Nuclear Waste Services

ENGINEERING PERFORMANCE ASSESSMENT

2026 Environmental Safety Case for the LLWR

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Preface

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

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

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

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

The 2026 ESC consists of documents at two levels:

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

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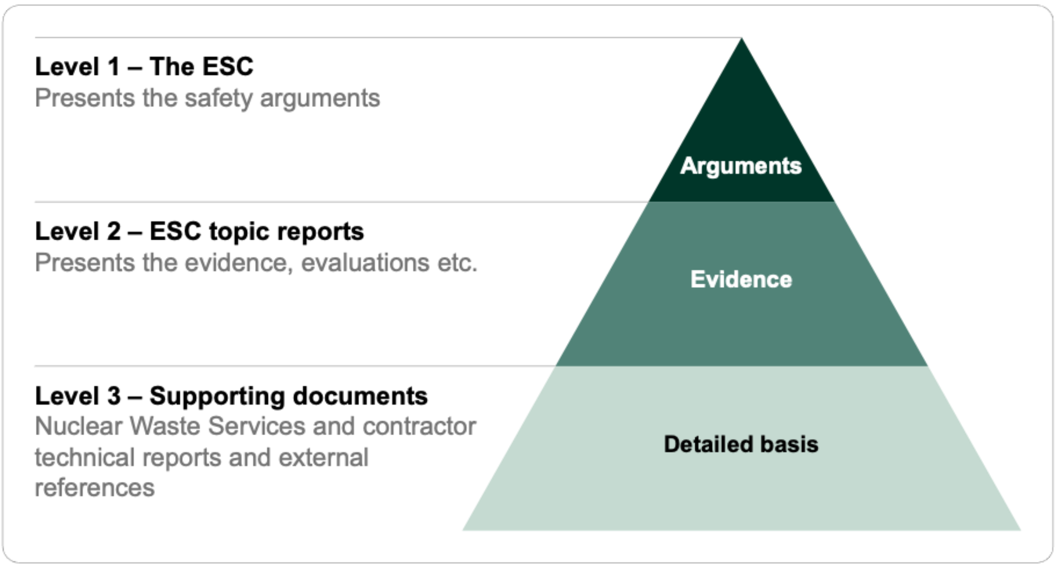
[1] In government policy, LLW is defined as radioactive waste having a radioactive content not exceeding four gigabecquerels per tonne (GBq t^{-1}) of alpha or 12 GBq t^{-1} of beta/gamma activity.

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



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

Near Field [6]	Describes our understanding of the chemical and physical evolution of the engineered disposal system
Hydrogeology [7]	Describes our understanding of the geology and hydrogeology of the site
Site Evolution [8]	Describes our understanding of how the site will evolve, with a focus on coastal erosion
Monitoring [9]	Presents our programme of environmental monitoring supporting the ESC
Optimisation and Site Development Plan	
Optimisation and Site Development Plan [10]	Describes our approach to optimising the design and management of the disposal facility and wider site, and sets out our Site Development Plan
Waste Management Plan [11]	Presents our plans for managing the wastes produced by previous uses and operation of the site
Assessments	
Safety Functions [12]	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 (this report)	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

This report presents the Engineering Performance Assessment (EPA) for the 2026 ESC. The EPA is an important part of our assessments. It describes:

- the nature of the key engineering components that provide environmental safety;
- conceptual models of the evolution and performance of each key component and the whole repository;
- evolution of the properties of the key engineering components, and calculated rates of infiltration through the final cap.

The conceptual models, component properties and cap infiltration rates are important inputs to ESC calculations of biogeochemical conditions, water levels and flows in the repository, and assessments of the transport of radionuclides and non-radioactive contaminants in water and gas (pathway assessments).

The EPA assesses the evolution and performance of the engineering throughout the lifetime of the repository, until it starts to be disrupted by coastal erosion. It does not assess the impacts of coastal processes and erosion on the performance of the engineering in areas still to be eroded. However, the EPA assessment timeframe is comparable to the longest projected timescales for complete disruption of the repository by coastal erosion. Therefore, the EPA does provide high-level insight into the performance of the remaining areas of the eroding repository at the level of detail needed by our assessments.

Repository optimisation, engineering design, the EPA, and assessments of the potential environmental impacts of the repository have been developed iteratively and integrated. This process will continue in the future.

Development of the EPA

Development of a formal EPA for the 2026 ESC started in 2015. The EPA builds on the assessment of engineering performance undertaken for the 2011 ESC, which principally comprised elicitation of the evolution, performance and properties of key engineering components and modelling water levels and flows within the repository.

The EPA has been developed using a systematic, five-step approach, to provide a comprehensive analysis of the evolution of the key engineering components and the whole repository.

1) Identification of conceptual models for plausible modes of the evolution of each engineered component.
2) Generation of supporting information concerning the evolution of components.
3) Understanding the consequences of component evolution and degradation.
4) Identification of interactions and correlations between components, and alignment of system performance.

5) Quantification of performance.

Reference and alternative conceptual models of evolution are described in different engineering evolution cases. Low likelihood and implausible 'what-if' cases are also considered. Iteration has been undertaken at each step of the process as needed.

The conceptual models describe the evolution of and performance of the key engineering components and the whole repository. The conceptual models for the individual components and the whole repository have been aligned so they are consistent. This has been done by considering interactions between components and feedback between conditions in the repository and degradation of the components.

The EPA has been developed by a multidisciplinary team, including experts in repository and landfill engineering and construction. Important insights were provided by our optimisation work, which considers the performance of many options in detail, and describes the arguments for our preferred options. The team also drew extensively on literature information and data, their experience and, where appropriate, models to develop understanding of component evolution and to parameterise performance.

Confidence that the EPA describes the credible envelope of potential evolutions and the performance of the repository is provided by:

- a systematic and comprehensive approach;
- iterative development;
- the range of modes of evolution considered;
- use of a multidisciplinary team;
- the amount of literature review and analysis conducted;
- the large number of multidisciplinary workshops;
- audit against the full EPA undertaken for the 2002 Post Closure Safety Case.

The envelope is expected to capture remaining uncertainties in the rates of processes and the effects of interactions.

Conceptual models and parameterisation of performance

Engineering components are expected to perform as designed during the Period of Authorisation (PoA). At the end of the PoA, management controls will be withdrawn, and the system will function passively. The condition and performance of the system at the end of the PoA are important as this will affect long-term evolution and performance.

The engineered barriers will slowly degrade over time and performance will decrease. The condition and performance of the engineered barriers become increasingly uncertain with increasing time after the end of the PoA. Therefore, although the EPA considers the whole lifetime of the repository, the focus is on the post-PoA period.

Post-PoA, the key engineering components are:

- the final cap;
- passive drainage features;
- the cut-off wall.

The aims of these components are to:

- reduce infiltration into the repository as much, and for as long, as can reasonably be achieved;
- passively drain infiltration out of the bases of future vaults to:
    - keep the waste dry;
    - minimise water contact with the waste;
    - prevent water levels in the repository rising to the point where leachate discharges to surface soils and shallow groundwater at the perimeter of the cap.

The final cap is the most important engineering component. It reduces rates of infiltration into the repository to very low levels. This reduces leaching from the waste, degradation of the containers, waste and other engineered components, and minimises the potential for clogging of passive drainage.

