an illustrative concept design.

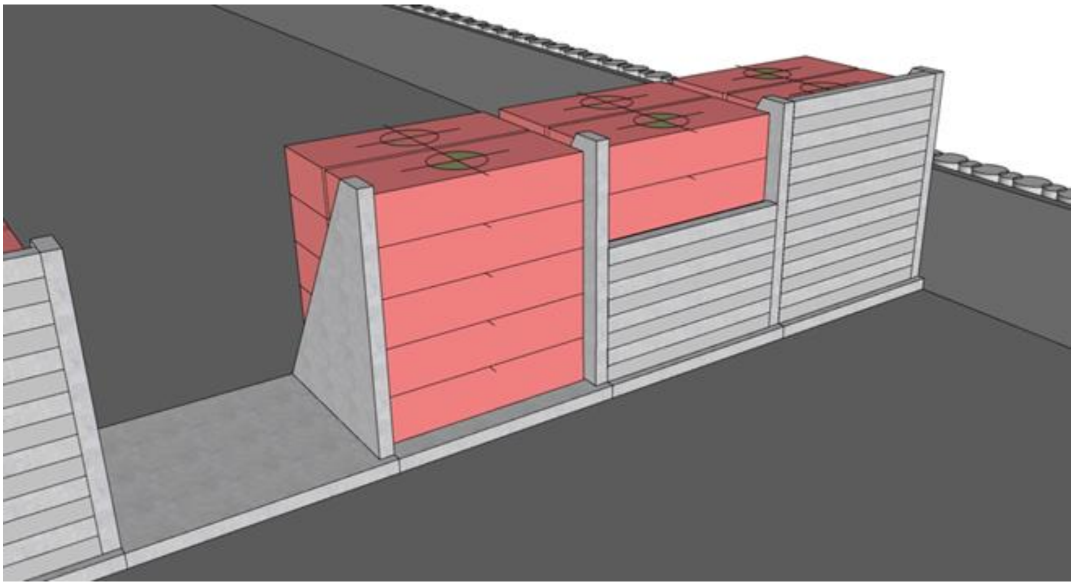

Figure 5.5: Illustration of retaining wall design to support an in-vault cap seal

Future LLW

For future LLW, for which there is the potential to change the container type for disposal, the main choice was between the use of an enhanced container approach with strength sufficient to support the cap, and the continued use of the existing containers, with surcharge. The disproportionality arguments for overpacks and roof-and-corridor approaches apply to future LLW as for existing and committed wastes.

A range of different categories of container options were identified, but it was noted that there is confidence that modifications to the existing container type to strengthen the load-bearing elements can be made, without significantly enhancing the cost of the containers. This was demonstrated in in the options process (see reference [75]) by the identification of an outline design for a modified HHISO, based on thickened corner elements. Alternative methods for strengthening HHISOs have since also been identified through subsequent work. Together, the options identified provide confidence in the choice of strengthened HHISOs as an assumption for the ESC.

We are continuing optimisation and design work for strengthened containers. We recognise that the containers and the vault bases operate as an integrated system. Therefore as well as considering interactions with the existing Vault 9 base, the final choice of design for strengthened HHISOs will be integrated with detailed design work for the future vault bases (Subsection 5.4.6).

Given that infrastructure and plant both at the LLWR and at consignor sites are designed around the current containers, this would clearly present a low-impact (and low-cost) solution across the industry. Other container approaches were considered but none offered notable advantages and so the strengthened HHISO approach was favoured as it delivers protection of the multi-barrier concept compared to surcharge, without disproportionate cost or wider industry impacts.

A drawback identified for the HHISO approach is the recognition of the weakness of the non-load bearing lids. The strengthening of the load-bearing elements alone would not address the weakness of the lid. Without being addressed this could lead to damage to the containment provided by the top-level container in each stack, when profile fill and other closure loads are applied to the lids, which would not withstand such loads.

It was considered consistent with the preference to maintain the multi-barrier concept for this category of wastes, therefore, to address this issue. The process was helped here by work that had previously been developed for the Repository Development programme before the decision not to undertake higher stacking. In that programme [66], work had been undertaken to look at options for protecting the containers and their lids from damage during the closure process, including the potential for plant trafficking over the container stacks whilst carrying containers, prior to their placement at Vault 8 higher stacking locations. This is because, to higher-stack in Vault 8, given Vault 8 is already full of containers, it would have been necessary to safely travel over the existing containers to emplace containers above them.

This is relevant as the dynamic loads calculated for these higher stacking implementation processes in Vault 8 were identified as presenting a very similar challenge in terms of required container (and lid) strengths to the static loads associated with closure engineering above the stacks. This means that the options considered previously in the Vault 8 programme also provided appropriate options for consideration of the protection of the upper container lids for future wastes in Vault 9. Initial outline designs had been produced for favoured options, and fabricating organisations approached to confirm they could be constructed in sufficient numbers on relevant timeframes, together with an estimate of costs.

From the analysis, it is clear that to protect the lids, a reinforced concrete (or metal, but a fully metal approach would be expensive and heavy) structure is required that can be emplaced on top of the upper stack containers. This would need to span across the container to protect the lids from load, and to direct closure loads down the load-bearing elements of the underlying stacks by taking advantage of the existing corner twist-lock mechanisms in the HHISO design. On that basis the reinforced concrete unit would have a metal frame that would include the twist-lock connection. The resulting outline option designs have been termed 'container protection units' or CPUs and are illustrated in Figure 5.6. They are estimated to be between 60 and 70 cm thick[65] (sufficient to support closure loads) and can be considered to be very similar to an enhanced HHISO base structure.

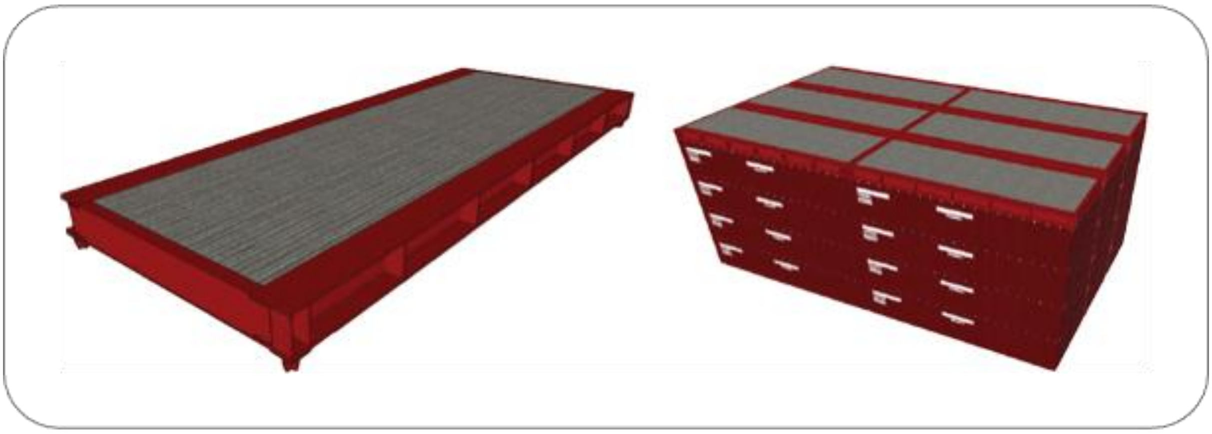

Figure 5.6: Illustration of the CPU approach for Future LLW (see [75] and supporting references for details)

While the CPUs add to the cost of each overall container stack, participants in the optimisation processes considered this not to be disproportionate to the benefits gained.

Other options were considered, but those that would provide sufficient protection against closure loads were not identified as presenting notable advantages over the CPU approach, and most had disadvantages. For example, strengthening the lids of every container would be disproportionate as only the upper containers require enhanced protection, and so the additional materials use and cost for the containers in other positions in each stack would be nugatory. Introducing a container manufacturing approach allowing for a subset of container lids to be strengthened may be more plausible, although this could add significant complexity and cost to the manufacturing process as more than one container design would be necessary. In addition, the upper container lids would require the same strength, thickness and overall construction as the CPUs already identified. Process participants considered overall therefore that separate CPU construction was likely to present a more flexible and less costly approach.[66]

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[65] 70 cm has been assumed in the ESC assessment calculations.

[66] These two approaches are very similar and can be considered to be variants of one another. Therefore, if subsequent detailed design and optimisation work identities arguments for use of the modified container lid approach for upper stack containers, that would be consistent with this broad outcome.

The strengthened container and CPU approach will also allow containers to be stacked above the current five-high limit, with the proviso that the stack heights (including the CPUs) do not impinge on the 2 m minimum thickness for the profile fill and that impacts on the vault base can be managed. Higher stacking will reduce the requirement for profile fill and enhance the volumetric efficiency of the disposal approach.

The options assessment process and relevant analyses to date provide confidence this option can be implemented and provide an appropriate basis for the ESC. An ongoing programme of detailed optimisation work however will be required to consider interactions with the vault base, stacking approaches, and container and CPU designs before the approach is finalised. It is anticipated that finite element modelling and physical container testing[67] are likely to be required as part of this process. This optimisation will consider the base of the vaults alongside the container stacks as an integrated system. Approaches include ensuring the 'open face' of container stacks during emplacement is limited in height, with steps in stack heights from the open face to the maximum height, which will help minimise rotational forces on the base (Figure 5.7). Such options could be considered alongside simple engineering measures (for example, mats, modified bases, reinforced elements under containers). Appropriate combinations will be considered within the option set to make sure container stacks do not challenge the vault base structures either in terms of stack stability and operational safety concerns, or the ability of the bases to manage waters.

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[67] Physical container tests are likely to be undertaken for the existing HHISO TC01 designs, to evaluate the potential specifically for operational higher-stacking for seven-high containers, for relevant disposals within the existing and committed LLW area that will be surcharged.

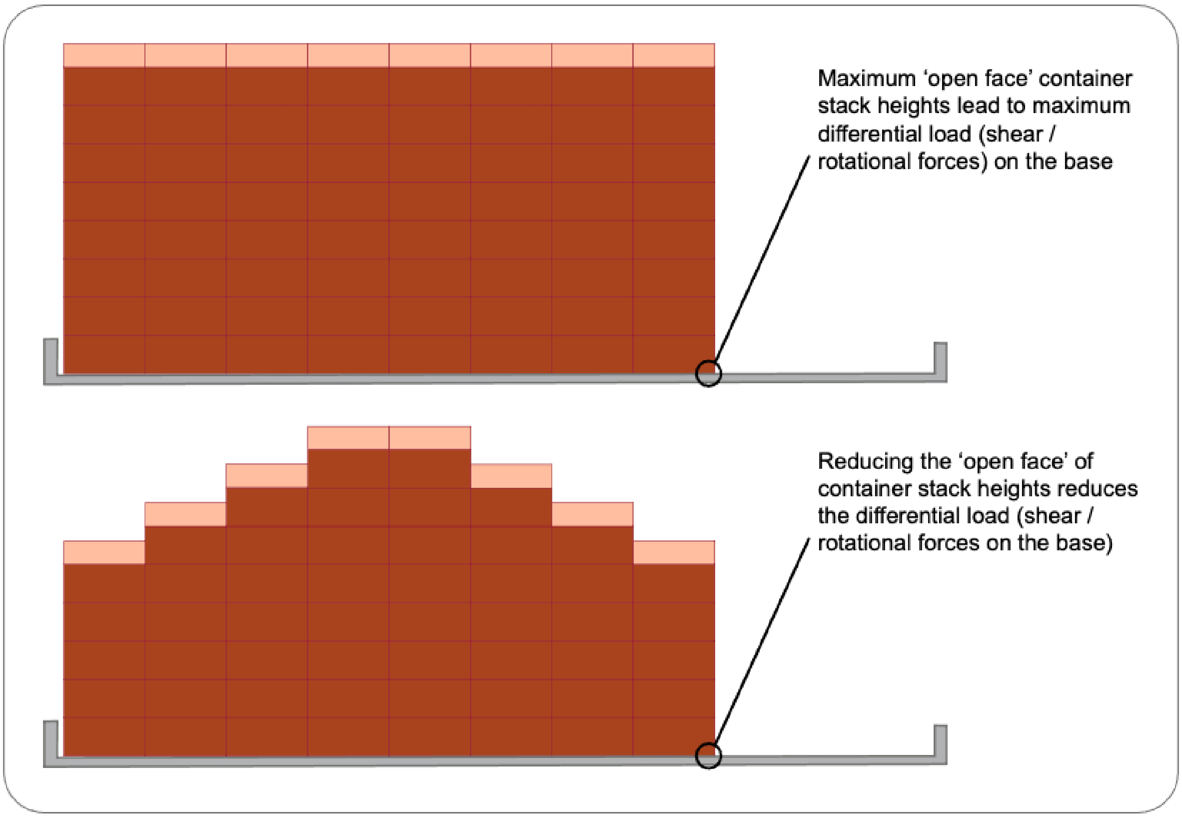

Figure 5.7: Illustration of the consideration of ‘open face’ arrangements as part of design and stacking optimisation for strengthened containers.[68]

ILW that can be managed as LLW

For ILW that can be managed as LLW, [69] optimisation work has identified that while such ILW can be stacked alongside future LLW in the open vault, for the majority of disposals it is likely that a new container will be utilised. This is due to transport requirements for ILW linked to specific activity limits and dose-rate requirements, leading to uncertainty as to whether wastes could be transported in an IP2-rated container. For this reason, the optimisation work has, potentially cautiously, assumed that it will be necessary to use a container which would, if required, fit inside a Type B transport container. We have therefore assumed the use of a smaller container which would fit inside a Standard Waste Transport Container (SWTC), as

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[68] CPUs also shown. The figure is for illustrative purposes only. The figure is not to scale. As well as stack arrangements and different options for container strengthening and stacking, options processes will also consider the potential for back-fitting of engineered elements under stacks for Vault 9, and equivalent options for adjustments to the base design for future vaults (whilst retaining the overall future vault base concept).

[69] ILW that cannot be managed as LLW is currently not being considered for disposal within Vault 9, for reasons detailed in Subsection 5.4.6.

illustrated in Figure 5.8. This is a proportionate response that avoids the need to design new transport containers.

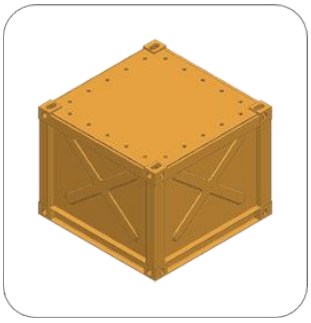

Figure 5.8: Mild steel strong SWTC compatible container (see reference [75])

The concept design assumes that in other ways the container will be similar to a HHISO, i.e. it will be made of mild steel with the strength provided by the container framework and in particular corner elements. This has been preferred over other options to date as mild steel containers are consistent with the current concept, and therefore the understanding of the evolution of the system. In addition, they are transportable with 'standard' plant (not being as heavy as other containers, e.g. concrete containers), and are less expensive than other containers (such as stainless steel) whilst still providing the required strength and containment. Using mild steel is also consistent with the preference not to emplace durable containers in bulk in the vaults (see reference [17]). The mild steel containers would deliver the required functions without excessive cost.

Given the similarity with existing containers, the design also assumes that the lids of the new containers, as for the HHISOs, would not withstand closure loads. We therefore also assume CPUs or equivalents would be placed on ILW stacks placed in the open vault. The arguments for CPUs for ILW mild steel containers are similar to those for HHISOs.

As for the position for the potential strengthened containers for future LLW, a programme of ongoing optimisation and design will be required for containers for any potential ILW disposals, again considering the base and container stacks as an integrated system.