In the vaults, the permeability contrast between the containers and the granular void fill between the container stacks will direct infiltration down the gaps between the container stacks and away from the waste. Passive drainage features provide routes for infiltration to drain downwards and out of the bases of the future vaults. The cut-off wall works with the drainage features by resisting lateral flows out of the repository but also resisting lateral inflows which might interact with the waste and would use some of the drainage capacity.

Cap

Profile material will be placed on top of the waste, and then the cap will be constructed on top of the profile material. The profile material gives the cap the desired shape and protects the cap layers from strains generated by settlement of the waste. General settlement is expected across the whole repository. Differential settlement may occur in locations where a material that degrades and compacts is next to a material that does not degrade and compact or degrades and compacts much more slowly (e.g. over a hard point). Differential settlements generate strains that could damage the cap, potentially including shearing of the cap layers.

The potential for settlement to damage the cap has been a key focus of our design and optimisation work. We are confident that the maximum plausible strains resulting from settlement of the waste would not damage the cap. Therefore, the EPA has focused on understanding the long-term performance of the cap layers. The final cap is a multi-layer, multi-barrier design. The key layers for preventing infiltration are the low permeability layers and the overlying drainage layers. The low permeability layers comprise a geomembrane and underlying Bentonite-enhanced Sand (BES) layer. Together the low permeability and overlying drainage layers resist infiltration and direct (shed) water sideways to the perimeter of the cap.

The geomembrane is a 2 mm thick sheet made from High Density Polyethylene (HDPE). It is supplied in rolls, so the layer is formed by strips which are welded together at their edges. Manufacturers include antioxidants in their geomembrane formulations to resist oxidation and embrittlement, maintaining the strain tolerance of the geomembrane. Consistent with literature conceptual models for geomembrane failure, once antioxidants have been depleted, we expect the geomembrane will become brittle, stress fractures will develop and the geomembrane will fail. Literature data show the time to loss of antioxidants, quickly followed by oxidation induction, and then failure of the geomembrane is strongly dependent on temperature, with degradation occurring faster with increasing temperature. A large body of research and field evidence developed over the last decade and more shows that in the low temperature, low strain, chemically inert environment of the LLWR cap, the geomembrane should remain intact for hundreds of years to a few thousand years.

HDPE is impermeable, so water will only be able to pass through defects (small holes) in the geomembrane. These may arise from manufacturing defects (pin holes) and damage during installation (small holes, tears, and defects in the welds between strips of geomembrane). Construction management and construction quality assurance (CQA) are key to the 'as built' condition and performance of all the cap layers, but particularly the cap geomembrane. We have considered construction risks and how they could be mitigated, capturing good practice guidance and learning from experience, to understand the quality of installation that can be achieved. We expect to achieve a good quality installation, but it is not plausible the geomembrane will be free from manufacturing or installation defects.

BES has low permeability (provided by the bentonite) and favourable geotechnical properties for cap stability (provided by the sand). The BES resists flow of water through small holes in the geomembrane. Once the geomembrane has degraded and failed, the BES will still be a good barrier to infiltration.

The permeability of the BES increases through cation exchange and washout of the bentonite. Under dry conditions the BES can crack, although cracks will largely self-heal through swelling when water becomes available and the BES rehydrates. The geomembrane protects the BES from water loss, cation exchange and washout, so the geomembrane should be in good condition and still performing well when the geomembrane fails. Degradation of the bentonite is expected to be slow, due to the low permeability of the material, with cation exchange being a largely diffusive process, and washout slowly progressing downwards from the upper surface of the BES layer.

Logical arguments and field experience reported in the literature agree that the combined performance of a geomembrane and a BES layer is greater than the summed performance of the individual layers.

We have undertaken an extensive elicitation exercise to quantify probability density functions (PDFs) for the types and prevalence of defects that may be present in the geomembrane, and the hydraulic conductivities of the BES and drainage layers, 'as built' and at later times. Modal input parameter values assume good CQA, and the types and numbers of defects that are consistent with this.

We have also elicited PDFs for the time to loss of antioxidants from the geomembrane and the time to complete failure of the geomembrane. The best estimate lifetime of the geomembrane is 1,800 years, which is similar to the longest projected timescale for start of disruption of the repository by coastal erosion. Therefore, the geomembrane is more likely to be intact and functioning well than failed when the repository starts to be disrupted by coastal erosion.

These datasets have been used to undertake probabilistic calculations of the distributions of potential cap infiltration rates as built and at later times. The resulting distributions are bimodal, with a range of lower rates of infiltration while the geomembrane is intact, and a range of higher rates of infiltration when the geomembrane has failed. Over time, the most likely infiltration rates shift from the lower distribution to the higher distribution as the probability of geomembrane failure increases.

Over the full assessment timeframe, the range of potential infiltration rates varies from very low to 100% of hydrologically effective rainfall (HER). The latter is unrealistic as there are strong arguments the cap will not be substantially eroded before it is disrupted by coastal erosion, so a substantial portion of HER would drain to streams via interflow, and at certain times of the year potentially also by overland flow. The calculated mean infiltration rates with the geomembrane intact are very low.

Passive drains

Passive drainage features will be constructed from inert, strong, coarse aggregate, so clogging is the only process that could impact their performance. We have undertaken an extensive search for literature on clogging in potentially analogous facilities such as conventional landfill sites. The literature focuses on sites where extensive clogging has been observed, and related supporting research. None of the sites and associated studies considered systems that are directly analogous to the LLWR. Nevertheless, the review provided confidence that, while localised clogging may occur, it is unlikely that any of the laterally extensive features associated with water flows and drainage within the system will be significantly negatively affected by clogging.

Given the limited applicability of literature to the LLWR, we have developed additional lines of reasoning reflective of LLWR conditions. We have used logical arguments, simple calculations, and complex models using the BioClog program to understand the potential for physical, chemical and biological clogging, and the coupled impacts of these processes. Our analyses all indicate the potential for clogging is low, due to the engineering design which provides large areas and multiple pathways for drainage, the chemical conditions which are not conducive to precipitation and chemical clogging, and the nature of the wastes, which have limited organic content and therefore limited potential to support biological clogging. Low rates of infiltration are also beneficial as they limit the potential fluxes of suspended solids, solutes and dissolved organics into the drainage features. Overall, we conclude that the hydraulic conductivity of the passive drainage system will evolve very little up to the time of facility disruption.

Cut-off wall

The cut-off wall is made from a cement-bentonite mix, which gives a low permeability material. The wall is expected to slowly degrade through loss of cement minerals, cation exchange and washout of the bentonite. The hydraulic conductivity of the wall is expected to increase as it degrades. The low hydraulic conductivity of the wall means degradation should be slow, with loss of cement and cation exchange of the bentonite being largely diffusive processes. Any washout of bentonite is most likely to occur from the outer surface of the wall. The hydraulic conductivity of the cut-off wall is expected to remain lower than the lateral hydraulic conductivity of the adjacent ground through the assessment timeframe.

Other components

We have also conceptualised degradation of the vault bases and walls and developed PDFs for the hydraulic conductivities of these components as built and at later times. The vault bases and walls have less impact on the post-PoA engineering performance than the final cap, passive drains, and cut-off wall. The vault bases and walls are primarily important during the PoA for operations and capturing leachate, however their continued presence will affect water levels and flows within the repository post-PoA.