In addition, we are retaining the option of implementing, most likely on a much smaller scale and opportunistic basis, occasional disposals of ILW in other containers e.g. HHISOs, should transport requirements be satisfied for particular ILW inventories.

Box 5.6: Summary: Further Optimisation of Vault 9

This box provides key optimisation arguments for Vault 9 and its closure.

- Observations of enhanced voidage in older disposals compared to the understanding at the time of the 2011 ESC, and the changed understanding of container deformations under load, mean that higher stacking of wastes above existing and committed containers in Vault 9 (and Vault 9a) will not be undertaken due to operational safety reasons. In addition, surcharge will be employed, as for Vault 8. This will ensure a stable formation for placement of the cap whilst accepting some minor damage to the containers. The existing and committed wastes will be covered by the final cap seal after Vault 8 closure, and disposals of relevant wastes in Vault 9, and construction of Vault 9a, are all completed. The early sealing ahead of cap construction is to ensure these older containers are provided with the level of protection associated with the cap as soon as can be practicably achieved.

- The majority of future LLW disposals will then be within containers of enhanced strength, to avoid the need for surcharge and to allow higher stacking. A design similar to the current HHISOs is anticipated. Other options do not offer significant benefits compared to mild steel HHISOs, but would either add cost or reduce disposal efficiency, in addition to requiring changes to infrastructure at the LLWR and at consignor sites. The use of CPUs to complement the HHISOs has also been identified as a proportionate response to the preference to protect upper container lids from damage upon closure.
- If taken forward, ILW disposals to the vault are also anticipated primarily to use mild steel containers, based on the arguments for LLW. These would be similar in principle to HHISOs but of a geometry consistent with the use of Type B transport containers if required to meet transport requirements. Compatibility with SWTCs has been assumed, as this is the simplest overall approach to achieve transport requirements. As the containers are similar in concept to HHISOs, they would also be paired with CPUs.
- For both future LLW and ILW there is flexibility to vary these outcomes within ongoing optimisation and design work, but the current position is considered to provide a robust basis for the 2026 ESC.

5.4.6 Future Vaults

5.4.6.1 Overview

Future vaults (Vaults 9a, Vault 10, and ongoing vaults as required);[70] will follow the same basic approach as for existing vaults. The levels of their bases will be stepped to follow the site topography. Consistent with the arguments set out in Subsection 5.2, the vault bases will be simplified compared to Vault 9, with a single composite geomembrane and BES layer

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[70] Inventory projections for the 2026 ESC [4][indicate that it is only necessary to create disposal capacity up to Vault 12 to accommodate all relevant projected disposals. However, designs to date have included vaults up to Vault 14. This approach has been continued in the current design, to provide flexibility with regards to inventory assumptions and national strategy. As the vaults are modular and this does not affect cap design for the first few tranches, this is considered useful in retaining flexibility.

providing the required water management functionality. This composite will be extended up to the 1 m level intended for outer vault walls.

Drainage features running the length of these walls will connect the vaults with the passive leachate management drainage blankets underneath each of the future vaults. The drains will be laterally extensive in recognition of the value of ensuring redundancy in drainage arrangements, to maximise confidence in their long-term performance given the potential for clogging.

5.4.6.2 Main Optimisation Outcomes

Key aspects of the optimisation status of the future vaults are summarised in what follows, including:

- approaches to future LLW disposals, and ILW that can be managed as LLW:
- ILW that cannot be managed as LLW;
- the role of Vault 9a and priorities for construction;
- requirements for container protection prior to capping, and the use of interim storage warehouses;
- the modular approach, aligned to the range of solutions identified for the different waste categories involved; and,
- confirmation of the approach to void fill and passive drainage in the future vaults.

Future LLW disposals, and ILW that can be managed as LLW

The future vaults will contain future LLW disposals, and ILW that can be managed as LLW, as for Vault 9. No existing and committed LLW will be disposed in Vault 10 onwards. The same optimisation outcomes and arguments (i.e. on containers and the use of CPUs) were identified as applying also for the future vaults for these waste categories, as for Vault 9. In optimising the detailed design of the vault slab, the interactions with the new container designs for future LLW and ILW that can be managed as LLW will be considered directly (rather than the 'back-fitting' options that may require to be considered for the equivalent work for Vault 9).

ILW that cannot be managed as LLW

For ILW that cannot be managed as LLW, additional arrangements will be necessary. This principally concerns ILW that is suitable for near-surface disposal, but for which shielding will be required. This includes protecting off-site receptors from doses, and in particular protecting workers, the group that would otherwise be the most likely to receive doses as a result of operations.

Optimisation work considered a range of options, from the use of LLW waste containers to shield ILW containers, through to the use of removable walls, amongst others. The work however favoured options which:

- maximise passive measures which do not rely unduly on human behaviours (e.g. to move a shielding wall repeatedly);
- are not susceptible to variations in receipt rates (such as the use of LLW containers to shield ILW, which relies upon suitable numbers of LLW containers always being present to shield ILW, which is challenging to guarantee given the variations in predicted receipt rates);
- minimise direct doses to workers overall; and also
- reduce scattered as well as well as direct doses.

Guidance was provided by our Nuclear Safety Case team that maximising robust passive controls for ILW is a priority, and that the use of LLW containers or removable walls for shielding was considered to fail this test. It was also noted that structures such as 'standard' warehouses are unlikely to provide the reduction in doses required.

On that basis, permanent structures that provide the required passive shielding were preferred. Simple shielding calculations suggested that a thickness of a few tens of centimetres of concrete would be sufficient to provide the required reduction in doses. Options development and assessment processes identified that the flexibility - and simplicity - of concrete-based options that could address both direct and scattered radiation impacts. This led to them being strongly preferred to other solutions. The inherent strength of such structures and their ability to resist closure loads also adds the flexibility of use, for example enabling containers to be placed within them without requiring CPUs.

The concept of reinforced concrete shielded modules was therefore preferred from the options work. The approach is illustrated in Figure 5.9. This is another area for which the overall approach is considered robust and optimised, but where design and optimisation work within that framework is ongoing.[71]

The basis of the approach is as follows.

- Modules shall consist of a series of reinforced concrete corridors whose walls are of sufficient thickness to provide both shielding and structural support.
- The corridors shall 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

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[71] The option is similar to the concrete corridor and roof option previously considered for LLW disposals (Subsection 5.4.5). For ILW which requires shielding, this is a necessary and proportionate response, in contrast to the arguments for LLW.

completion of disposals to a module. This is required both to provide vertical shielding and to resist closure loads.

- 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. This is to minimise doses to workers and other groups through direct radiation. The open end will be orientated so as not to face areas with active disposal operations, also to protect workers; the current working assumption is that the open ends will face the vault walls adjacent to the trenches.
- Drainage channels will be incised in corridor bases to ensure passive drainage. Arrangements will be made (small holes with coves) to allow drainage through the corridor sides also whilst ensuring shielding of shine is maintained.
- The corridors will be backfilled with standard vault drainage material, which will also be emplaced around the shielded module units, consistent with the overall vault concept driver for maximising redundancy in drainage capacity, as well as minimising voids for cap resilience reasons.
- Bunding and/or drain arrangements will be used to isolate waters and leachate associated with the shielded module units from those associated with adjoining vault disposal modules for other categories of wastes. This will include intercepting clean waters shed from the unit roofs during the operational period so they do not become leachate. This is consistent with the principle of minimising overall leachate volumes.
- Shielded module units will not be constructed in Vault 9 or Vault 9a but are assumed to be present in several of the future vaults. They will not be constructed in Vault 9 in part to separate construction approaches from operations, which is favourable from the perspective of conventional safety. In addition, the requirements of the bases of the units are different from that already in place in Vault 9 (they need to be thicker). Therefore, back-fitting to Vault 9 would be the same cost and effort as for creating a unit in the areas of the site currently allocated to future vaults, without the benefit of creating new disposal volumes. Therefore, it is logical to create the new modules as future vaults.
- The sizes of external structures units (i.e. the extent of the future vault slab areas they occupy) will intentionally be kept flexible, to match the evolving projections of disposals with time, noting that disposals to external structures units are not anticipated in the short to medium term. On the basis of engineering judgements to date, and the need to create a stable and efficient disposal structure, a minimum size of 20 m by 20 m has been identified. In practice units are expected to be larger than this minimum. The default assumption is that external structures units will always be the maximum height that will fit under the cap, for volumetric efficiency reasons.

- The design is intentionally flexible and comparatively uncomplicated, consistent with the vault disposal approach and the level of hazard involved. Standard plant and waste transport containers would be used to support disposals. This provides confidence that the approach can be implemented in advance of detailed design. The use of standard materials also provides confidence in long-term performance and the associated understanding of the likely evolution of the units.[72]
- Any ILW wastes received at the site would need to be subject to waste receipt, inspection and monitoring processes, as required for ILW. This process, and the required facilities and approaches, is outside the scope of this document, as it does not focus on the disposal system itself. However, an outline design for such an appropriate receipt and monitoring facility has been created [75] to demonstrate the overall practicability of ILW disposals at the site. This provides confidence that an ALARP case for the processes and facilities associated with ILW disposal will be able to be made in the future, and to support cost estimates to feed into final NDA decision making.

As for other proposed developments for future wastes, ongoing design and optimisation work will be required before the approach is finalised. The overall design approach is however robust and provides a sufficient level of detail to ensure an appropriate basis for the ESC.

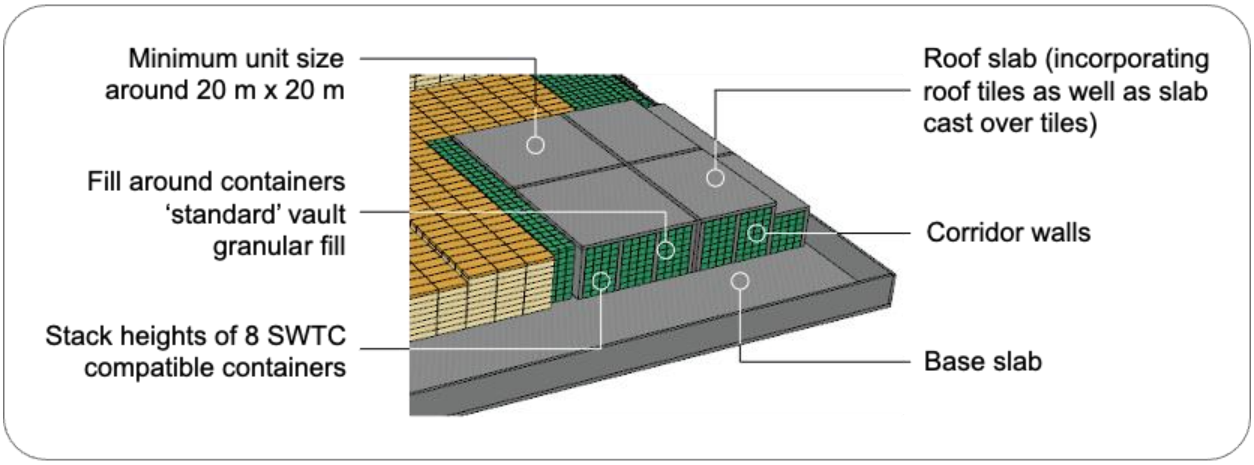

Figure 5.9: Shielded Modules (external structures) units – illustration. Note that a 'cut-away' representation of the corridors is shown, which would in practice be closed at all times when not involved in active emplacement operations.

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[72] As for other engineered components, plausible modes of evolution are explored further in the EPA [12].

Role of Vault 9a

When designing Vault 9, the original intent was that it would be augmented at a later date by the construction of Vault 9a, bringing the western edge of the vault in line with Vault 8. The optimisation study reported in reference [75] included a review process to consider whether construction of Vault 9a remains part of the optimised outcome.

This study recognised that the existing planned future vaults would be more than sufficient to accommodate projected future LLW arisings, and that it was appropriate to consider if deciding not to construct Vault 9a could potentially save money, spread spend and thus enhance affordability,[73] or could lead to a reduction in programme risks given the priority to implement the vault seal over existing and committed wastes as soon as is practicable.

However, whether or not Vault 9a is built, in full or in part, in order to ensure implementation of the optimised long-term passive drainage concept, a drainage feature is required to be constructed prior to completion of capping of the first strip of Vault 9, to connect Vault 8 drainage with the under-slab drainage blankets planned in the Vault 9a and Vault 10 areas. Consistent with the design, a laterally extensive connection is required to similarly extensive blanket features, i.e. this cannot be simple local discharge point.

The Vault 8 base is lower than that for Vault 9 which means that a lower Vault 9a is of benefit in supporting efficient long-term passive drainage of Vault 8 waters to a future vault under-slab drainage blanket.[74]

Therefore, a substantial drainage feature is required to be constructed in the Vault 9a area before the first section of Vault 9 is subject to sealing, whether or not the drainage feature is constructed as a vault. However, there is confidence that Vault 9a can be constructed without representing a significant risk to timely sealing of the first section of Vault 9 (and 9a). Vault 9a construction should be an efficient process, noting experience gained in constructing Vault 9, and also noting that the base for Vault 9a will be of a simpler design than for Vault 9, as well as being much smaller.

Options were also considered that did not involve construction of a full vault but provided the necessary post-closure passive drainage capacity. These included a much smaller 'strip' of vault akin to Vault 9a but with only a drainage function. Further options included the use of two or three concrete drain functions within excavated, protected culverts. The rationale for such drainage-only systems would be to minimise construction effort during implementation

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[73] Total lifetime costs are the primary consideration for financial aspects of optimisation assessments for the LLWR. When affordability is considered, this is a second tier judgement reflecting aspects of wider practicability. It is not a primary consideration in determining BAT.

[74] Other options that have been considered involve the potential routing of Vault 8 leachate, post-closure, via Vault 9 and thence into future vault drainage blankets. These would be much more complex features given the void between Vault 8 and Vault 9, the step in the base at the northern end of Vault 9, the relative heights of the bases; use of such features alone to drain Vault 8 post-closure have therefore not been favoured to date. Potential improvements to this category of options will however be kept under review as the future vault design programme progresses.

of Vault 8 closure within the capping programme. However, any of the options would involve excavation and construction of non-trivial features and the programme risks involved would overall be similar.

Construction of the full Vault 9a approach could yield disposal capacity of around 2,200 HHISO containers. This is of significant value in itself. However, the disposals would also offset a significant volume of profile fill that would otherwise be required to fill in the void under the cap, where the stacks extend above current ground level. Excavation materials would also be produced that could be used as profile fill and further offset the costs, as well as assisting with the closure process by reducing material imports. Omitting Vault 9a would be unlikely to reduce the total profile fill requirement as ‘stepping in’ the cap profile locally would not be practicable due to the constraints of minimum and maximum gradients and the need to maintain alignment with the line of the cap already required for Vault 8 and the future vaults.[75]

An alternative drainage feature would generate lower volumes of excavation materials for use as profile fill. It would also require significant volumes of profile fill to be imported into the volume under the cap (with Vault 9a construction, much of this volume would instead be occupied by disposals). Therefore, for full Vault 9a construction, the savings made in avoiding above-vault profile fill volumes and generating excavation material for use within the trench profile fill would potentially be sufficient to cover the majority of the cost of constructing Vault 9a, when compared to other options.

The concept design for Vault 9a (as for other future vaults) is mature and reflects a logical development of the approach already demonstrated by the existing vaults, being consistent with the general concept strategy for future vaults. It is also comparatively simple. This means that its design is inherently consistent with minimising overall programme risk. This is of importance given the objective of early sealing of existing and committed LLW.

Overall, it was considered logical to implement Vault 9a and associated drainage, capacity and profile fill avoidance (and generation) benefits rather than constructing slightly simpler options that would not have these advantages. These arguments and the related understanding of practicalities and costs will be developed and monitored as the design process continues. Further information on these outcomes and the supporting rationale is provided in reference [75].

There is the potential for flexibility, to be explored through ongoing design and optimisation processes, concerning the mode of implementation of Vault 9a. The current baseline assumes that it would be constructed in entirety before sealing of the first section of Vaults 9 and 9a. However, it could also be constructed in two phases, for example with one module being created in advance of the sealing programme for the first section of Vaults 9 and 9a,

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[75] In general, constraints associated with minimum and maximum gradients mean there are no major reasons for narrowing the future vaults from their present footprint even if not all disposal capacity will be required, as the footprint of the cap will not change to a significant extent.

and with the remainder being constructed separately, for example as part of the same programme of work associated with construction of modules in Vault 10.

These alternative options for the construction of Vault 9a cannot be differentiated in broad terms from the perspective of the ESC and key optimisation arguments. They will deliver the same broad outcomes and confidence in performance.

Final choices will therefore be made in association with the programme of ongoing design, informed by the more detailed understanding of the options developed during that process. For example, if projections for future disposal rates reduce further, in turn reducing the near-term requirement for additional disposal space, creating Vault 9a in two phases may offer advantages. In particular, this would reduce the overall level of construction work on the site over relevant timeframes, reducing programme risks and allowing a focus on priorities such as early sealing of existing and committed wastes, and creating interim storage warehouses for future LLW. Ancillary benefits may also include minimising maintenance requirements for an empty vault, and assisting in the management of spend profiles, without changing the final closure disposal model or challenging environmental performance.

Container protection and interim storage warehouses for Future LLW

Past optimisation studies for the LLWR (as described in references [73] and [74]) have recognised the importance of protecting consigned waste containers from environmental effects such as precipitation and wind-blown chlorides at an early stage. This is to minimise the potential for enhanced degradation of containers (e.g. via corrosion) prior to final closure. The maximum protection will be provided by the final cap and vault seal.

The previous intention, e.g. as set out in the 2011 ESC, was that receipt rates would be sufficient that strip-capping on a vault-by-vault basis could plausibly be implemented within an appropriate timeframe. However, in addition to the existing containers that have already been in the vaults for several decades without protection, current waste receipts [4] have already significantly slowed, as a result of waste volume minimisation and diversion strategies (Section 2). This means the previously anticipated link between waste receipts and vault closure has been broken and without a different approach, wastes could continue to be left in open vaults for decades.

Although the existing containers that have been in the open vault for a prolonged period have not led to any notable negative effects (e.g., no enhanced releases observed through leachate monitoring) this is not considered optimal. A guideline target of protection within ten years of future receipts was therefore previously identified [73].

A series of optimisation studies have assessed options for container protection (Section 8). Options have ranged from simple approaches like tarpaulins (which would have the negative qualities of not being sufficiently robust, and promoting conditions prone to condensation) to full concrete structures like those planned for ILW (which would be very expensive and inflexible), and implementing smaller strips of the cap over parts of the vault. Option sets also considered both protection measures in-situ over wastes in final disposal positions, and locations elsewhere in the system.

The preferred approach (see reference [75]) is that ‘interim storage warehouses’, similar to standard industrial warehouse designs, will be constructed. Options studies identified that these warehouses are a proportionate response which will ensure that future disposals are protected from precipitation and wind-blown chlorides, if the timeframes for final capping suggest that they may otherwise remain outside and unprotected for more than around ten years. This level of protection does not require a full climate-controlled store, but rather a structure that will provide basic weather protection with passive venting. 'Standard' warehouse type structures were identified as providing a sufficient and pragmatic response to this requirement, with designs ensuring they can be easily dismantled as disposals progress.

These will initially be constructed in the Vault 10 area to provide interim storage of containers prior to being moved to their final disposal positions in Vaults 9 and 9a, shortly before the implementation of relevant strips of the cap. The warehouses will be removed prior to closure and therefore have limited implications for the ESC, other than ensuring that the containers are in good condition at the time of disposal. Locating the warehouses apart from vaults that are receiving active disposals and closure programmes will also ensure the segregation of operations which will enhance efficiency and help reduce aspects like worker dose.

Note that 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 constructed with sufficient frequency that the interim warehouses are not required. However, the default assumption is that the warehouses will be employed, to accommodate uncertainties in arising rates. After warehouses in the Vault 10 area have been removed, the assumption is that warehouses will then be created in the Vault 11 area and so on.[76]

For Vaults 9 and 9a, the warehouses are combined with an augmented approach to vault closure. Given the priority for early sealing of existing and committed LLW, the use of warehouses for containers that will be disposed to Vaults 9 and 9a is focussed on future LLW, and ILW that can be managed as LLW.

In summary, the warehouses, with their standard design and passive venting, will provide the required step-change in protection of the containers without being overly complex, and is thus a proportionate response.

Warehouses are not required for ILW that cannot be managed as LLW as the shielded modules will already provide the required protection. Any management at the site prior to disposals will be handled in the receipt and monitoring facility for ILW.

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[76] Flexibility is embedded in the approach and there remains the possibility that warehouses could initially be constructed in the area currently defined as Vault 11 so they do not require to be moved when Vaults 9 and 9a are filled; also, they could be moved and re-used. In both cases, the age and condition of the structures will be a consideration in their continued use.

Modular approach

A range of optimised approaches for the different waste categories are presented, within the overall remit of the optimised disposal model and concept. This logically leads to a modular approach for the future vaults[77]. For the future vaults, discrete disposal modules will therefore be constructed for the different wastes[78]. These modules might be constructed on the same base slab or utilise separate slab units. While no strong optimisation arguments have been identified to require a formal choice to be made at this stage, the current assumption for design purposes is that they will be constructed on contiguous slab units within each of the future vaults. These will include locally thickened units where necessary (i.e. for ILW requiring shielding) and with bunding or other drainage features to separate run-off and leachate from different disposal areas. This approach also provides flexibility, for example allowing re-use of slab areas for warehouses and then disposals, and allowing for variations in turning circles and access routes to supply containers to their disposal locations; smaller vault module bases connected by road-type access routes would be less flexible. In any case, vault bases are by definition laterally extensive concrete structures that would normally be built in sections with joints, and so this approach, and the alternative of specifically separate module basis, are arguably variations on a theme.

The future vaults are anticipated to be delivered in a flexible manner, allowing for the sizes of modules to be altered in response to updated disposal projections with time. However, the overall size of the different future vaults is governed by topography and the desire for simple geometries (continuing the line of existing vaults) to ensure, for example, that cap and cut-off wall geometries are not unnecessarily complicated. The assumption, therefore, is that the same broad future vault geometries and areas will continue to be used, just delivered in a modular fashion. However, it is recognised that not all of the current footprint of the vaults may be required for future disposals. There is flexibility therefore as to the final size and shape of future vaults, and in particular the vault modules that will be used for the final stages of disposal.

The modular approaches identified for the different LLW and ILW categories are all consistent with the overall LLWR pre- and post-closure engineering concept and therefore can be used together in a flexible fashion. Moreover, the approaches to individual waste categories will apply whatever combination of wastes are disposed. For example, if the option to dispose ILW in the vaults is not pursued, this will not affect the preferred approach to relevant LLW categories, other than the distribution of disposals within the vault footprint.

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[77] The range of approaches will be maximised if ILW disposal is taken forward. However, even for LLW disposal only, there will be separate areas of the vaults for disposals and for temporary storage warehouses. In addition, the modular approach also allows for flexibility in the rate of disposal capacity provision within the future vaults area.

[78] The use of the modular approach for Vault 9, within the constraints of existing engineered features for Vault 9, is described in Subsection 5.4.5.

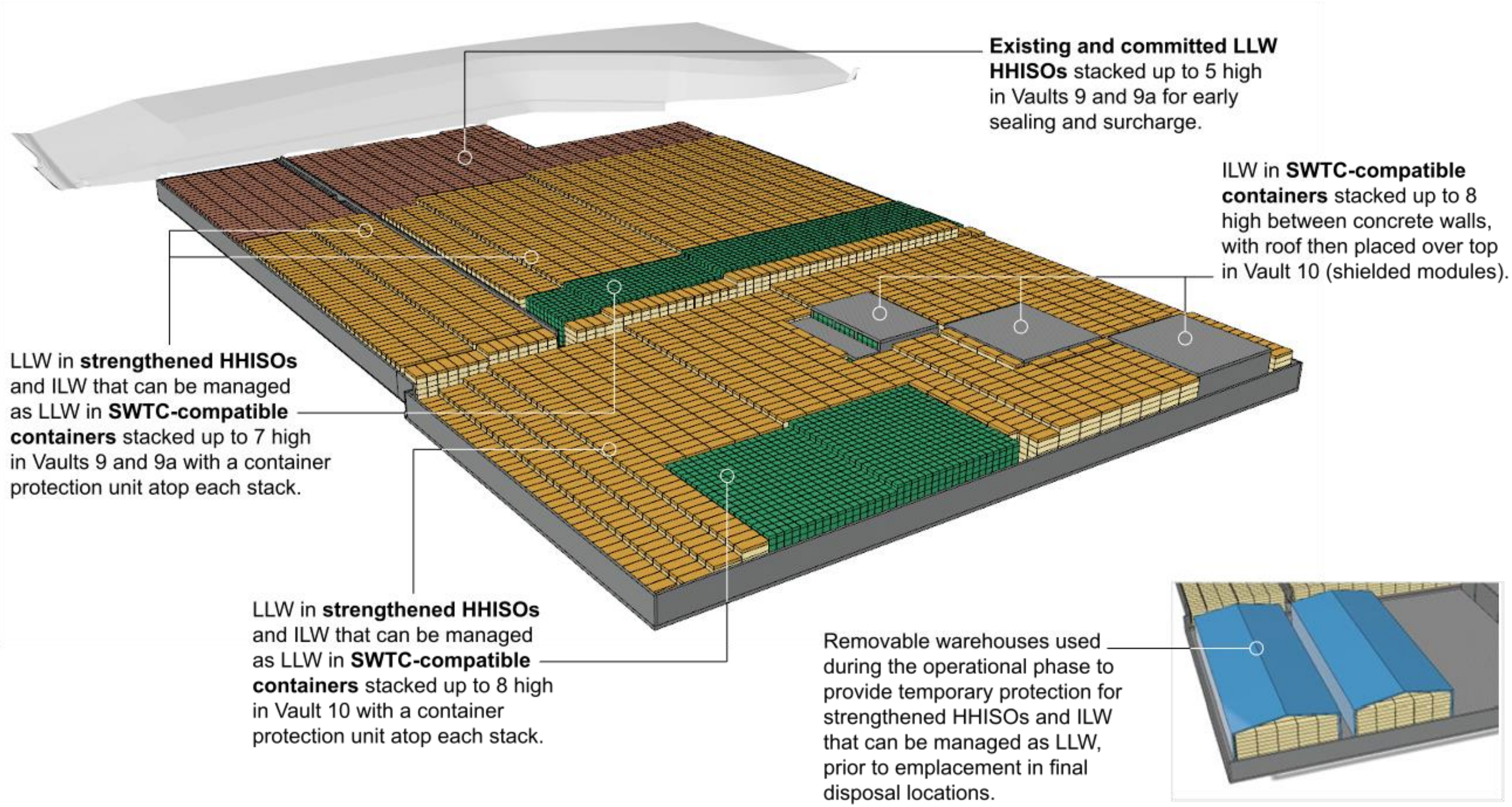
Void fill and passive drainage

The assessment of options for future vault modules has served to review and support previous assumptions on passive drainage for the future vaults. That is, inert, low-fines granular void fill will be used [75], as for Vaults 8 and 9 and for similar reasons, in between LLW and ILW stacks and wherever voids are large enough to require filling.

Similarly, the use of drainage blankets underneath the future vaults continues as an essential aspect of the overall design and concept. Passive drainage arrangements will therefore be constructed to manage leachate at the 1 m level in the future vaults, implemented within the modular scheme, and will also provide for the required management of leachate from the existing vaults. The drainage blankets will be separated from one another with low-permeability material to ensure they function independently and to avoid preferential flows through the entirety of the drainage blankets to the south of the facility.

5.4.7 Illustration of the Modular Approach

For Vault 9 and the future vaults, Figure 5.10 illustrates how the designs for the different vaults and waste categories could work together (note while the design basis is underpinned and robust, the approach is intentionally flexible in terms of, for example, the size and location within the vaults of different disposal areas or modules). The figure is illustrative of the overall design rather than an exact representation of the waste volumes and disposition, which will in any case vary as inventory projections develop in the future, and include some aspects that will continue to be part of the detailed design process in the forward plan.



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 5.10: Illustration of optimisation outcomes for the vaults: Vaults 9, 9a and 10.

Box 5.7: Summary: Further Optimisation of the Future Vaults

This box provides key optimisation arguments for the future vaults.

- For ongoing disposals of LLW, optimisation arguments for the concept for the future vaults identified in the 2011 ESC have been confirmed as remaining valid (see Box 5.1). On that basis, vault bases and relevant walls to the 1 m level will be reinforced concrete with a single composite liner for water management. Similarly free-draining, inert, low-fines granular backfill will continue to be used. Over-topping waters will then be directed to the drainage blanket underlying each vault to maximise the connection with vertical drainage capacity. Relevant future vaults will accept flows from the existing vaults to their drainage blankets at closure to ensure consistency with the overall concept.
- Future LLW and ILW that can be managed as LLW will use the same basic container approach as for Vault 9, and for similar reasons (see Box 5.6). Interim storage warehouses, located on slabs separate from ongoing disposals, will be used to provide interim container protection from environmental effects in advance of capping; other options will either not be as effective, or represent a disproportionately complex response.
- ILW that cannot be managed as LLW will be accepted into shielded modules that use reinforced concrete external structures to provide shielding and to support the cap. This option has been identified as a proportionate response to the additional external radiation hazard otherwise presented during the PoA, consistent with the principles of ALARP. Containers will be as for ILW that can be managed for LLW for similar reasons.
- The modular approach is a natural consequence of the need to manage different waste categories within the areas defined for the future vaults. It also offers further benefits such as flexibility in the rate and sizes of module construction, and the ability to segregate waters and minimise overall leachate volumes.

6 Management of the Trenches

6.1 Introduction

This section describes optimisation studies focussed on the trench disposals. These are specific to the trenches, noting that common engineering such as the final cap and the cut-off wall have already been discussed in Section 5.

The approach to trench surcharge is integrated with that for profile fill and has already been summarised in Section 5. In addition, discussion of the makeup and broader properties of the trench wastes is outside the scope of this document and is discussed in our '*Disposal Facility Inventory*' [4] and '*Near Field*' [6] reports. On that basis the focus here is on the approach to trench hydrological management (Subsection 6.2) and consideration of the potential for retrievals (Subsection 6.3).

A summary of the design of the trenches is provided in Subsection 4.2. A more comprehensive overview is presented in reference [5].