The bases and walls are constructed from several sub-components made from different materials. Hydraulic conductivity PDFs have been developed for each sub-component, so assessment modellers have the choice of representing each sub-component explicitly or calculating upscaled conductivities for the whole component.

Conclusions

The EPA provides substantial confidence the engineering should perform well throughout the assessment timeframe. Confidence is provided by:

- use of a systematic approach with integration and iteration at appropriate points;
- development of the EPA by an experienced multidisciplinary team;
- extensive use of literature resources such as good practice guides, data and potential analogues, including resources developed by the Environment Agency;
- interactions with other radioactive waste management organisations and direct experience from contractors involvement in their programmes;
- application of a wide range of calculations and models to develop understanding and help quantify performance.

This is reflected in the reference engineering evolution case, which describes our best estimate of evolution and performance. Alternative engineering evolution cases, and cap infiltration and component hydraulic conductivity PDFs, provide the information needed to explore the implications of uncertainty in engineering performance in our pathway assessments. The engineering evolution cases need not necessarily correspond on a one-to-one basis with pathway assessment calculation cases. However, they inform the pathway assessment calculations, which also consider a wider range of factors.

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1 Introduction

The Low Level Waste Repository (LLWR) provides 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.

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The 2026 ESC consists of documents at two levels.

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

This is a Level 2 report.

1.1 Objectives

This report presents the Engineering Performance Assessment (EPA) for the 2026 ESC. In this subsection we describe the role and content of the EPA. Then we describe how it fulfils Environment Agency requirements and addresses Forward Issues (FIs) identified by the Agency in their review of the 2011 ESC.

1.1.1 Role and Content of the EPA

The EPA is an important part of our assessments. It describes:

- the nature of the key engineering components for environmental safety;
- conceptual models of the evolution and performance of each key component and the whole repository.
- evolution of the properties of the key engineering components, and calculated rates of infiltration through the final cap.

The conceptual models, component properties and cap infiltration rates are important inputs to ESC calculations of biogeochemical conditions, water levels and flows in the repository, and assessments of transport of radionuclides and non-radioactive contaminants in water and gas. The EPA only provides some of the parameter values for ESC calculations. Outputs from our biogeochemical and flow models feed into our assessments and back into the EPA.

Parameter values derived in the EPA are consistent with the conceptual models of engineering evolution and performance. The parameter values are underpinned by multiple lines of evidence. The values and their justification have been agreed through detailed elicitation exercises and review workshops, involving experts in a range of relevant disciplines.

The EPA provides an important step from optimisation [10] and engineering design [5] to assessments of the potential environmental impacts of the repository. The EPA feeds back into ongoing optimisation and design work (e.g. specifications for the cap geomembrane [19]), and repository operations (e.g. operational container protection). Our near-field [6], groundwater [7], and assessment work [14] also feed back into the EPA, repository optimisation and engineering design. For example, pH conditions, container corrosion rates and potential for stack settlement, and requirements for long-term management of cap gas pressures.

Development of the EPA

The EPA has been developed using a systematic, five-step approach (Figure 1.1), to provide a comprehensive analysis of the evolution of the key engineering components and the whole repository.

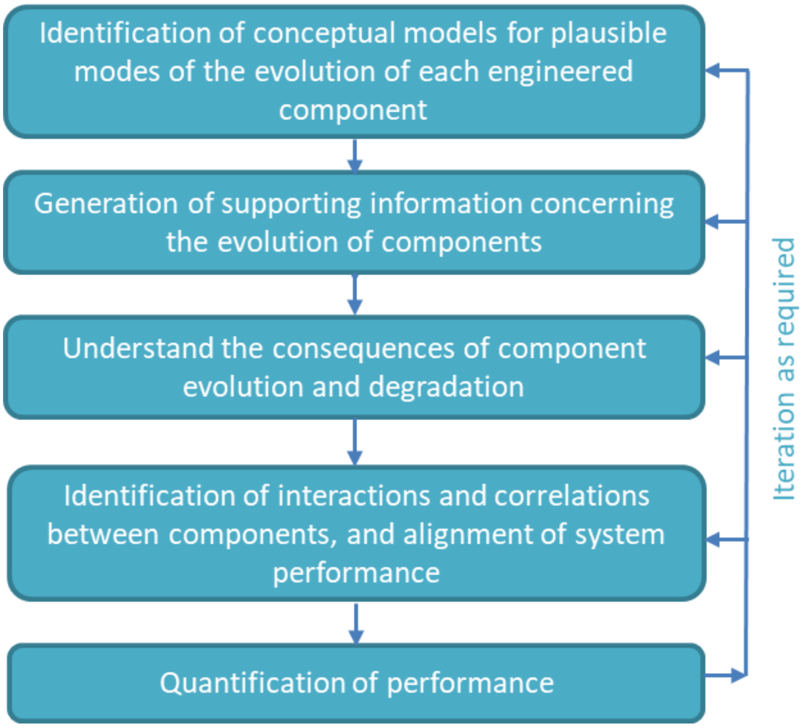

Figure 1.1: The five-step approach to developing the EPA

Evolution and performance of the engineered components is uncertain. Uncertainty increases with time into the future. An important objective of the EPA is to explore these uncertainties. Reference and alternative conceptual models of evolution are described in a suite of engineering evolution cases. Low likelihood and implausible 'what-if' cases are also considered. Iteration has been undertaken at each step as needed.

By systematically exploring uncertainties we ensure the EPA describes the credible envelope of potential evolution and performance. This gives us confidence that we have captured the main modes of evolution of the system, and less likely alternatives, and fed this understanding into our assessments.

The EPA has been developed by a multidisciplinary team, including experts in repository and landfill engineering and construction. Important insights were provided by our optimisation work [10], which considers the performance of many options in detail, and describes the arguments for our preferred options. The team also drew extensively on literature information and data, their experience and, where appropriate, models to develop understanding of component evolution and to parameterise performance. The approach and its implementation are described in more detail later in this report (Section 4).

Repository optimisation, engineering design, the EPA, and assessments of the potential environmental impacts of the repository have also been developed iteratively. This process will continue in the future. The first iteration of the EPA [20] followed the five-step process (Figure 1.1), while the latest iteration [21] focused on updating the engineering evolution cases and quantifying performance (step 5), without repeating some of the early steps to develop conceptual models and cases. In this report, we follow the full five-step process to set out the basis for how we expect the engineering to evolve and perform. To simplify the narrative, this report focuses on the reference engineering evolution and performance. More detail on alternative evolutions is proved by reference [21]. The relationships between optimisation, engineering design, the EPA and our assessments are described in more detail in reference [10].

Wider objectives

The EPA fulfils wider objectives and provides additional benefits.

- We have used the EPA to integrate understanding relevant to engineering performance from across the ESC in a single place, and to provide relevant feedbacks.
- Integration enabled us to identify gaps in information or understanding which were then addressed to the level needed for the 2026 ESC.
- We have used an approach that ensures our understanding of the evolution of the individual key engineering components and the whole system is aligned and consistent.
- The EPA outcomes help articulate our overall views on engineering performance and evolution, and the remaining uncertainties.