6.2 Trench Hydrological Management

6.2.1 Overview

Requirements for optimisation

Optimisation studies have been undertaken since the 2011 ESC [80, 81] following the recognition that water balance data suggested that the existing interim cap over the LLWR trenches was not performing as intended. As a result, it was recognised that a larger fraction of precipitation than originally expected was entering the trenches (e.g. reference [81]). 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 geomembrane is damaged in several areas, and this damage is extensive, including some substantial geomembrane tears, gaps and areas of wrinkling [81]. Only contaminant releases from the trenches were affected by the performance of the interim cap. Groundwater is not currently extracted for drinking water in the vicinity of the LLWR, nor is this likely on the timeframe for the PoA,[79] and therefore it was noted during the execution of the study that contaminant releases from the trenches were not likely to lead to radiological impacts to humans above relevant criteria.[80] Nevertheless, at the time that the BAT studies commenced [81], tritium had been identified in groundwater between the facility and the coast, and this was considered sufficient to require consideration of a proportionate

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[79] The NDA has a 999-year lease on the land to the west of the site which will assist in controls over the relevant periods.

[80] This has since been confirmed by assessments for the 2026 ESC (see e.g. [14] and [13]).

response. In addition, other radiological and non-radiological contaminants will also be affected by the condition of the trench interim cap. Improving the hydrological management of the trenches was therefore recognised as important in helping to reduce further release and migration of contaminants. It was agreed during the reviews undertaken that action needed to be taken to improve the cap over all the trenches, as its condition was not considered consistent with good practice, and therefore could not represent BAT.

Overview of relevant BAT studies

The concerns associated with the existing interim trench cap performance were first identified in 2012 [81]. Three iterations of BAT studies followed, combined with progressive investigations of the state of the interim cap, guided by the BAT studies. A final study reviewed the outcomes in the context of the Repository Development programme including aligning outcomes with the approach to surcharge of the trenches and the closure of Vault 8 [67].

6.2.2 Main Optimisation Outcomes

Overview

Options considered in the BAT study [81] included, in broad terms:

- taking no action;
- improvements to drainage and run-off catchments only;
- selective remediation of specific areas of the existing cap to prioritise areas of the worst damage; and
- full upgrade amounting to a replacement of the interim cap.

Different options for cap replacement (including use of a geosynthetic clay liner (GCL), geomembrane, or clay or BES alone) were considered. It was decided during the final iteration of BAT review that there was sufficient concern about the performance of the whole of the interim cap that it needed to be upgraded in its entirety.

The areas of the trenches adjacent to Vault 8 will be subject to final capping at the same time as Vault 8. It was agreed that it is important not to delay the final cap emplacement. As upgrading the interim cap would have the potential to result in such delays, it was agreed that it would not be logical to upgrade the interim cap for the northern strip of the trenches. In addition, placement of profile fill (including fill material used for surcharge) will provide an interim improvement to the hydrological management of the northern trenches, by reducing the overall permeability of material above the existing cap, and by encouraging run-off. The final cap over these areas will then be completed by 2037.

The remaining areas of the trenches will not be covered by the final cap in the next few years. A new interim cap will therefore be constructed over these areas of the trenches, as part of the programme for closure of Vault 8. This cap will be emplaced over the existing geomembrane so that it is not necessary to excavate down to levels that could lead to interactions with the existing wastes. The existing geomembrane will however be systematically punctured to ensure predictability of hydrological performance, and to ensure that it does not provide a construction slip-plane that could provide risks to stability of final cap layers.

Of the range of options considered for the new interim cap, a GCL was selected as providing an excellent barrier for an interim cap. It will provide many of the benefits of a full BES and geomembrane composite barrier, but GCLs are comparatively simpler to construct and to remove.

The GCL option is consistent with international good practice (e.g. as described in reference [82]) showing that longer-term performance of GCLs is typically favourable compared to other options such as clay or BES caps on their own, and provides additional advantages compared to a geomembrane such as self-healing properties.

A full composite (BES and geomembrane) cap would require final cap-like materials and gradients and would necessarily become an L-shaped extension of the final cap. This was considered in the final cap optimisation work but would be inefficient; for example, the gradients involved from Vault 9 and the future vaults to the crest of the cap over the trenches would involve an extensive cap seal which would itself be a geomembrane or GCL. The requirements for surcharge would need to be integrated into the design which would add to the challenges. The GCL approach, however, can be emplaced comparatively quickly with later surcharge prior to cap emplacement. This combination of performance and expediency led to the GCL approach being favoured for areas of the trenches that will not be covered by the first strip of the cap.

Ease of removal is important as, again, the GCL cannot be left in place prior to final cap completion due to arguments including the focusing of flows to the facility perimeter and the slip-plane hazard along the edges. It cannot easily or reliably be punctured due to its self-healing properties and this could also lead to challenges in predictability of hydrological performance into the longer term. However, as it will be required to perform for several decades for the trenches further to the south of the system, confidence in performance arguments meant that the GCL was preferred over a geomembrane alone despite the requirement for later retrieval.

Drainage will be assisted by the use of a man-made drainage layer constructed over the cap. Again, this is appropriate 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 BAT process is provided in Figure 6.1.

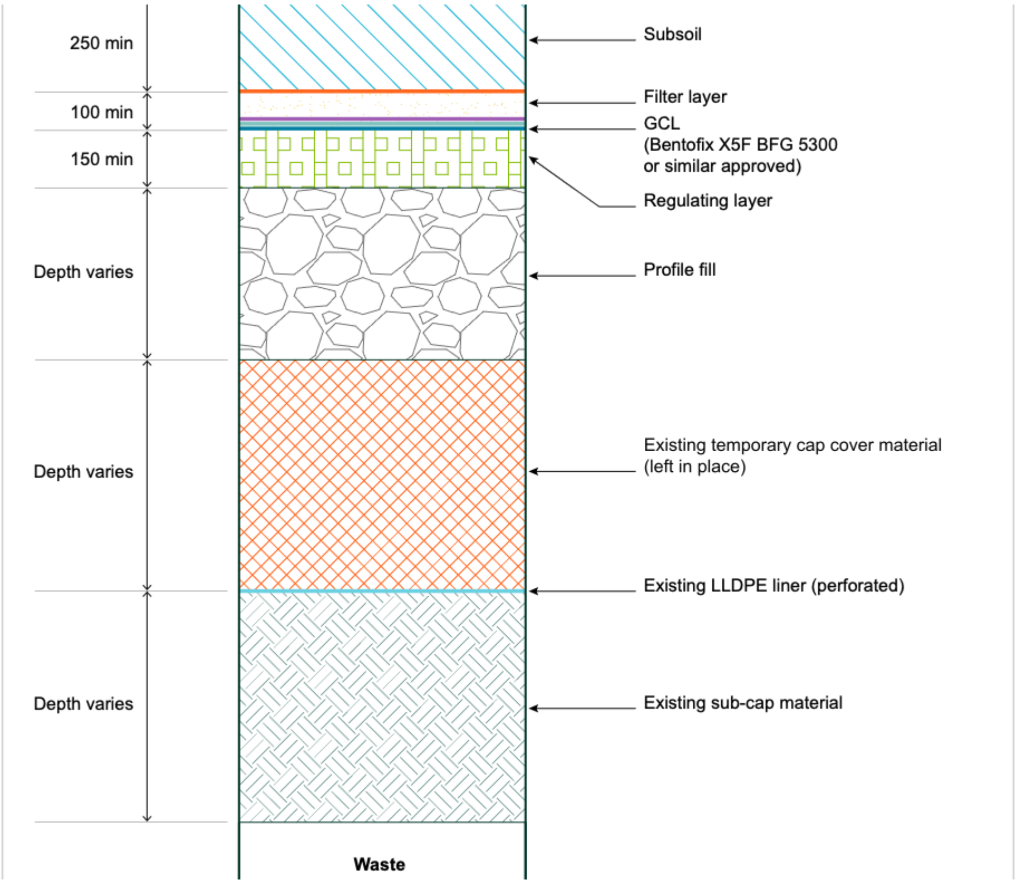

Figure 6.1: Basis of trench cap design. Illustration taken from reference [80].

6.2.3 Implementation

At the time of writing, construction of the upgraded cap over the southern area of the trenches is at an advanced stage, being implemented via the STIM programme.

6.3 Consideration of Trench Retrievals

6.3.1 Overview

A major optimisation study considering options for retrieval from the trenches was presented in the 2011 ESC [31]. This was undertaken as a response to assessed doses and risks to people and the environment resulting from past trench disposals, which were an important safety consideration in the 2002 PCSC [28]. This was assessed as part of the 2011 ESC [30] and lower doses were calculated than in 2002. Notwithstanding this, options of selective retrieval or in situ remediation of trench waste were considered in the 2011 ESC. The work concluded that the doses associated with trench disposals were ALARA and that the effort required for either selective retrieval or in situ remediation would be grossly disproportionate to the benefit that would be gained.

The Environment Agency's review of the 2011 ESC [83] agreed with the conclusion, but recommended that the decision regarding both selective retrieval or in situ remediation of trench waste should be reassessed in future updates of the ESC to determine whether safety arguments or the viability of retrievals or in situ remediation had changed in the interim. The Environment Agency also recommended that the cost model for retrieval and re-disposal of certain trench waste should be reassessed if the English policy for the disposal of Higher Activity Waste (HAW), which comprises High Level Waste (HLW) and ILW, changed.

On that basis, a further optimisation study was undertaken for the 2026 ESC [84], in order to provide a structured review of the previous study. The review considered relevant developments in the understanding of the LLWR system, inventory projections, cost models, and the wider context of UK policy.

6.3.2 Main Optimisation Outcomes

Details of the original study were provided in the 2011 ESC [31] and underpinning references. These details are still relevant as the 2026 ESC study [84] served to review and confirm that the outcomes remained valid, and that retrieving from the trenches would not be ALARA. Given that details of the optimisation arguments and their review are available in the 2011 ESC [31] and reference [84], only a brief summary is presented here.

Each iteration of study and review has taken into account the outcomes of contemporary assessment calculations for relevant pathways. In the 2011 ESC [31] and the 2026 ESC [14, 84] our assessments indicate that calculated impacts are broadly consistent with or below regulatory guideline levels for all pathways. The highest calculated impacts are currently associated with the coastal erosion pathway arising from Th-228 and Ra-228 ingrown from Th-232, which are comparable to but slightly above the regulatory guideline level (33 µSv compared to 20 µSv). Calculated impacts from other pathways are below the relevant guideline levels and have either remained similar, to or have reduced since, equivalent calculations for the 2011 ESC.

The Th-232 decay chain has been a particular focus of retrievals arguments throughout the iterations of options assessment, together with other longer-lived radionuclides that are of interest from the perspective of coastal erosion but are not associated with the same levels of calculated impact (e.g. the Pu-240 chain). In addition to the potential for full trench retrievals, options involving selective waste retrievals have been explored. This is because disposals of Th-232 (and other longer-lived radionuclides) are not spread evenly throughout the trenches. Disposal records show they are located in specific sub-bays in a subset of trenches.

In addition to selective retrievals, further classes of selective management options have also been considered. These complement those focussed on retrievals by considering approaches such as modification of the physico-chemical characteristics of the wastes, modifying the local chemical environment, or providing local protection by introducing barriers such as cut-off walls for isolation and containment reasons.

When reviewing the options and their potential benefits, the 2026 study reconsidered the previous assessment of options given:

- changes in assessment approach or understanding of environmental safety since the 2011 ESC;
- changes in government policy for the disposal of HAW;
- changes in the viability of selective retrieval or in situ remediation of waste, which would be driven by improvements in technologies and/or reductions in cost.

We briefly summarise changes in these areas, in turn, in the discussion below.

- From the perspective of *the assessment approach or understanding of environmental safety*, there have been no changes of significance since the 2011 ESC. In particular, the understanding of the location and magnitude of disposals of key radionuclides has not changed. There have been updates in understanding in system performance (e.g. concerning infiltration through the cap and trace gas transport through it). Calculated impacts have either stayed at similar levels (coastal erosion, human intrusion) or reduced (other pathways).
- In terms of *government policy for the disposal of HAW*, whilst government policy advocates exploring alternative NSD options, no proposals are forthcoming of material importance to these options. The coastal erosion pathway dominates assessed impacts. If wastes were to be retrieved to reduce impacts, it would therefore be necessary to dispose of them in a deep repository that is not susceptible to erosion, rather than re-disposing in the vaults. This means the proposed Geological Disposal Facility (GDF) would remain the preferred disposal approach for any retrieved wastes, in the absence of plans for any alternative facility below the erosion horizon.
- From the perspective of *the viability of selective retrieval or in situ remediation of waste*, we have undertaken a detailed review of options, viability and costs. This has been facilitated by identifying recent developments in relevant options for other studies, and in particular reviews of options for the Dounreay Pits [85], which (to an extent) present some analogous challenges to the trenches. In general, we did not identify any innovations or developments which would enhance the viability of options. On the contrary, our review of practicalities and costs across the options identified suggested that solutions involving retrievals, modification of physico-chemical properties, or local protection options involving barriers, are now considered less viable than for previous assessments. The assessed viability of modifying the local chemical environment, meanwhile, has not changed.

On this basis, it can be summarised that:

- there has been no substantial increase of the need to implement relevant options (for example, peak calculated environmental pathway impacts remain consistent with regulatory guideline levels);

- the viability of key options has been further challenged, in relation to aspects such as cost, time, and worker safety risks.

We therefore consider that the previous conclusion that the current strategy to managing the trenches is optimised − including the use of the cut-off wall, interim cap and then the final cap to reduce impacts − remains valid. That is, the potential benefits of retrievals were assessed as disproportionately small compared to the cost, time, and risks to workers associated with relevant options.

6.4 Summary

The outcomes of the optimisation studies for the trenches are summarised in Box 6.1.

Box 6.1: Summary: Optimisation of the Trenches

This box provides key optimisation arguments for the optimisation of the hydrological management of the trenches and the consideration of retrievals.

- The interim cap over the southern trenches is currently in the process of being upgraded. This was considered necessary given the issues observed with the performance of the existing interim cap. A GCL is being used to provide the required reduction in infiltration and confidence in performance prior to completion of the full composite cap. The GCL can also be effectively removed prior to construction of the final cap.
- The interim cap does not need to be upgraded over the northern trenches, as that area will be covered by the final cap in the next few years. Implementing upgrades here would therefore be nugatory effort that would delay the implementation of the final cap over both the trenches and over Vault 8.
- Remediation of the trenches is not considered appropriate. Approaches such as selective retrievals would involve disproportionate costs, time and worker risks compared to the very limited reduction in calculated impacts they might achieve, noting also that those impacts are in any case already broadly consistent with regulatory guidelines.

7 Optimisation of Operational Controls and Monitoring

7.1 Overview

This section provides an overview of the optimisation arguments for operational controls relevant to the ESC, including supporting monitoring arrangements.

Consistent with the role of the ESC, discussions focus on the impacts to the surrounding environment and the public, balanced appropriately against wider considerations such as worker safety. The overview of operational controls and monitoring activities complements and builds on the engineering descriptions in previous sections.

Prior to completion of disposals and the closure engineering we must prepare the repository, and the wider site, to ensure it is in a physical condition that is consistent with reaching the Site Reference State at the end of active institutional control. In addition to the disposal area, this includes remediation, in-situ disposal, or leaving of contamination in place as appropriate, consistent with the provisions of the GRR and the role of the ESC as a full-site SWESC. While the focus of this document is on the repository, relevant aspects of the wider Site Reference State are noted in the discussions that follow. A full description can be found in reference [10].

There are four key lifecycle phases covering the period of repository operations and institutional control (Figure 7.1, reference [86]):

- **Operations**: This phase occurs between the present day and final waste emplacement. Operations include waste disposals, plus progressive capping and installation of the cut-off wall.
- **Closure Engineering**: This phase includes completion of capping of the disposal area, completion of the cut-off wall installation, and removal of the site security fence. The Nuclear Site Licence is likely to remain until the end of disposal operations and we will seek to delicense by the time closure engineering is completed. This will enable the site to move into the active institutional control period with controlled public access.
- **Active Institutional Control**: The active institutional control period with ongoing environmental monitoring and surveillance of the closure engineering infrastructure. During the active institutional control period, meeting of the Site Reference State should be demonstrated and the monitoring infrastructure subsequently decommissioned.
- **Passive Institutional Control**: This period can only start once the environmental Permit has been surrendered. The site will then be subject to planning restrictions and records will be available in order to deter, or prevent, inappropriate site uses.

Decommissioning will occur as required up to and during the active institutional control period. This is an ongoing activity rather than an identified “phase” in Figure 7.1.

During operations, redundant infrastructure will be decommissioning progressively as is currently the case. Once the major closure engineering is completed and the site enters the active institutional control period, there will be decommissioning activities carried out as needed. This will include decommissioning of the leachate management system which is likely to occur relatively early in the period, with monitoring infrastructure (e.g. boreholes) decommissioned later, once the Site Reference State has been demonstrated. All decommissioning activities will be completed before entering passive institutional control.

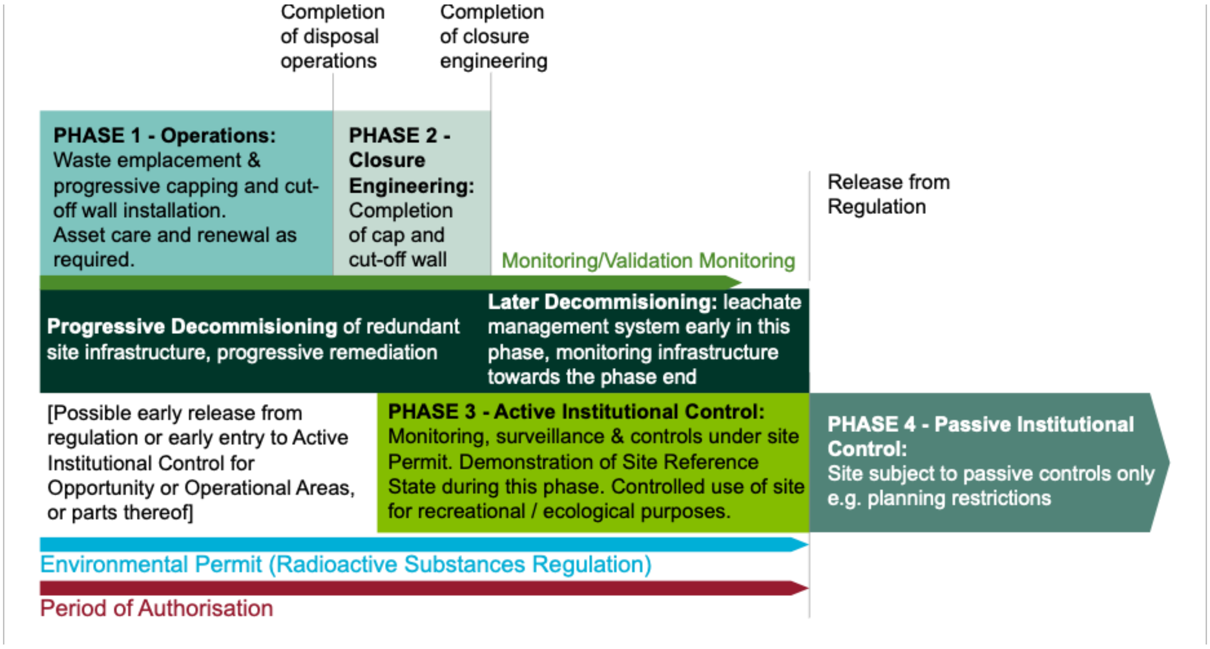

Figure 7.1: LLWR Lifecycle Phases. From reference [86].

During the period of repository operations and installation of closure engineering, controls relate to aspects such as WAC and emplacement, controls on discharges, monitoring to support the implementation of these controls, and access and information controls. These include activities and controls that are already part of routine operations, and activities that will be implemented in the future as disposals and the closure process progress. Controls and actives cover, for example, disposals and operations, physical activities to develop and close the repository and to achieve the Site Reference State, and knowledge management activities to capture information on the repository and its wastes and to preserve that information for future decisions and to underpin the passive institutional control period.

During the subsequent active institutional control period, after operations have ceased and the closure engineering is in place, controls will focus on access and surveillance. The length of the period over which those controls will be provided is a key assumption (Subsection 7.3.5).

Given the significant time period between now and the end of the PoA, it is not appropriate to claim definitively which methods will be used to implement the required controls, especially during the period after closure. The discussion presented here, therefore, focuses on controls that are expected to be required at this stage and are assumed for the 2026 ESC. Approaches to implementing those controls are discussed but, for those that will occur over long time frames, the choices discussed here are indicative rather than definitive.

The following subsections expand upon these aspects. For simplicity, the four timeframes identified above are addressed within two subsections:

- Subsection 7.2 considers the operations and closure engineering periods, as there is significant overlap in the relevant controls; and
- Subsection 7.3 addresses the active institutional control period, leading to delivery of the Site Reference State and thereby arrangements which will persist into the period of passive institutional control.

In both cases, reference [86] expands and provides details.

7.2 Controls during Repository Operations and Completion of Closure Engineering

7.2.1 Controls on Waste Receipts, Capacity Management, and Emplacement

Key controls on waste receipts during the operational period include WAC and radiological capacity controls. These controls are optimised as they reflect outcomes from the ESC, translated into proportionate and practical arrangements.

The controls are described in the '*Implementation*' report [17]. Relevant aspects are highlighted here in the context of demonstrating how they contribute to delivery of wider optimisation priorities.

7.2.1.1 Optimisation and Waste Acceptance

The WAC ensure consistency between ongoing disposals and ESC outcomes. They also reflect broader optimisation priorities including:

- the need for consignors to demonstrate that the LLWR is the optimal disposal route for the wastes (in comparison with, for example, diversion of lower activity wastes to other facilities);
- the need for consignors to demonstrate that their approach to disposal at the LLWR is consistent with BAT, considering, for example, appropriate treatment methodologies, and application of the Waste Management Hierarchy including waste avoidance and volume minimisation;
- controls on the waste form and the physical composition of wastes, for example voidage needs to be minimised and meet voidage targets specified in the WAC; and

- controls on the biogeochemical properties of wastes for example, limitations on complexants.

These and other requirements ensure that the principle of optimisation in the context of disposals to the LLWR is reinforced at the consignor level. That is, the priorities embedded in the WAC are aligned with ensuring ongoing optimisation across the waste life-cycle leading to disposal.

The WAC therefore help implement NDA priorities for the LLWR in its wider national context. This includes prioritising protection of disposal volume consistent with recognising the facility as a national asset. WAC have provided, and continue to provide, important contributions to the wider programme for the optimisation of disposal capacity at the LLWR. For example, they reflect priorities for diversion and waste treatment, the latter including volume reduction processes such as metal decontamination and melting, supercompaction, and incineration (see Subsection 2.3).

7.2.1.2 Capacity Controls

As outlined in references [1] and [17], a key component of our optimised controls for the repository is the application of capacity controls. These include the radiological capacity of the facility, but we also identify capacity limits for specific non-radiological substances, together with capacity limits on specific complexing agents.

Optimisation of these controls is inherent in the approach to their identification.

- Optimisation of the usage of the volumetric capacity offered by the facility is a key feature of UK policy and strategy.
- The capacities are derived using our environmental safety assessments for relevant pathways. These are based on our optimised disposal model. The assessments and the capacities derived from them therefore directly reflect our optimised SDP.

Taken together, these two components ensure that the usage of different categories of capacity at the repository is optimised.

A comprehensive summary of the development of radiological capacity controls and associated WAC, taking these optimisation considerations into account, is provided in the '*Implementation*' report [17].

7.2.1.3 Emplacement Controls

The potential for emplacement strategy controls also provides options for further reduction of impacts.[81] Specific studies on emplacement strategies have considered options and the potential of such strategies to contribute to optimisation. The potential for associated controls is again discussed further in the '*Implementation*' report [17].

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[81] The focus here is on impacts via key environmental pathways. Direct and indirect radiation, including emplacement controls for any future ILW associated with elevated dose rates, is discussed in Subsection 7.2.2.

Our emplacement controls focus on stacking waste packages in the vaults. One key aspect concerns the potential to reduce future differential settlements (i.e. by controlling and distributing stack voidage), as described in reference [17].[82]

Controls are also proposed to limit impacts from the coastal erosion, human intrusion and gas pathways. These proposals reflect an optimised and proportionate response to the understanding generated by the assessments for these pathways, and calculated impacts. The potential controls described include:

- emplacement controls to limit the co-location of containers with elevated activity concentrations of key radionuclides to limit impacts from coastal erosion;
- container-specific activity concentration limits for containers placed at the bottom or top of stacks to limit impacts from specific human intrusion pathways; and
- container-specific Ra-226 activity limits to control heterogeneity from the perspective of limiting calculated doses from the gas pathway.

These proposals and their rationale are discussed in detail in the *ESC Implementation* report [17].

If ILW disposal is implemented at the site, ILW emplacement strategies will be implemented. ILW that requires additional operational control measures for dose management reasons will be placed only in shielded modules (See Subsection 7.2.2). Assessments have also indicated potential benefits in minimising impacts during coastal erosion if disposals of LLW and ILW are spread throughout the future vaults such that they are not all eroded at the same time [17, 14]. This assumption has been reflected in the assessments of ILW presented in this ESC but is not considered a formal decision at present. If it is decided that ILW disposal will be taken forward at the LLWR, this will be one of a range of aspects that will be considered in more detail through subsequent optimisation and design processes.

7.2.2 Controls on Direct and Indirect Radiation

The potential for direct and scattered radiation to irradiate off-site receptors during the PoA is recognised and assessed in reference [13]. Monitoring results show that impacts from existing wastes are very low given the following considerations.

- The low intrinsic hazard offered by the wastes.
- The presence of the interim cap and associated overburden for the trench wastes together with the cut-off wall, as well as self-shielding within the wastes disposed, in-trench structures and geometries, and cover soils mixed with the disposed wastes.
- Self-shielding within the vault wastes, and shielding from the grout and the container structures, in addition to shielding of wastes by adjacent container stacks, and

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[82] As part of this, stack heights for future LLW and any ILW disposed in the vaults will be controlled to be within the disposal envelope (i.e. ensuring a minimum distance of 5 m between the waste and the cap surface).

shielding of lower containers by upper containers in stacks. The vault engineering (e.g. walls) also provides some shielding for adjacent stacks.

Further control of impacts for the remainder of the PoA will also be provided by the following engineering measures. The optimisation arguments for these measures have already been presented in Sections 5 and 6 and are not repeated here.

- CPUs planned to be installed over future LLW wastes (and any ILW that might be disposed and managed as LLW) will contribute to a reduction in doses from scattered radiation doses.
- The progressive implementation of the final cap will attenuate doses from direct and scattered radiation, and will eventually lead to a complete elimination of these dose pathways to the relevant receptors.
- For any ILW that might be disposed associated with elevated dose rates, disposal in shielded ILW modules will be implemented. A shielded receipt and monitoring facility would be used for relevant operations prior to disposal. Emplacement arrangements will be designed to minimise dose to both workers and the public.[83]

Appropriate use of WAC will ensure only wastes with appropriate dose rates are disposed. However, there is the potential that certain waste streams associated with future LLW could contain elevated levels of radionuclides including Cs-137 and Co-60 compared to current disposals. While the assessed average vault external irradiation doses presented in reference [13] are below the applicable dose constraint for future LLW, there is the potential that specific LLW streams may require additional dose management arrangements. These would only be a potential concern if containers from relevant waste streams are disposed, or stored within interim storage warehouses prior to disposal, in locations with direct 'line of sight' to potential off-site receptors.

Subsection 6.4 of the '*Implementation*' report [17] describes the issues and potential responses; a summary follows. The assessments we use are arguably cautious, and the future inventory remains subject to uncertainty. On that basis, we will adopt a flexible approach that includes continuing monitoring to inform on the potential off-site doses from external irradiation, together with working with consignors and analysis of future iterations of the UK Radioactive Waste Inventory (RWI) to refine assessments of inventory projections for relevant radionuclides.

Example approaches for managing higher dose rate future LLW, if it arises, are listed below.

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[83] Current assumptions, for ongoing consideration in optimisation studies including ALARP are as follows [75]. Orientation of the corridors will take into account the minimisation of off-site doses during the brief periods where corridor end-doors are open; the end-doors will only be open during active emplacement processes; removal of the wastes from SWTCs will be undertaken at the corridor location, and placement will be undertaken quickly with appropriate, proportionate shielding measures to minimise doses to workers and others.

- We could adopt an emplacement strategy with higher dose rate containers placed in the centre and bottom layers of warehouses and vaults.
- We could consider locating warehouses out of direct line of sight of receptors, limiting stack height to avoid wastes being in direct line of sight or implementing some form of shielding of wastes in the warehouses if required.
- We could consider increasing the height of future vault walls or adding a separate shielding wall or berm to reduce direct dose, if the forecast increase in activity for future vaults is realised and it is deemed appropriate within wider design optimisation of future vaults.

This could be supported by the use of dose threshold dose-rate values, calculated on the basis of PoA assessments, to inform on whether any of the above controls are required, as uncertainties are progressively reduced.

It is not necessary at this stage to commit to the provision of the above controls. The priority is for ongoing assessment and optimisation. However, the controls listed all represent proportionate measures that could practicably be implemented if requirements arise. On that basis, we argue that there is full confidence that any issues arising can be managed without requiring any overall change to disposal practices or repository design.

7.2.3 Controls on Discharges

The main categories of environmental discharge associated with current site operations, for which controls need to be considered, are as follows:

- solid wastes, dominated by disposals, but also including arisings on site through operations and ongoing decommissioning activities;
- liquid discharges, such as leachate, groundwater, surface water, sewage effluent, and other minor arisings; and
- gaseous discharges and other aerial releases, including gaseous discharges from disposed wastes, other permitted discharges (from the grouting facility and waste store), and dust which may be generated by waste handling, vehicular movement, earthworks, and the disturbance of soils or waste material.

For discharges associated with disposals, the controls are provided by the optimised disposal model, and associated engineering and barriers, as set out in Sections 5 and 6. Discharges associated with other aspects of site operations are subject to controls including:

- physical controls relevant to the category of discharge, such as high efficiency particulate air (HEPA) filters on stacks to limit aerial releases; and
- operational controls, such as working practices to limit dust generation.

These are presented as selected examples. Optimisation of these wider categories of controls is not described further in this document, as arrangements and optimisation arguments are set out in detail in the '*Waste Management Plan*' report [10].

7.2.4 Land Contamination

There is minor land contamination on site arising from operations. Contaminants have both radiological and non-radiological signatures. Land contamination is outside the scope of this document and is covered in the '*Waste Management Plan*' report [10].

7.2.5 Optimisation of Monitoring

7.2.5.1 Monitoring during Engineering Construction

Monitoring during the construction of engineering components is important to demonstrate that they meet design requirements. This includes the potential for remediation or other mitigation actions if deviations are observed. As noted in reference [5]. approaches used during installation of an engineering component will be specific to the design and function of that component.