1.1.2 Fulfilling Environment Agency Requirements

The LLWR is regulated by the Environment Agency under Schedule 23 of the Environmental Permitting (England and Wales) Regulations 2016 (EPR 2016). Submission of the ESC is a requirement of the site's Permit. Guidance on the specific regulatory requirements relevant to near-surface disposal of solid radioactive waste is set out in the environment agencies' Near-surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation (the GRA) [22].

Development of an EPA is not an explicit requirement in the GRA. However, the EPA plays an important role in addressing GRA requirements. For example, paragraph 7.2.8 in the GRA states,

> *' After the period of authorisation and while any significant hazard remains, the environmental safety case should explore the consequences not only of the expected evolution of the disposal system, but also of less likely evolutions and events…'*

The EPA fulfils this requirement by describing the reference evolution of the engineering and less likely evolutions and events. The EPA also helps to fill the wider requirements of the GRA to identify and evaluate the potential implications of uncertainties in assessments. The approach to treating uncertainties in the EPA is consistent with the requirements of the GRA.

GRA requirements that are fulfilled in whole or in part by the EPA are listed in Table 1.1 (also see reference [18]).

Table 1.1: Mapping GRA requirements to the EPA

GRA paragraph	GRA Requirement	Role of the EPA
6.2.17	Lessons should be learned from internal and external sources to assure continuous improvement in all aspects that affect environmental safety.	The EPA captures learning from earlier iterations of our own assessments and from other facilities and research programmes, particularly relating to cap performance and longevity.
6.2.31	All engineered measures will degrade with time, and this should be recognised in the environmental safety case.	Degradation of engineered measures with time is recognised in the ESC and is accounted for in our models used to assess the long-term performance of the disposal system. The EPA provides conceptual models of engineering evolution and barrier degradation, and parameter values to inform our long-term assessments.
6.4.24	At the design stage, and periodically during the lifetime of the facility, demonstrate that it is possible to close the disposal	The EPA considers redundant operational engineering that will remain at closure and presents arguments that

GRA paragraph	GRA Requirement	Role of the EPA
	facility and, where relevant, seal any preferential pathways that will or may be introduced as a result of the siting, construction and operation of the disposal facility.	these features will not impact long-term performance.
7.2.1(a)	The environmental safety case should demonstrate a clear understanding of the disposal facility in its geological setting (‘the disposal system’) as it evolves.	The EPA describes evolution and performance of the repository engineering, including interactions between the engineering and the geological setting.
7.2.8	After the period of authorisation and while any significant hazard remains, the environmental safety case should explore the consequences not only of the expected evolution of the disposal system, but also of less likely evolutions and events.	The EPA describes a reference engineering evolution case and uncertainties within the bounds of that case that are of equal likelihood; alternative cases which consider evolutions and events that are less likely; and 'what-if' cases which consider evolutions and events that are very unlikely or implausible.
7.3.3(a)	The environmental safety case should include an explanation of, and substantiation for, the environmental safety functions provided by each part of the system. It should also identify which radionuclides each function is relevant to and the expected time period over which the function is effective.	The safety functions provided by the repository are described in reference [12]. Many of the safety functions are provided by the waste form (outside the scope of the EPA) and the repository engineering. The engineering provides multiple safety functions. The EPA implicitly describes how the safety functions provided by the engineering will evolve, and parameterisation of the performance of some of the functions.

The 2011 ESC considered how the engineering would evolve. Engineering properties were elicited during workshops involving experts in a range of relevant disciplines [23]. However, a formal EPA was not developed as part of the 2011 ESC.

We decided to develop the elicitation into a full EPA for the 2026 ESC to fulfil the objectives described in the previous subsection (1.1.1). In parallel, the Environment Agency completed their review of the 2011 ESC, which raised Forward Issues (FIs) and gave recommendations for future developments to the ESC. The FIs are areas of work where the Environment Agency saw scope for continued improvement in the ESC and its implementation [24]. The EPA contributes to addressing FI-026, which includes development of a proportionate EPA, and FI-027, which requires further assessment of the performance of the capping system. These two FIs, and how they are fulfilled, are further discussed in reference [18].

1.2 Scope

The EPA considers the evolution and performance of the key components of the repository engineering. The key components include barriers that act to isolate and contain radioactive and non-radiological contaminants in the waste. The EPA only considers natural evolution of the components. Human actions that might impact the components are addressed in references [14] and [25]. Performance includes the thickness and stability of the barriers isolating the waste from the environment, and hydrological performance of the barriers to contaminant migration. The EPA does not include other aspects of the LLWR site engineering that are needed to operate the repository, e.g. site rail sidings and roads, waste handling facilities, utilities, etc.

The EPA considers the engineering performance during and after the Period of Authorisation (PoA). The PoA includes disposal operations, progressive installation of closure engineering as vaults are filled, and a period of active institutional control (including ongoing monitoring and maintenance) following closure of the final vault. At the end of the PoA the Permit will be surrendered, and the repository will no longer be under active institutional control.

As part of work to develop 2026 ESC, we have reviewed our plans for active institutional control. Considering the outcomes of the EPA, our assessments, and other factors, we have concluded that active institutional control should last for 100 years following closure of the last vault, consistent with our earlier plans [10].

The engineering is expected to perform as designed during the operational phase, and there is expected to be limited degradation by the end of the PoA. However, the condition of the waste and engineering components at the end of the PoA is important as this will affect their long-term evolution and performance.

Post-PoA the engineering will function and evolve passively. The condition and performance of the engineering become increasingly uncertain with time into the future. Therefore, the focus of the EPA is on the long-term (post-PoA) evolution and performance.

The repository is located close to the coast, which is slowly eroding. Even without climate change and associated relative sea-level rise, the repository is expected to be disrupted by coastal erosion. Climate change and sea-level rise are expected to increase the rate of coastal erosion. However, future global greenhouse gas emissions, climate change, sea-level rise and response of the coastal system are uncertain. The repository is expected to be disrupted by coastal erosion on a timescale of several hundred to a few thousand years after present, with erosion of the repository being complete within one to a few thousand years after present [8]. The end point for the EPA is the time when the effects of sea-level rise and coastal erosion start to disrupt the engineering.

While the repository is being eroded, the engineering will continue to reduce the potential environmental impacts from the areas of the repository inland of the erosion front. For example, the final cap will continue to isolate the waste from people and biota using the area inland of the erosion front. The EPA considers timescales comparable to the longest projected timescales for complete disruption of the repository by coastal erosion, to inform assessments of the potential environmental impacts from the remaining area of the eroding repository at an appropriate level of detail.

The optimised engineering design developed for the 2026 ESC [10] [5] is the basis for the EPA. The EPA was frozen in November 2024 to feed into assessments of the potential environmental impacts of the repository. Design and optimisation work has continued post-November 2024, for example reference [19], and will continue after submission of the 2026 ESC. The EPA will therefore continue to be updated and further developed in the future.

Design developments post-November 2024 are generally detailed in nature, so they do not significantly affect the EPA presented in this report or our assessments for the 2026 ESC. The only significant development is recognition (by our assessments) that long-term gas pressures in the repository could be higher than considered previously [26] [6]. This might affect our approach to long-term gas management. The issue is described in detail in reference [10] and is summarised below.