Option studies have therefore been undertaken to ensure optimisation of monitoring associated with construction activities for the capping programme for Vault 8 and the adjacent trenches. The studies and their outcomes also serve as examples of the general approach. For the capping programme the resulting strategy includes, for example (see references [9] and [87]):

- the use of a cap construction trial, which will inform on construction monitoring as well as construction techniques;
- plans to monitor the Vault 8 and trench surcharge process before cap construction, including the use of defined hold periods at different heights of surcharge fill construction, and approaches such as:
    - surface profile analysis (before and during surcharge, the latter at the defined hold-points) through techniques such as unmanned aerial vehicle (UAV) photogrammetry, total station, laser surface scanning, or Global Navigation Satellite System (GPS) methods involving buried GPS devices;
    - continuous hourly automated data collection, reported at defined periods, from local tilt detection installations (using the LT-Inclibus methodology, which uses chains of gauges separated by rods, installed at appropriate locations), supported by targeted manual readings to check outputs.

7.2.5.2 Monitoring of post-Construction Engineering Performance

Continued monitoring of engineering performance after construction is essential to build confidence in the understanding of performance of the facility, and to inform on requirements for remedial or other mitigating activities in the unlikely event that performance issues are noted. The outcomes of the relevant optimisation studies are reported elsewhere, in references [9] and [87]. The optimised approach includes, for example:

- the continuing use of surface profile analysis and local tilt detection options to track any cap surface movements;

- monitoring of gas evolution through the upgraded interim trench cap, the final cap leading edge and vault seal and trench seal, and the final cap vent, to inform progressively on final cap venting options and decisions on vent closure; and
- the potential for long-term monitoring of the geomembrane evolution through sample exhumation and testing.

7.2.5.3 Environmental Monitoring

Environmental monitoring is essential to demonstrate a robust understanding of the impacts associated with the facility and its disposals, aligned to different release pathways. This includes informing on options to ensure appropriate controls are provided mapped to potential releases from the facility. Monitoring data, and the interpretation of those data through judgements and models, therefore provide important inputs into wider facility optimisation processes, and the validation of outcomes. In turn, our environmental monitoring strategy is itself the outcome of optimisation studies.

The environmental monitoring strategy and its optimisation is described in full in reference [9].

7.2.6 Access Controls

Institutional controls will necessarily continue during repository operations and completion of the closure engineering, reflecting management requirements consistent with its position as an operational nuclear site.

Controls will apply to aspects of the site that continue to be associated with disposals and associated operations. However, aspects of the site could be released from regulatory control ahead of the end of the period of operations under the provisions of the GRR (for example the 'opportunity area' at the south end of the site; see reference [99]). These areas of the site would then no longer require any kind of access controls.

For all areas of the site that remain under regulatory control during the operational period, the site fence and associated security presence will deter unauthorised access and associated activities during this period. In addition, other institutional arrangements, such as NDA's lease on the land immediately coastwards of the site, will contribute to minimising the potential for developments such as groundwater abstraction. Further details of site management arrangements are set out in the '*Management and Dialogue*' report [2] and the institutional control plan [86].

7.2.7 Knowledge Management

One function of institutional control is the retention of key records relating to environmental safety, to inform the approach during institutional control and to provide a lasting societal memory beyond the active institutional control period, to help to continue to minimise the risk of inadvertent human intrusion.[84] Such processes are part of the wider focus on knowledge management including succession planning and the long-term maintenance of suitably qualified and experienced resource. Record management and related activities will support site management as well as contributing to the optimal implementation of controls and associated activities during subsequent periods.

Records management processes will build on existing NWS processes and tools for the management and retention of LLWR records, which are designed to be robust during the institutional control period. Records for the LLWR will be preserved in a range of forms and locations throughout the periods of active and passive institutional control, including NDA's national facility in Caithness, with the intention that they will continue to be recognised as being of value to societal generations. Continuing regulatory and wider stakeholder engagement will also support this aim. Further information is provided in references [2, 86].

7.3 Controls during the Active Institutional Control Period

7.3.1 Introduction

This subsection focusses on controls over the repository and its wastes, during the active institutional control period, that are relevant to environmental safety.[85] In addition, a further aim of this period will be to support final applications for removing the site from radiological substances regulation at the end of institutional control, upon confirmed delivery of the wider Site Reference State. This means that controls that will persist into the passive institutional control period are also discussed here. The controls described will not be required for any area of the site that is subject to early release from regulatory controls.

It is important to recognise that the management controls discussed address a period that will occur many decades into the future, and it would therefore be inappropriate to claim that a final, fully optimised plan is in place. Nevertheless, the material summarised represents a basis for current planning and has been adopted where appropriate in related assumptions for the ESC.

7.3.2 Continuing Controls on Environmental Safety for Key Pathways

During the active institutional control period, a range of continuing controls, established during the repository engineering and closure engineering phase, will provide the basis for ensuring safety.

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[84] Deliberate human intrusion with knowledge of the risks does not require assessment within the ESC. However, knowledge preservation will also assist any future official actors to make informed decisions on any such interventions.

[85] Wider aspects of controls, e.g. relating to other sources of contamination on the site, are discussed in reference [10].

Closure engineering

The optimised disposal model, and in particular the optimised engineering closure design, provides key controls. These include reducing and controlling releases to groundwater and gas pathways, as well as deterring human intrusion, and reducing direct doses through the isolation of the wastes from the environment. These controls will also provide the basis for long-term performance into the passive institutional control phase. Relevant optimisation arguments are summarised in Sections 5 and 6 and are not repeated here.

Access controls and surveillance

Controls will be in place to limit access to areas of the site, save any that are released from regulatory controls in advance of the main Site Reference State being achieved.

Public site access, consistent with the designated next use (recreation and nature conservation), is expected to be allowed from the start of the active institutional control period to promote education and knowledge management within the local community. However, activities that could result in direct exposure to radiological hazards (e.g. human intrusion) will be prevented via planning restrictions, surveillance, landscape features and other appropriate controls. Site markers will be maintained for as long as the site holds a nuclear licence; there are no definitive plans for markers into the longer term, but options will continue to be assessed. Fences may be considered for the purpose of preventing erosion damage to the cap until passive landscape and vegetation features are established. Passive landscaping measures will also be employed. and will be designed to last as long as possible (rather than being constrained by the length of the active institutional control period).

Site surveillance is expected throughout the active institutional control period to help detect and prevent undesirable activities on the site, in parallel with other measures such as planning restrictions and passive landscape features. However, detailed plans on the nature (e.g. site visits, on-site cameras, Unmanned Aerial Vehicle (UAV) surveys) and frequencies of surveillance will be developed later, at the appropriate point. This recognises that state-of-the-art and best practice is likely to have significantly evolved by the start of active institutional control. Another possibility is that, particularly if site-based techniques are used, LLWR and Sellafield could have a shared surveillance service due to their proximity.

Monitoring

The performance of the engineering and wider environmental system will be subject to monitoring up to the end of active institutional control, integrated with wider surveillance and site access controls.[86] Monitoring will address regulatory requirements and provide reassurance the facility is performing safely and as expected. It will also be needed to demonstrate the Site Reference State has been achieved.

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[86] Long-term aspects of monitoring arrangements are described in Subsections 7.2.5.2 and 7.2.5.3.

For some aspects of monitoring, a step change reduction in activity is anticipated once monitoring results are stable and demonstrate the site is evolving as expected. For other aspects, effort may taper if appropriate. Surface infrastructure required for monitoring will be maintained after facility closure for as long as needed, before being decommissioned in advance of delivery of the Site Reference State. Access ways to this infrastructure will be similarly maintained.

A focus of monitoring across all phases will be the continuing reduction of uncertainties, which will be key to informing iterative updates to the institutional control plan and the ESC. As part of this, system performance reassurance monitoring, such as milk, grass and high-volume air sampling, and perimeter dose monitoring will continue, although they will likely be tapered during the active institutional control period. Coastal evolution monitoring will also be a key aspect. References [9], [87] and [86] provide further details.

It is not expected that remedial actions will be required during the active institutional control period, as optimisation arguments and assessments of engineering performance [12] provide substantial confidence that the engineering will provide its functions for a prolonged period beyond the cessation of active institutional control. However, a response capability (as part of the broader arrangements noted in Subsection 7.3.4) will be maintained during active institutional control in order to provide remedial actions in the unlikely event that monitoring reveals the need for such work.

7.3.3 Knowledge Management

Complementing the provision of capability and expertise will be wider knowledge management processes. These will take forward into the active institutional control period, and build upon the approaches for the previous phase (Subsection 7.2.7), in terms of preservation of knowledge and associated long-term records management processes. As part of this, final documentation will be provided to the NDA's national facility in Caithness.

Planning controls and associated legal measures such as land-use covenants are anticipated for the active institutional control period are also expected to extend into the passive institutional control phase. Regulatory and wider stakeholder and community engagement will also be ongoing to the end of institutional control. These approaches will also be used to help maximise the longevity of societal memory and access to information into the passive institutional control phase.

7.3.4 Capability Provision to Support Controls

It is important that capability is retained throughout, to ensure the range of institutional controls identified are provided and maintained until delivery of the Site Reference State.

As part of this, throughout the active institutional control period, a suitably qualified and experienced capability will be maintained to implement the activities required (such as monitoring, knowledge and records management, remedial capability etc) are appropriately supported. This will include iterations of the ESC and associated institutional control plans. Existing NDA strategies and NWS plans and internal procedures are already in place to ensure capability maintenance and succession planning, and these will be subject to further development as appropriate until the end of active institutional control.

7.3.5 Length of the Active Institutional Control Period

A core component of the consideration of options for post-operational institutional arrangements concerns assumptions on the length of the period for which active controls are retained. As for other assumptions on institutional control, approaches do not need to be finalised at this time. However, it is important to identify clear and underpinned assumptions given the influence of the control period on calculated impacts to various pathways.

From the perspective of impacts to potential receptors, these controls necessarily focus on preventing intrusive activities or the use of the cap for subsistence farming (smallholding) arrangements. Iterations of options assessment for the length of the control period (most recently reported in references [86] and [88]) have led to the following outcomes.

- There are a range of comparatively short-lived radionuclides disposed to the LLWR. An institutional control period of around 100 years would ensure that these have decayed to very low levels of activity by the time that unrestricted access is allowed to the site. Whilst the impacts associated with relevant radionuclides would not be substantially increased with a shorter period, the 100-year assumption also has the benefit of ensuring decades of monitoring and reassurance activities prior to the end of controls. Given the expectation that the engineered components will evolve very slowly, a period of this length will provide reassurance that the system is evolving as expected, as well as providing more opportunity to respond to any issues observed. This opportunity would be significantly compromised for a much shorter period. While the costs for a 100-year period will be greater than a shorter period, this potential cost differential is considered proportionate given the benefits gained.
- International good practice and UK regulatory guidance both recognise that it is plausible to assume institutional control periods of up to 300 years. However, from the perspective of environmental safety at the LLWR, longer timeframes are of depreciating additional benefit compared to the 100-year period. The 300-year period would therefore not notably reduce peak calculated impacts compared to a 100-year period, nor would it add notably to reassurance in system performance. However, a 300 year period would involve greater cost [88].

In summary, recent reviews have found no strong reason to change from the previous 100 year assumption, and so this duration is retained for the 2026 ESC.

7.3.6 Site Disruption in the Longer Term

We recognise that no practicable steps can be taken to protect the site in the long term from the expected effects of coastal erosion (reference [8]). In addition we cannot rely on any coastal defences that would need to be maintained beyond the period of active institutional control. In addition, any such measures would need to be part of a regional management plan. On that basis, it is appropriate to assess the impacts of such disruption as part of the anticipated evolution of the facility.

While this situation is unusual for a radioactive waste repository, we observe that in the long term all near-surface disposal facilities are vulnerable to disruption by natural erosion processes, human actions or combinations of natural and human events. This is taken into account by setting limits on the types and activity of waste that may be disposed to a near-surface facility. The key question is whether the potential impacts when erosion occurs are consistent with regulatory guidance levels, that is, sufficiently low.

Coastal defences could be an effective way to prevent erosion over tens to a few hundreds of years. However, rising sea levels are expected to minimise the effectiveness of the coastal defences in preventing coastal erosion. As described in reference [8], it is not considered feasible for us to guarantee protection from erosion over many hundreds to a thousand years using engineered structures, and we cautiously assume no coastal defences will be present in the projected estimates.

This position is consistent with regulatory guidance, which requires the repository to be passively safe without ongoing management and maintenance, including provision of coastal defences. It is appropriate also to assume that any future generation that chooses to implement and maintain coastal defences would implement their own controls to ensure safety.

On that basis, the key measures reflected in the SDP relate to waste acceptance and radiological capacity controls (see Subsection 9.2).

8 Summary of Disposal Model Optimisation Studies Since the 2011 ESC

Previous sections summarise the optimised disposal model for the LLWR, on the basis of work undertaken prior to the 2011 ESC, and since. This work was delivered through a range of studies, undertaken within the framework of the ESC optimisation process, including iteration and alignment steps to ensure consistency.

Key studies are listed below and provide a summary of the main areas of development since the 2011 ESC. The summary is specifically focussed on disposal model optimisation; studies that are tangential, or entirely focussed on other aspects of LLWR operations, are omitted. It is also not intended to be 'complete' in that it focusses on the main, rather than all, optimisation studies.

- A series of studies on the hydrological management of the trenches, concluding with optimisation and design work for the repository development and capping programme [80], leading to the upgrades to the trench cap that are currently being constructed.
- Studies considering the protection of containers from environmental effects in Vault 8 and Vault 9 [73, 74, 75] prior to closure.
- Optimisation studies for the Repository Development programme [66, 67] covering:
    - iterations of optimisation on the approach to Vault 8 closure (leading to decisions including, for example, the surcharge of Vault 8 wastes);
    - the design of the final cap;
    - the approach to the cut-off wall;
    - further confirmation and development of approaches to other parts of the concept (e.g. profile fill, drainage material, ullage void management).
- Consideration of the use of the ‘remaining disposal area’ in Vault 8 for disposals (including the area of the vault floor to the north of the vault that was free from disposals at the time of the study, and the disposal envelope above the existing containers but below the 2 m of profile fill).
- Optimisation of existing and future disposals in Vault 9 and the future vaults [75], including, for example:
    - the approach to different categories of existing and future LLW disposals in Vault 9 and the future vaults;
    - the approach to disposal of any ILW that may be consigned to the vaults.

- A specific options study considering the application of learning from the EPA to the approach to selection of the geomembrane for the final cap [72].
- Review of the optimised approach to institutional control [86].
- Review of the options and arguments for trench management including the potential for retrievals [84].
- Ongoing development of the leachate management strategy, for both pre- and post-closure conditions [63]
- Reviews of the long-term monitoring strategy of the LLWR, its engineering, and the surrounding environment [87].
- Ongoing consideration of potential options for gas venting (Subsection 5.4.1).

9 Site Development Plan

9.1 The Role of the Site Development Plan

As discussed in Subsection 1.2, our Environmental Safety Strategy lays out our approach to achieving the continuing environmental safety of the LLWR disposal facility and site. The Environmental Safety Strategy is the process and means by which we achieve our strategic plans in a demonstrably environmentally safe way. Our Environmental Safety Strategy leads to an optimised SDP. Our SDP can be viewed as our plan for implementing our Environmental Safety Strategy and the way we will ensure environmental protection as the site is developed. In doing so it provides a summary of the optimised disposal model and plans for its implementation.

The SDP forms the basis of our assessments of repository performance, an important part of our demonstration of environmental safety. The LLWR's ESC therefore demonstrates the safety of the SDP.

The ESC and the optimisation studies we have carried out in support of the ESC have played an important role in developing the SDP. It is through these studies that we have determined a preferred set of management and engineering control measures that are consistent with the goal of achieving radiation doses and risks that are ALARA. We have taken into account a range of factors, including the need to ensure adequate protection from the non-radiological hazards presented by the wastes. The optimised control measures form part of our SDP. They also become part of our Environmental Safety Strategy. The ESC thus lays out the arguments that demonstrate that it is an optimised plan.