Our closure engineering design [5] includes a gas vent at the apex of the final cap. The reference assumption in the 2011 ESC was that the vent would be closed at the end of the PoA. However, the possibility of leaving the vent open at the end of the PoA for long-term management of gas pressures was retained. It was recognised that monitoring evolution of the waste and gas production during the PoA would provide the best evidence to underpin a decision.

Our reference assumption, and approach to deciding whether to closure the vent, are unchanged for the 2026 ESC. Our assessments have considered cases where the vent is closed at the end of the PoA (reference case) and left open (variant cases) where this uncertainty is important [26].

Given the recognition that long-term gas pressures in the repository could be higher than considered previously, we are considering further work to optimise our approach to managing bulk and trace gases generated in the repository, and design of gas management features. Arguments on safety in the 2026 ESC are not contingent on the outcomes of this work, so it is scheduled as a continuing ESC activity consistent with the principles of ongoing optimisation.

1.3 Structure

This report is structured as follows:

- Section 2 provides additional background information. It describes key features of the LLWR site and its anticipated future evolution.
- Section 3 provides an overview of the engineering design.
- Section 4 describes our approach to developing the EPA.
- Section 5 presents conceptual models describing the evolution and performance of the key engineering components and the properties of the components for future timeframes.
- Section 6 describes the reference conceptual model of evolution of the whole repository.
- Section 7 summarises the outcomes of the EPA and changes compared with the 2011 ESC.
- Section 8 looks ahead to future iterations of the EPA.

2 Context

In this section we provide additional background information which gives important context to the EPA. This includes the history of development of the EPA, key developments affecting the repository design and development plans, and aspects of the site setting and evolution that affect the engineering design, evolution and performance.

2.1 History of Development of the EPA

Environmental safety assessments for the LLWR have been developed and updated over several decades. Earlier assessments predated the current GRA and the concept of an ESC. Major updates to the environmental safety assessments were submitted to the Environment Agency in 2002 [27] and 2011 (the 2011 ESC [28]), with ongoing maintenance, development and update between submissions.

An EPA was developed as a component of the 2002 Post-closure Safety Case (PCSC) [29]. The EPA included:

- Detailed fault and event trees describing how degradation or failure of one engineering component could affect other components.
- Conceptual models exploring best estimate, upper and lower bound performance of individual engineering components and the whole repository.
- Cap infiltration calculations for best estimate, upper and lower bound cap properties using the hydraulic evaluation of landfill potential (HELP) model. Cap properties were elicited by experts in landfill capping.
- Parameter values for the properties of other engineering components, elicited by experts in a range of disciplines.

The cap infiltration rates and component properties were used in assessment models to calculate flows in the repository. The results were fed back into the conceptual models and parameter values, and the process iterated until the conceptualised and calculated flows broadly aligned. Flows were calculated for best estimate, upper and lower bound engineering performance cases. Potential environmental impacts were then calculated for these cases [30].

Evolution and performance of the engineering was an important part of the 2011 ESC, but a full EPA was not developed. The assessment included a formal elicitation of cap performance and infiltration rates, and engineering component evolution, performance and properties [23]. The outcomes of the elicitation were fed into groundwater flow models to calculate heads and flows in the repository, and assessment models to calculate the potential environmental impacts of the repository [31].

Following the 2011 ESC, we identified that a formal EPA would be required to underpin the claims, arguments and assessments in the next major review of the ESC. In parallel the

Environment Agency raised the FIs discussed previously (Subsection 1.1). Development of a formal EPA for the 2026 ESC started in 2015.

2.2 Key Developments

The optimised repository design and development plans have changed since the 2011 ESC. Changes have occurred in response to major developments in waste treatment and diversion, changes to Government policy, changes to the amounts of waste producers are generating and the types of waste they are managing, monitoring results and ongoing development and optimisation of the engineering design. The main changes are described below.

- The NDA asked us to explore options for disposing of Intermediate Level Waste (ILW) at the LLWR site, in line with Government policy to consider alternative options for the management of ILW [32]. The 2026 ESC explores the potential impacts of disposing certain, less hazardous, ILW in the repository. This provides a basis to engage with the regulators and other stakeholders 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. The engineering design for the 2026 ESC includes optimised approaches to disposing certain types of ILW in the vaults.
- There have been major advances in the treatment of LLW since the 2011 ESC, enabling waste to be recycled, or greatly volume reduced. Routes have also been developed to divert substantial volumes of Very LLW (VLLW) and Lower Activity LLW (LA-LLW) to Permitted landfills rather than the LLWR. This has greatly reduced the volumes of waste being disposed to the LLWR. Delays to major decommissioning projects have also reduced the volumes of waste arriving at the LLWR for disposal. While this affects current and near-future waste arisings, it is anticipated that these wastes will still need to be disposed in the future, so disposal rates are expected to catch-up with projections in the UK Radioactive Waste Inventory (UKRWI). In response to low rates of waste arisings, the engineering design for the 2026 ESC includes revised, and improved, operational approaches to protecting containers of waste from the weather.
- Recent closure engineering design work identified that it would not be possible to install the closure engineering in the way described in the 2011 ESC without damaging waste containers of the current designs [10] [5]. This would reduce the contribution of the containers to the multi-barrier repository concept. Therefore, work has been undertaken to re-optimise the vault design, including optimising the closure approach for containers of the existing designs, and to optimise the container design for future waste and approaches to protecting future containers from damage during closure. This work has been integrated with developing optimal approaches to potentially disposing ILW in the vaults. The preferred approaches are optimal whether ILW is disposed or not.

- Analysis of monitoring data indicated the interim cap over the trenches is not performing as well as expected from the design. Intrusive investigations undertaken in 2013 revealed damage to the geomembrane in the interim cap, which likely occurred during construction. The type and extent of damage found are consistent with the outcomes of the analysis of monitoring data. We have developed an optimised approach to improving the performance of the interim trench cap [33]. The interim trench cap over the northern area of the trenches will soon be replaced by the final cap. The interim trench cap over the southern area of the trenches is currently being replaced to improve isolation and containment of the trench wastes until the southern trenches are covered by the final cap. The resistive elements of the interim trench cap will be punctured (existing) or removed (new) prior to final capping, so the existing interim trench cap, and improvements to the southern area, will not affect the performance of the final cap, or introduce uncertainties.

The implications of these changes for repository evolution and performance have been captured through iterative development of the EPA. The EPA has also fed back into optimisation of the repository and design. Changes have occurred at different times, for a variety of reasons, and in parallel with development of the EPA. Therefore, the history of interactions between the EPA, optimisation and engineering design work, and assessments over the last decade is complex. The history is outlined in references [5] and [21] but is not described here. This report integrates all the EPA iterations and developments into a single narrative.

2.3 Site Setting and Evolution

2.3.1 Site Setting

The LLWR is located on the coastal plain of West Cumbria near the village of Drigg and approximately 0.5 km from the Irish Sea coast at Drigg Beach (Figure 2.1). It is approximately 3 km north of the Ravenglass Estuary where the Rivers Irt, Mite and Esk converge.

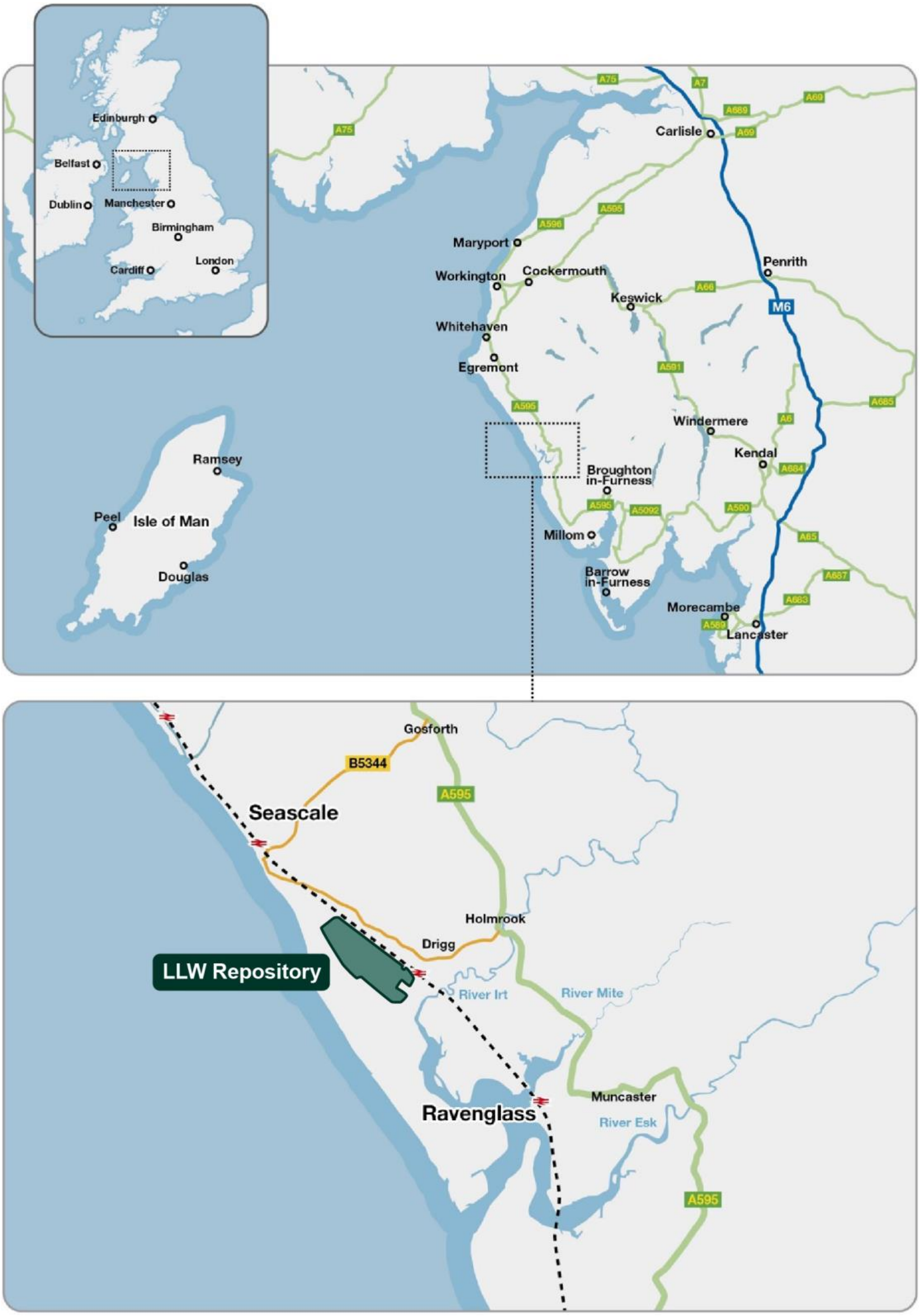

Figure 2.1: Location of the LLWR site

The LLWR site is about two kilometres long and half a kilometre wide and lies on a north-west to south-east axis. In this EPA and our assessments, we simplify this to north to south. Therefore, the coast is to the west, and inland is to the east.

The total area of the LLWR site is approximately 110 hectares. The repository is in the northern part of the site and has an area of approximately 40 hectares. The topography varies from about 20 m above Ordnance Datum (OD) to the north-east and west of the site to less than 5 m above OD at the south-eastern site boundary. To the west of the site, the topography gently undulates towards a small cliff line marking the edge of the Drigg Beach. The surface of the interim cap that covers the trench area is around 25 m above OD. Inland of the LLWR site the topography rises, initially gradually but then steeply, to be dominated by the Lakeland fells.

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

The Drigg Stream rises immediately to the south of the repository area (adjacent to the vaults) and flows through the LLWR site roughly parallel with the western site boundary. Towards the centre of the site, the Drigg Stream is joined by the East-West Stream, which originates off the site to the north-east, draining farmland and taking water from a drain in the base of the railway cutting. The Drigg Stream leaves the site to the south and discharges into the River Irt, which is tidal at that point. The Irt forms the northern arm of the Ravenglass Estuary, comprising also the rivers Mite and Esk, which discharges to the sea opposite the village of Ravenglass.

An aerial photograph of the repository is shown in Figure 2.2. Key features are listed below.

- The interim cap which covers the seven waste trenches.
- Vault 8, which is nearly full. The small remaining disposal volume at the north end of the vault is now full.
- Vault 9, which is currently operating.
- The area for future vaults.