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

The SDP forms the basis of future development of the site through to attainment of the site reference state, which describes the state of the site when all work involving radioactive substances has ceased and the site is fully compliant with the requirements for release from radioactive substances regulations. The SDP sets out our proposals and assumptions on operations, remedial activities, vault design, capacity and future waste disposal practice, disposal facility closure design, site decommissioning and restoration, and management up to the end of regulatory control. The SDP:

- ensures that management and development of the site is consistent with the requirements of the ESC and optimised;
- provides a high-level framework for continued optimisation of the site.

The SDP is flexible, however, and will be amended as necessary in the light of UK radioactive waste management needs, operating experience, results of monitoring, future iterations of the ESC, regulatory and planning guidance and decisions, and stakeholder views.

Maintenance of our ESC will ensure that a suitable tool continues to be available to support future regulatory and management decisions concerning the facility, and that the SDP continues to provide optimised environmental performance. As an example, we derived an optimised SDP on the basis of work undertaken to develop the 2011 ESC. As we have undertaken work to revise the ESC, we have identified new optimised outcomes on the basis of new understanding, which update the SDP.

The SDP addresses both the disposal facilities and any on-site contamination outside the disposal facilities. The SDP is presented in the following subsections, and we show how the SDP is updated by our optimisation outcomes reported earlier in this report.

9.2 The Optimised Site Development Plan

The SDP covers two main phases of site development, consistent with the timeframes identified in the optimised plan for institutional control (see Section 7 and reference [86]):

- operations and completion of disposal engineering;[87]
- active institutional control (including decommissioning).

We present the SDP we have identified for each phase in the following subsections. This statement of the SDP summarises the optimisation outcomes set out in Sections 5 to 7.

9.2.1 Operations and Completion of Disposal Engineering

During the period of disposal operations, the site is principally focused on the continued safe management and disposal of LLW. LLW operations on the site include all aspects of receipt, treatment and disposal of LLW from UK consignors, as well as on-site generated LLW, ensuring the safe, secure and environmentally compliant management of LLW:

- receipt of LLW for grouting and disposal in licensed packages, from UK consignors, at LLWR by rail or by road;
- general site monitoring, surveillance and operations;
- general monitoring, surveillance and operations of the Drum Store including storage, accountancy, and transport of drums containing Low Activity-LLW, LLW, Plutonium Contaminated Material and Legacy;
- historical waste management and disposal [10].

Data in the UKRWI indicate that waste disposals will continue until around 2135. During the operational phase the site needs to:

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[87] To assist presentation of the SDP and consistent with the approach in Subsection 7.2, these two phases from the institutional plan are here combined.

- maintain its capability for LLW receipt and disposal, including construction of future vaults as required [5];
- continue to manage the aqueous effluent generated from wastes in the trenches and vaults, which is discussed in our WMP [10];
- continue to manage aerial discharges as laid out in our WMP [10];
- manage any solid waste arisings as discussed in reference [10];
- progress the phased placement of a final cap over the trenches and vaults [5].

In the near term, the site is preparing for a major construction phase, with the phased construction of the final cap over Vault 8 and the northern area of the disposal trenches. Subsequent steps will include construction of Vaults 9a and 10, and of the enhanced operational leachate management arrangements including the gravity drain to the seaward side of the vaults.

In the longer term, once filled with sufficient waste, Vaults 9 and 9a will be progressively capped, with leading edges of the cap sealed to ensure the establishment of post-closure conditions. This will likely take place in parallel with continued waste disposal operations in Vault 10. In due course, Vault 10 will be capped and Vaults 11 and 12 will be constructed, filled and capped.

The arisings rates and volumes of waste which will require disposal at the LLWR are uncertain and we have therefore developed a plan that prioritises flexibility with respect to:

- the number of vaults;
- the timing of vault construction;
- the size of vaults.

To achieve this, our approach to future vaults will be modular and, as discussed in Subsection 5.4.6, we will build vault modules on an as-required basis. The size of the modules will be appropriate for the anticipated waste arisings. While we have assumed for ESC purposes that future vaults will occupy the footprint allocated to Vaults 10 to 12, our approach provides flexibility to fill the area currently designated as Vaults 10 to 14 with vault modules if required.

During this phase the plan for the disposal facilities is as follows.

- Trench wastes will be left in situ, with no intrusive remediation. Active leachate management, installation of the final cap and, for the southern portion of the trenches, upgrading of the interim cap, will optimise the long-term environmental performance of the trenches.
- Waste will only be accepted for disposal in the vaults consistent with the requirements of the ESC as presented in reference [17]. Waste will only be accepted for disposal when it shown that it is appropriate to dispose of it in an engineered vault. The capacity of the repository will be managed to ensure it was used optimally.

- On the basis of our understanding of coastal erosion reported in reference [89], we have concluded that we would not dispose large quantities of durable containers in the vaults. This is to minimise adverse effects on the amenity value of Drigg Beach.
- A final cap will be progressively constructed over the vaults and trenches. Eventually, the whole area of the trenches and vaults will be covered by a single gently domed low-permeability engineered cap, designed for stability and resisting erosion and presenting acceptable visual impact. Suitable long-term vegetation cover will be established over the cap area and periphery.
- A passive gas venting system will be incorporated into the final cap to provide confidence that differential pressures will not threaten the performance of the cap as a barrier to infiltration. On the basis of work to examine bulk gas generation, we have identified that there is the potential to require the gas vent to remain open in the long term. It is not necessary at this stage to make a decision regarding vent closure and our approach is flexible. The current vent design is mature and is an appropriate basis to support our gas assessment [90]. We recognise, however, that further optimisation studies will be necessary to ensure that the approach to gas venting will provide both pre-closure and post-closure functions, if required.
- The vaults will step down in the southerly direction following the natural slope of the site and containerised waste will be stacked in the vaults, using as much as possible of the profile volume below the engineered cap.
- In Vault 8, we will not pursue stacking of containers above the existing containers. Similarly stack heights will be limited in the northern portion of Vaults 9 and 9a, which will also be filled with TC01 and TC08 HHISOs. The wastes in Vault 8 and the northern portion of Vaults 9 and 9a will be surcharged prior to cap installation to ensure that the wastes will provide a stable base for cap installation. While this will reduce the barrier the containers provide, this is more than outweighed by increased confidence in long-term cap performance. In Vault 9 and Vault 9a, relevant disposals will be stacked at the northern edge of these vaults and will be closed via an extension of the cap seal over the relevant wastes as soon as practicable after Vault 8 closure. This will provide closure-levels of protection of the wastes as soon as is currently practicable.
- We will develop a new strengthened HHISO design for wastes not yet committed to a disposal container. We assume strengthened HHISO containers will be higher stacked and will be disposed to the southern parts of Vaults 9 and 9a and we expect will comprise the majority of disposals in vault modules associated with Vaults 10, 11 and 12. The top-most container of each stack will be fitted with a CPU designed to protect the vulnerable container lid from the loads which will be imposed during and after cap installation. These containers will not be damaged during, or after, cap installation and will therefore provide an effective barrier to contaminant transport.

- Strengthened HHISO containers will be stored in interim warehouses prior to emplacement in final disposal locations. We assume the interim warehouses will initially be constructed in Vault 10 and will always be one vault module ahead of where disposals are occurring. The warehouses will protect the containers from precipitation and wind-blown chlorides, thus maximising the integrity of the containers and helping to ensure that they will provide an effective barrier to contaminant transport after closure.
- Vault modules will be constructed as needed, filled, closed and capped progressively, at the same time capping over the adjacent strip of trench area. The volume between the current interim cap over the trenches and the final cap profile will be filled with inert materials.
- During operations, leachate from the trenches and rainwater run-off from the open vaults will be managed by collection, monitoring and controlled discharge to the sea via the Marine Pipeline, subject to the requirements of the Permit. The effect of progressive capping will be to reduce infiltration to the trenches and hence progressively reduce trench leachate. It will also minimise the area of open vaults and hence degradation of the waste containers and potentially contaminated rainwater run-off. The use of warehouses to protect waste containers prior to emplacement in final disposal locations will also reduce the volumes of leachate generated.
- In order to promote unsaturated (that is, partially saturated) conditions in the vaults for as long as possible following closure, future vaults will be designed with 1 m-high side walls and will incorporate engineered passive drainage arrangements so that, following final closure, residual infiltration through the cap will be able to drain freely. Drainage arrangements will be put in place in Vault 8 so that leachate is directed to the passive drainage arrangements in future vaults.
- An underground low-permeability cut-off wall will be constructed, integrated with the final cap near its perimeter, and with the existing cut-off wall at the northeast corner of the site. The wall will extend to 2 m below the bases of the vaults. The wall will be of sufficient depth to limit inflow of surface water and shallow groundwater at the level of the under-vault drainage blankets and trenches and outflow of contaminated leachate close to the ground surface near the facility.
- Monitoring will continue during disposal operations, and the subsequent completion of disposal engineering, to meet regulatory requirements and to provide reassurance that the process of engineering construction is consistent with design requirements for performance and associated CQA, and after completion, that repository is performing as expected.[88]

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[88] As discussed in Section 3, and in particular Subsection 3.8.

Potential Modifications to the SDP to Allow Disposal of ILW

The SDP is based upon the disposal of LLW only and does not, therefore, include the provision of capability required for ILW disposal. We are, however, ensuring the SDP provides the required flexibility to accept ILW pending relevant decisions.

If ILW disposal were to be pursued at the LLWR, then the SDP would need to be modified in the following ways.

- We would dispose all ILW in containers sufficiently strong to withstand the loads imposed during and after installation of the final cap. If the ILW were to have external dose rates comparable to those from LLW, the containers would be stacked in the vaults alongside LLW (although stacked separately). The exact stacking arrangements would be dictated by several factors, including operational and nuclear safety case considerations. The topmost container of each stack would be fitted with a CPU to protect the weak lid of the topmost container. Depending on waste receipt rates, containers would be interim stored in temporary warehouses alongside LLW containers prior to emplacement in final disposal locations.
- ILW which gives rise to high dose rates would be disposed in shielded modules which would be constructed as required in Vaults 10, 11 and 12. We would allow for flexibility with respect to the location and size of the shielded modules in the vaults as this offers a means of managing uncertainty in the volumes of waste which may require such shielding. It also provides flexibility in ensuring that operational and post-closure impacts from wastes in shielded modules are ALARA. Bunding or drain arrangements would be used to isolate waters and leachate associated with the shielded module units from those associated with adjoining vault disposal modules for other categories of wastes. This would include intercepting clean waters shed from the unit roofs during the operational period so they do not become leachate. This is consistent with the principle of minimising overall leachate volumes.
- Appropriate measures (e.g., controls associated with the design, protective measures on plant, working patterns) would need to be identified and implemented to ensure that the operational impacts from ILW operations would be ALARP.
- Consideration would need to be given as to whether wastes would require transport in Type B transport containers. If this were to be required, then the site would require the capability of unpacking disposal containers from transport containers. Buffer storage capability may also be required. Our current assumption is this capability will be required.

9.2.2 Active Institutional Control

This includes disposal facility decommissioning, which will occur during the latter part of the active institutional control period.

The reference date by which operations cease and the repository is capped is 2135, followed by 100 years of active institutional control[89]. Active institutional controls ensure that activities are restricted to those demonstrated to be safe: they do not necessarily imply the land cannot be released for alternative uses.

During this period:

- the site will remain under regulatory control;
- there may be measures such as access restrictions, security and surveillance, and fencing;
- active leachate collection and management will continue;
- monitoring to meet regulatory requirements and to provide re-assurance about facility performance will continue;
- the final cap will be maintained and remedial actions for the cap and other components of the system will be taken if required;
- the cap will be managed in accordance with the landscape and ecological management plan to provide a habitat consistent with the next land use;
- infrastructure will be required to support monitoring and the leachate management system;
- the leachate management system, supporting infrastructure and monitoring infrastructure will be maintained.

Prior to release from regulatory control:

- monitoring infrastructure, the leachate management system and any supporting infrastructure will be decommissioned;
- all cap penetrations associated with monitoring will be sealed;
- gas venting arrangements will be sealed if required by the ESC.

These activities will require approval from the regulators and decommissioning plans will need to be developed. The development of any decommissioning plans will need to comply with the arrangements established under Licence Condition 35 and be approved by the Office for Nuclear Regulation (ONR).

During the active institutional control period, arrangements will be put in place to maintain knowledge of the hazardous nature of the facility following final closure. Through

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[89] Note that in our inventory analyses we have assumed, based on the final year in the UKRWI, that disposal operations would cease in 2135, with an assumed period of seven years required to cap Vault 12 and complete installation of the final cap, resulting in a release from regulatory control at 2242. The effect of this discrepancy on assessed impacts and ESC arguments is insignificant. As a live plan, the SSDP retains the flexibility to respond to changes in the operational lifetime of the repository.

consultation, a sustainable use of the site will be established consistent with the long-term environmental safety of the repository. The aim will be to provide a sustainable amenity to the local community and, also, thereby help maintain knowledge of the facility and lower the likelihood of developments or uses that might lead to adverse impacts.

Wastes generated during decommissioning and on-site contamination outside the disposal facilities will be managed in accordance with our WMP [10].

We will demonstrate through our SWESC and WMP that the site will reach its reference state in 2235 and hence will cease to be regulated by an environmental permit. This is currently defined for the whole site but is primarily driven by requirements for the repository.

The designated next use of the site is defined as waste management and recreation and nature conservation. For the disposal facility, at the reference state:

- disposed waste will remain in situ as determined in the ESC;
- the physical state of the repository will reflect the optimised closure engineering described in the ESC.

9.3 Summary

In the preceding sections of this report, we have demonstrated optimisation of the repository and its operations. We have identified a preferred set of management and engineering control measures that are consistent with the goal of achieving radiation doses and risks that are ALARA. We have taken into account a range of factors, including the need to ensure adequate protection from the non-radiological hazards presented by the wastes. As part of this demonstration, the report describes our approach to optimisation including underpinning options processes. Our optimised disposal model incorporates controls relating to:

- controls over waste inventory, including existing and future disposals;
- controls over design and operation; and
- institutional controls.

The outcomes, together with optimised wider controls including those related to waste acceptance, discharges, monitoring, and active and passive institutional controls, as well as providing the plan for ongoing developments that will also be subject to further optimisation, are reflected in our optimised SDP.

Delivery of the SDP as part of the Environmental Safety Strategy will ensure that the optimised controls are implemented. It will also ensure that future iterations of Environmental Safety Strategy will continue to be demonstrably optimised. The SDP therefore provides a framework for continuing, forward-looking optimisation of the repository.

10 References

[1] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Main Report,” LLWR/ESC/R(26)10166, May 2026.

[2] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Management and Dialogue,” LLWR/ESC/R(26)10167, May 2026.

[3] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Site History and Description,” LLWR/ESC/R(26)10168, May 2026.

[4] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Disposal Facility Inventory,” LLWR/ESC/R(26)10169, May 2026.

[5] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Engineering Design,” LLWR/ESC/R(26)10170, May 2026.

[6] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Near Field,” LLWR/ESC/R(26)10171, May 2026.

[7] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Hydrogeology,” LLWR/ESC/R(26)10172, May 2026.

[8] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Site Evolution,” LLWR/ESC/R(26)10173, May 2026.

[9] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Monitoring,” LLWR/ESC/R(26)10174, May 2026.

[10] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Waste Management Plan,” LLWR/ESC/R(26)10176, May 2026.

[11] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Safety Functions,” LLWR/ESC/R(26)10177, May 2026.