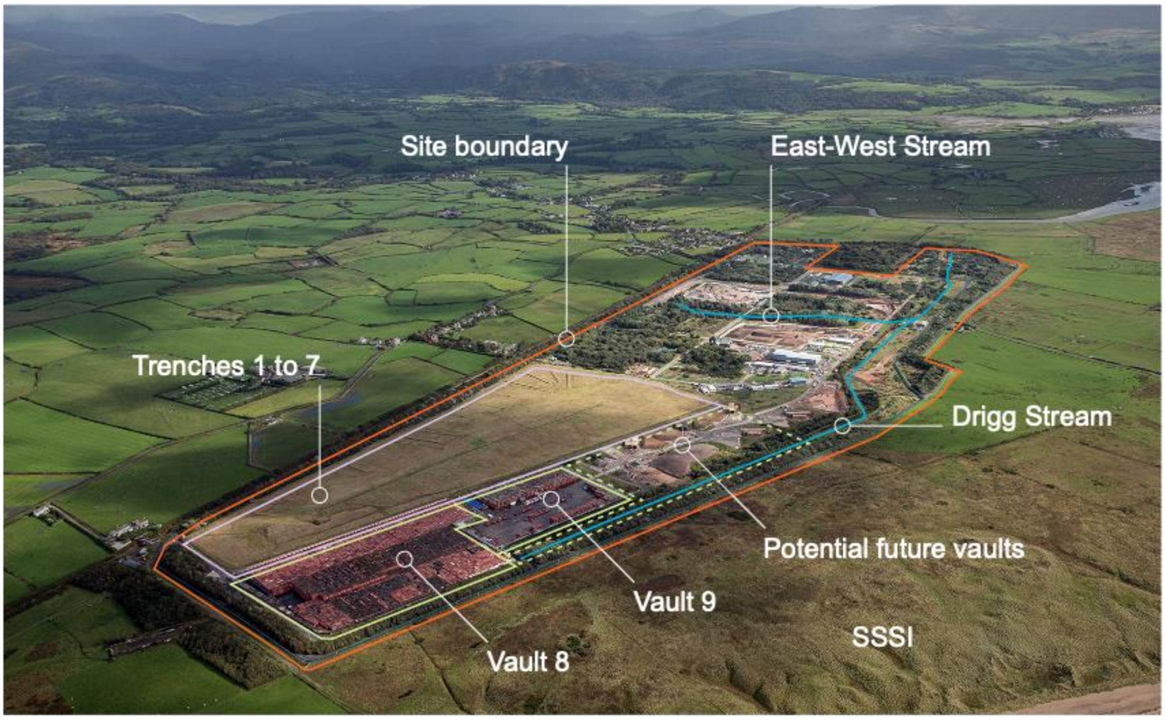

Figure 2.2: **Aerial photograph of the LLWR**

The geological structure in the region of the LLWR consists of Quaternary age deposits (up to 2.6 million years old) overlying older bedrock. Quaternary deposits at the LLWR site are a result of complex glacial processes, which were responsible for the deposition of a sequence of deposits of clay, sands and gravels up to 70 m thick. The Quaternary deposits overly Triassic Ormskirk Sandstone (around 240 million years old) in the vicinity of the LLWR site.

A schematic representation of the hydrogeological conceptual model is shown in Figure 2.3. The Upper Groundwater occurs in the shallower Quaternary sediments. Regional Groundwater occurs within the deeper Quaternary sediments and the underlying bedrock. There is a high (approximately unit) vertical gradient in the Upper Groundwater, with water draining downwards into the Regional Groundwater, although in places flow has a significant horizontal component. Flow in the Upper groundwater has an upwards component where it discharges to streams. Flow is sub-horizontal in the Regional Groundwater, driven by a weak horizontal gradient that is generally perpendicular to the coastline, i.e. approximately from north-east to south-west. In areas where the upper part of the bedrock is at relatively shallow depth, flow in the upper part of the bedrock makes a significant contribution to the regional groundwater flow. Flows in the Regional Groundwater discharge into the sea.

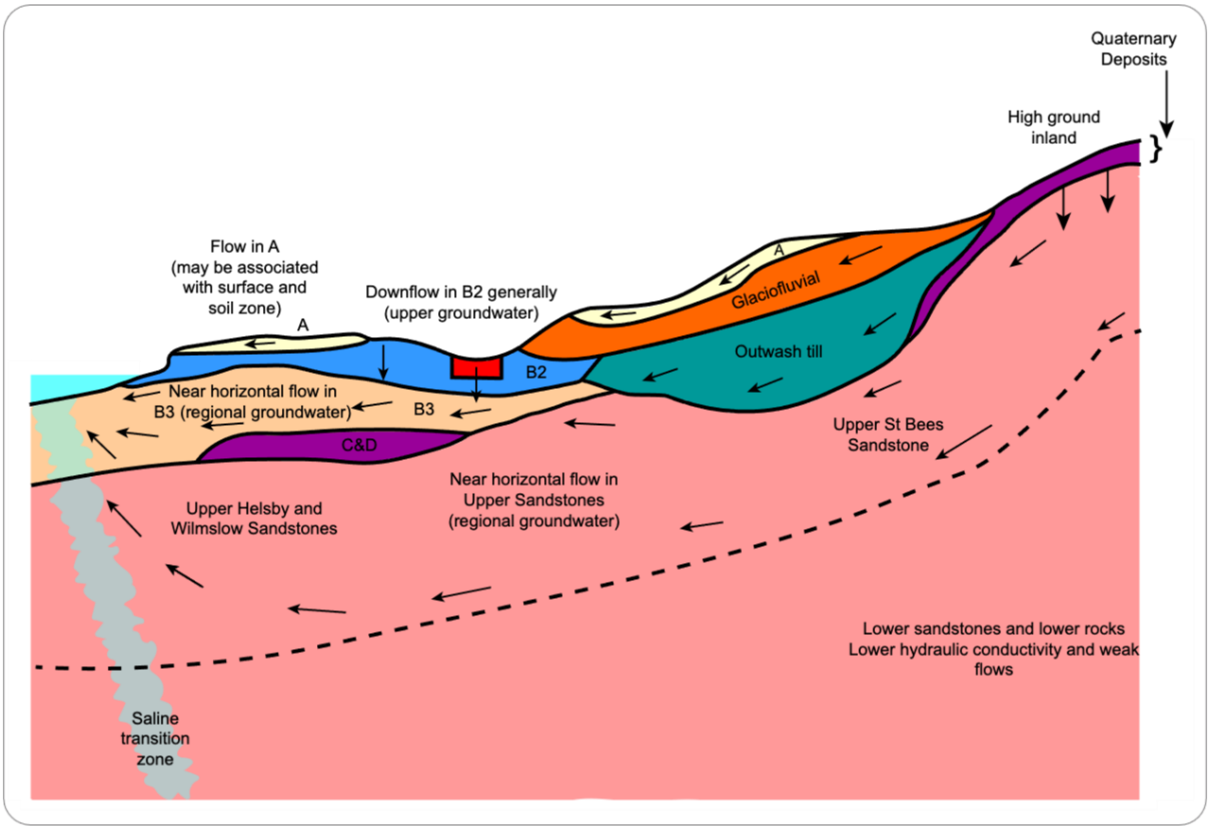

Figure 2.3: Hydrogeological conceptual model (schematic east-west section)

Further information on the geology and hydrogeology in the vicinity of the site is given in the '*Hydrogeology'* report [7].

2.3.2 Development Plan and Evolution

Areas where waste disposal operations are complete will be closed, and closure engineering installed, as the repository is developed. This closure engineering includes a thick, multi-function, multi-layer cap. This will be installed as a series of strips, so wastes are covered and protected as soon as practicable.

The reference future inventory projection for the 2026 ESC suggests installation of the closure engineering will be complete around 2142 [10]. The repository will then remain under a period of active institutional control until the hazard has further reduced, and monitoring results provide confidence the repository is evolving and performing as expected.

The period of active institutional control will last 100 years [10]. At the end of the period of active institutional control the Permit will be surrendered and the PoA will cease. There is assumed to be no management or active control following the end of the PoA. The engineering must function passively. Inevitably the engineering performance will slowly degrade following the end of the PoA.

Climate change and sea-level rise will change the characteristics of the site setting and will affect the engineering performance. Future global greenhouse gas emissions, and the resulting changes to climate and sea level are uncertain. Climate change and sea level rise could have the following impacts.

- Climate changes would likely lead to changes to the cap vegetation. For more extreme climate scenarios, the potential for loss of vegetation during summer, leading to erosion of cap soils needs to be considered. Loss of vegetation, combined with more extreme rainfall events, could result in greater incision of small runoff gulleys into the cap.
- Climate and vegetation changes will lead to changes in Hydrologically Effective Rainfall (HER). This will affect infiltration through the cap, and surface and groundwater flows.
- Sea-level rise may result in rising regional groundwater heads below the repository. This may affect water levels in the repository.

Three emissions and climate change scenarios are assessed in the 2026 ESC [8]. They are summarised in Table 2.1. We expect that the repository will be disrupted by coastal erosion over a timescale of several hundred to a few thousand years.