[12] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Engineering Performance Assessment,” LLWR/ESC/R(26)10178, May 2026.

[13] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Environmental Safety During the Period of Authorisation,” LLWR/ESC/R(26)10179, May 2026.

[14] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Assessment of Long-term Radiological Impacts,” LLWR/ESC/R(26)10180, May 2026.

[15] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Hydrogeological Risk Assessment,” LLWR/ESC/R(26)10181, May 2026.

[16] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Assessment of Radiological Impacts on Non-human Biota,” LLWR/ESC/R(26)10182, May 2026.

[17] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Implementation,” LLWR/ESC/R(26)10183, May 2026.

[18] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Addressing Regulatory Requirements and Feedback,” LLWR/ESC/R(26)10184, May 2026.

[19] IAEA, “The Safety Case and Safety Assessment for the Disposal of Radioactive Waste: Specific Safety Guide,” Safety Standards Series No SSG-23, STI/PUB/1553, September 2012.

[20] IAEA, “Predisposal Management of Radioactive Waste: General Safety Requiremets,” Safety Standards Series, GSR Part 5, STI/PUB/1368, May 2009.

[21] International Commission on Radiological Protection, “The 2007 Recommendations of the International Commission on Radiological Protection,” *Annals of the ICRP,* vol. 37, 2007.

[22] IAEA, “Disposal of Radioactive Waste,” Specific Safety Requirements No SSR-5, STI/PUB/1449, April 2011.

[23] NDA, “NDA Strategy Effective from March 2021,” SG/2021/48, March 2021.

[24] Environment Agency, “RSR : Principles of Optimisation in the Management and Disposal of Radioactive Waste,” Version 2.0, April 2010.

[25] Scottish Environment Protection Agency, Environment Agency and Natural Resources Wales, “Management of Radioactive Waste from Decommissioning of Nuclear Sites: Guidance on Requirements for Release from Radioactive Substances Regulation,” Version 1.0, July 2018.

[26] Environment Agency, Northern Ireland Environment Agency, Scottish Environment Protection Agency, “Near-Surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation,” February 2009.

[27] Environment Agency, “The Environment Agency’s Assessment of BNFL’s 2002 Environmental Safety Cases for the Low-level Radioactive Waste Repository at Drigg,” NWAT/Drigg/05/001, June 2005.

[28] BNFL, “Drigg Post-closure Safety Case: Overview Report,” September 2002.

[29] BNFL, “Drigg Operational Environmental Safety Case,” 2002.

[30] LLW Repository Ltd, “The 2011 Environmental Safety Case: Main Report,” LLWR/ESC/R(11)10016, May 2011.

[31] LLW Repository Ltd, “The 2011 Environmental Safety Case: Optimisation and Development Plan,” LLWR/ESC/R(11)10025, May 2011.

[32] NDA, “UK Strategy for the Management of Solid Low Level Radioactive Waste from the Nuclear Industry: Strategic Environmental Assessment,” June 2009.

[33] NDA, “Integrated Waste Management Radioactive Waste Strategy,” September 2019.

[34] UK Government, “UK Policy Framework for Managing Radioactive Substances and Nuclear Decommissioning,” May 2024.

[35] UK Parliament, “Energy Act 2004,” c. 20, The Stationery Office, London, U.K., 2004.

[36] H. Cassidy, A. Paulley, D. Collier and H. H. Kozich, “"A Good Decision Is Based on Information, Not on Numbers" - A Process for National Strategic Decision,” in *43rd Annual Waste Management Conference (WM2017)*, Phoenix, Arizona, USA, March 2017.

[37] Nuclear Industry Safety Directors Forum, “Best Available Techniques (BAT) for the Management of the Generation and Disposal of Radioactive Wastes,” December 2010.

[38] ONR, “Safety Assessment Principles for Nuclear Facilities,” 2014 Edition, Rev. 1, January 2020.

[39] UK Government, Department for Energy Security & Net Zero, “Ways of Working - Principles to Guide the Application of ALARP and BAT in the Nuclear Industry,” November 2025.

[40] M. Egan and A. Paulley, “LLWR Pre- and Post-closure Engineering Optimisation Quintessa Report for LLWR Ltd,” QRS-1443O-1 Version 1, August 2010.

[41] A. Paulley, “Generic Overview of the BAT Optimisation Process for RDP,” LLWR/ESC/Mem(19)365, March 2018.

[42] NDA, “The NDA Value Framework,” v2.0, August 2021.

[43] A. J. Baker, “LLWR Lifetime Plan: Managing Existing Liabilities and Future Disposals at the LLWR,” 10001 LLWR LTP, Volume 1, Issue 1, April 2008.

[44] D. Collier, J. Penfold, A. J. Baker and A. J. Wood, “LLWR Lifetime Plan: Assessment of Options for Reducing Future Impacts From the LLWR,” 10002 LLWR LTP Volume 2, Issue 1, April 2008.

[45] Halcrow, “Drigg Engineering Studies – International Overview of Low Level Radioactive Waste Disposal Facilities,” Report prepared for the Low Level Waste Repository, Drigg, U.K., 2003.

[46] IAEA, “Scientific and Technical Basis for the Near Surface Disposal of Low and Intermediate Level Waste,” Technical Reports Series No. 412, Vienna, Austria, 2002.

[47] IAEA, “Considerations in the Development of Near Surface Repositories for Radioactive Waste,” Technical Reports Series No. 417, Vienna, Austria, 2003.

[48] IAEA, “Upgrading of Near Surface Repositories for Radioactive Waste,” Technical Reports Series No. 433, Vienna, Austria, 2005.

[49] IAEA, “Management of Long Term Radiological Liabilities: Stewardship Challenges,” Technical Reports Series No. 450, Vienna, Austria, 2006.

[50] IAEA, “Retrieval and Conditioning of Solid Radioactive Waste from Old Facilities,” Technical Reports Series No. 456, Vienna, Austria, 2007.

[51] L. Williams and A. Proctor, “Low Level Waste Repository (LLWR) Modular Vaults Project: Single Option Selection Process,” British Nuclear Group Project Services Report BNGPS/LLWR/MV/1/003/1, May 2007.

[52] Nuclear Waste Services, “ Disposal System Specification – Part A: High-Level Requirements,” Version 2, 2025.

[53] Nuclear Waste Services, “ Disposal System Specification – Part B: Technical Requirements, Requirements Managed within the Requirements Management Database (RMD),” DSSC-402-01, 2025.

[54] S. G. Higson and R. P. Hows, “Packaging for Transport and Disposal of Low Level Waste at Drigg, International Conference on Engineering Solutions to the Management of Solid Radioactive Wastes,” in *Proceedings of the Institute of Mechanical Engineers*, 12 November 1991.

[55] L. F. Johnson, “Developments in Support of Low Level Waste Disposal at BNFL’s Drigg Site,” in *10th Annual USDOE Low Level Waste Management Conference*, Denver, Colorado, 1988.

[56] Radioactive Waste, “House of Commons Environment Select Committee, First Report,” HMSO, February 1986.

[57] Ove Arup, “Drigg Capping and Drainage Study,” DTP/06, 2000.

[58] Halcrow, “Drigg Engineering Studies: Engineering Options Report,” DTP/035, 2003.

[59] BNFL, “Post-closure Safety Case Report: Engineering Design,” September 2002.

[60] BNFL, “Drigg Post-closure Safety Case: Site Development Plan,” September 2002.

[61] LLW Repository Ltd, “Vault 8 Container Issues Project,” RP/LLWRGR/PROJ/00139, July 2013.

[62] Environment Agency, “Decision Document - Future Regulation of Disposals of Radioactive Waste On/from the Low-level Waste Repository at Drigg Cumbria Operated by British Nuclear Group Sellafield Ltd,” February 2006.

[63] S. Stead, “Leachate Management Strategy (LMS) Position Statement,” LLWR/ESC/Mem(26)491, April 2026.

[64] Development Control and Regulation Committee, “Planning Application for LLW Repository Development,” Application No: 4/15/9012, July 2016.

[65] A. Paulley and M. Nutting, “LLWR Vault 8 Closure Plan: Optimisation Engineering Study Report,” QRS-1719A-1, Version 3.1, March 2015.

[66] LLW Repository Ltd, “Repository Development Programme Overview,” LLWR/ESC/R(20)10115, October 2020.

[67] LLW Repository Ltd, “LLW Repository Development Programme Tranche 1 Project Updated Vault 8 Closure BAT Study: Final BAT Outcomes Report,” LLWR-RDP-T1.00-RP-174-A, March 2021.

[68] Aecom, “LLWR Repository Development Programme – Tranche 1 Design Package 1B Final Cap BAT Outcomes Report,” AEC-RDP-T1.00-RP-51-A, July 2019.

[69] AECOM, “ LLW Repository Development Programme Tranche 1: Design Package 1a - Surcharge and Profile Fill, BAT Outcomes Report,” AEC-RDP-T1.00-RP-026, 2019.

[70] AECOM, “LLW Repository Development Programme Tranche 1: Design Package 8c Void Fill, BAT Outcomes Report,” AEC-RDP-T1.00-RP-039, 2019.

[71] AECOM, “LLW Repository Development Programme Tranche 1: Design Package 1d Cut-off Wall, BAT Outcomes Report,” AEC-RDP-T1.00-RP-025, 2019.

[72] A. Paulley, B. Zhang and R. Jones, “Geomembrane BAT Study Final Report,” LLWR/ESC/Mem(26)492, in preparation, 2026.

[73] J. Shevelan, “Response to Environment Agency Environmental Permit Improvement Condition IC1(a),” LLWR/ESC/R(15)10070, November 2015.

[74] J. Shevelan, “Response to Environment Agency Environmental Permit Improvement Condition IC1(b),” LLWR/ESC/R(15)10071, November 2015.

[75] Nuclear Waste Services, “Evaluation of Near-surface Disposal Options: Optimisation and Engineering of the Vaults,” LLWR/ESC/R(23)10140, August 2023.

[76] LLW Repository Ltd, “The 2011 Environmental Safety Case: Engineering Design,” LLWR/ESC/R(11)10020, May 2011.

[77] LLW Repository Ltd, “Repository Development Programme, Design Package No 1 - Tranche 1 Final Cap, Design Justification Report,” AEC-RDP-T1.00-RP-193, December 2022.

[78] Nuclear Waste Services, “Note for the Record Report in support of the 2026 ESC Development of Repository Topographic Models and Derived ESC Grid Data,” NFR-3409334.01-TECH-00001, Issue 1, March 2026.

[79] Nuclear Waste Services, “Vault 8 Remaining Disposal Volume: BAT Update,” LLWR/ESC/R(23)10136, March 2023.

[80] AECOM, “Aecom, Repository Development Programme - Tranche 1 Design Package 7 - Interim Hydrological Management of the Trenches BAT Outcomes Report,” AEC-RDP-T1.00-RP-052 A 2019, 2019.

[81] A. Paulley and M. Nutting, “Trench Cap Hydrological Management Optimisation: Outcomes of the BAT Review,” QRS-1724A-R1, Version 3.1, December 2015.

[82] K. R. Rowe and S. Jefferis, “Protecting the Environment From Contamination With Barrier Systems: Advances and Challenges,” in *20th International Conference on Soil Mechanics and Geotechnical Engineering*, Sydney, 2022.

[83] Environment Agency, “Review of LLW Repository Ltd's 2011 Environmental Safety Case: Optimisation and Engineering,” Issue 1, May 2015.

[84] Amentum, “LLWR Environmental Safety Case: Assessment of Selective Trench Retrievals,” DEPWMP67_TR02, Issue 1, January 2026.

[85] D. Kirkby, I. Cox, S. Crane and G. Garrard, “Dounreay Low Level Waste Pits Closure Assessment: Options Appraisal Report,” 209894-TR-023, Issue 3, April 2021.

[86] Nuclear Waste Services, “The Institutional Control Plan for the LLWR,” LLWR/ESC/R(25)10162 (In Preparation), 2026.

[87] M. Gran, G. Román-Ross, J. L. García-Siñeriz and A. Perri, “ Approach to Long-term Monitoring, Review of Monitoring at LLWR,” ESC-L2-TO387, Amphos 21 3976_MOPRE_IF_Monit_review_v0. 2025 Draft will be updated and finalised.

[88] J. C. Farrow and J. D. Bedford, “The Institutional Control Period for the LLWR,” 2504-3, Version 1, Draft 2 (In Preparation), October 2025.

[89] S. Stead and P. Tulip, “Disposal of ‘Durable’ Containers in the LLWR Vaults,” LLWR/ESC/Mem(23)443, July 2024.

[90] Nuclear Waste Services, “L3: 2026 Environmental Safety Case: Gas Assessment,” In Preparation, December 2025.

[91] Quintessa, “LLWR 2026 ESC: Engineering Performance Assessment. Vaults and Trenches,” QRS-1895C-PR2 Version 1.6, October 2024.

[92] Aecom, “LLWR Repository Development Programme - Tranche 1: Design Package 1b – Final Cap Detailed Design Cap Resilience Report,” AEC-RDP-T1.00-RP-130 Rev BP1, May 2023.

[93] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Optimisation and Site Development Plan,” LLWR/ESC/R(26)10175, May 2026.

[94] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Near Field,” LLWR/ESC/R(26)10171, May 2026.

[95] LLW Repository Ltd, “Stored Wastes and Emplacement Strategy Assessment,” LLWR/ESC/R(15)10064, Issue 2, March 2016.

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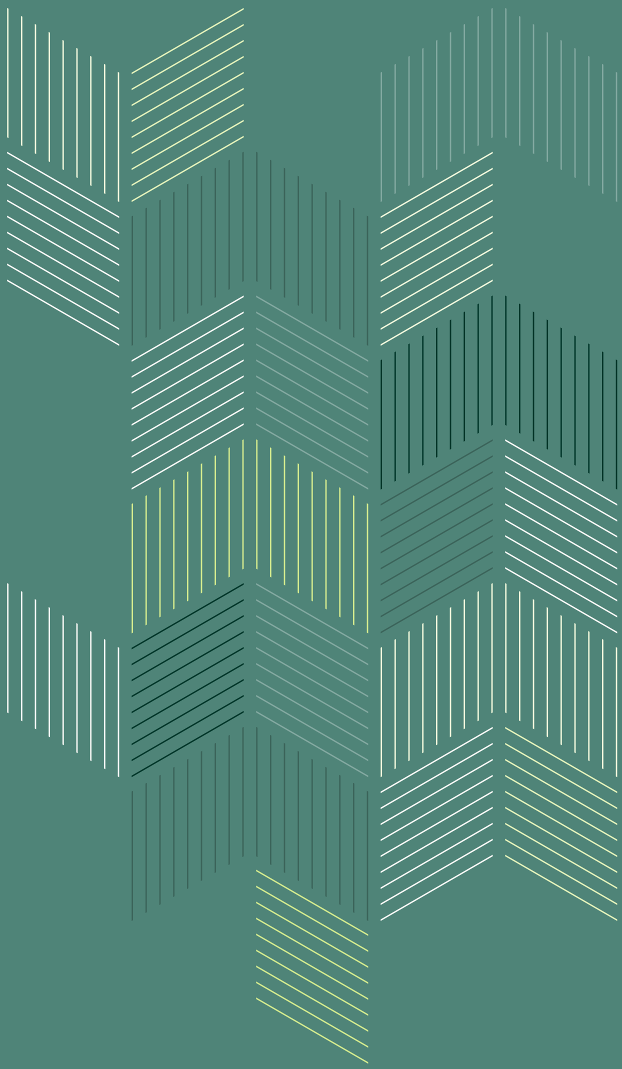

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