Table 2.1: Emissions and climate change scenarios

Attribute	Emissions scenario		
Greenhouse gas emissions	Reference (SSP 2-4.5)	High (SSP5-8.5)	Low (SSP1-2.6)
Temperature rise 100 years after present, C	+1.9	+3.2	+1.0
Temperature rise 1,000 years after present, C	+1.9	+6.8	+0.70
HER 100 years after present, mm y^{-1} (currently 641 mm y^{-1})	632	623	635
HER 1,000 years after present, mm y^{-1}	632	599	636
Relative sea-level when repository first exposed, m OD	6	10	2
Relative sea-level when repository completely eroded, m OD	8	21	2

3 Design Overview

This section describes the features of the repository. It then describes the primary functions of the engineering as part of the optimised approach to isolating the waste from the environment and containing contaminants in the waste. Further details of the engineering design and repository development plans are then provided. Full details of the optimised design and development plans are presented in references [5] and [10] respectively. EPA focussed information needed to describe the evolution and performance of the key engineering components is provided in Section 5.

3.1 Features

The trench wastes were tumble tipped (Figure 3.1) with minimal engineering. The trenches were dug into natural clays to provide a low permeability base (except for Trench 1). The natural clays extend part way up the sides of the trenches [34]. Bentonite was rotovated into the bases of Trenches 3 to 7 where the natural clays were thin or absent [35]. The trench bases are graded to the south, directing leachate towards drains at the southern ends of the trenches. However, some leachate drains through the bases of the trenches into the ground.

The trench wastes are covered by an interim cap. A cement-bentonite cut-off wall resists lateral flow of leachate from the trenches towards the north and east site boundaries. This includes resisting flows to the drain in the base of the railway cutting, which runs along the outside of the eastern (inland) site boundary.

Figure 3.1: Tumble tipping of trench waste in the 1980s

Since the late 1980s, LLW has been placed in mild steel ISO containers for transport to the LLWR site. At the site, residual void spaces within containers are filled with cementitious grout. Half-height ISO containers (HHISOs) are predominantly used, but other height ISO containers are also used. The grout fills voids in the containers to minimise settlement but also conditions any infiltrating waters to a high pH, which reduces steel corrosion rates, reduces the solubility of many radioactive and non-radiological contaminants, reduces microbial activity, and provides a substrate for sorption of contaminants.

ISO containers are stacked in the vaults. A small quantity of waste has also been placed or directly grouted into Vault 8, including drummed wastes and large items. These approaches could also be applied to a small proportion of future waste in Vault 9 and subsequent vaults, if optimal.

Key features of the vaults are the bases and walls. The bases provide flat surfaces for repository operations and stacking containers. The vault bases and walls are designed to capture rainfall and any leachate from the containers and prevent it from entering the ground. Therefore, the vault bases comprise concrete slabs, for operations and stacking, underlain by low permeability layers to prevent leachate from entering the ground[2]. The design details of Vaults 8, 9 and the future vaults are discussed later in this report.

Leachate from the vaults and trenches is piped to the Marine Holding Tank (MHT) and then discharge via the marine pipeline in accordance with the Permit.

A small remaining space for disposals at the north end of Vault 8 (Figure 2.2) has recently been filled with containers from Vault 9, treated radwaste store (TRS) drums and bagged demolition waste. Around a third of the disposal volume in Vault 9 has been used, but the containers are not in their final disposal positions. They are currently placed to support operations.

The layout of the future vaults is shown in Figure 3.2. The Reference Inventory [4] indicates only Vaults 8 to 12 would be needed to dispose of relevant LLW in the national inventory, plus ILW that may be suitable for vault disposal, if this is Permitted. Vault 12 would only be part filled. There is uncertainty in future waste arisings over timescales of one hundred years. Therefore, the design also includes Vaults 13 and 14 to provide additional disposal space if it is needed.

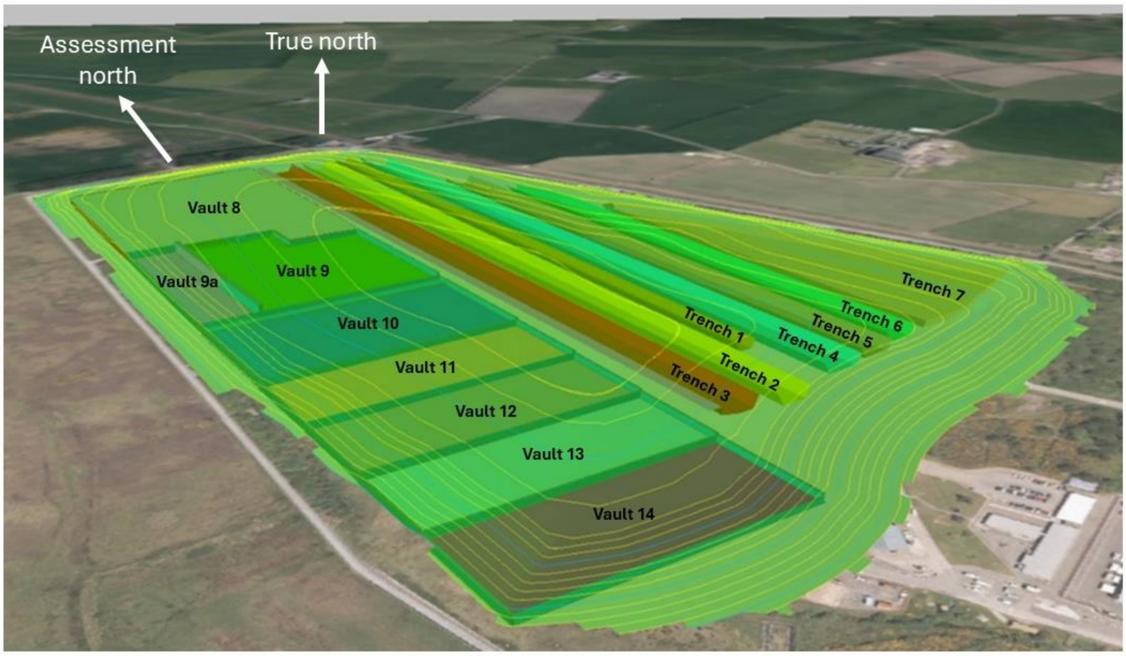

Figure 3.2: Layout of the trenches (1 to 7) and vaults (8 to 14) with illustrative cap contours.

Closure will involve installation of engineering that is designed to provide passive long-term isolation and containment. A 3 m thick final cap will be constructed over the trenches and vaults. The cap will be underlain by a minimum[3] of 2 m of profile fill, increasing to around

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[2] The concrete slabs have construction joints and operational cracks that do not impact their performance for operations and stacking. The concrete slabs are not expected to provide complete containment of leachate on their own.

[3] The minimum thickness of the profile fill has been increased from 1 m in the 2011 ESC to 2 m over the waste, to reduce strains on the cap from the maximum plausible waste settlements.

10 m below the crest of the cap over Trench 3. The profile fill gives the cap the optimal shape and protects the cap from strains generated by waste settlement. The cap and profile fill will provide 5 m to around 13 m thickness of material isolating the waste (Figure 3.3).

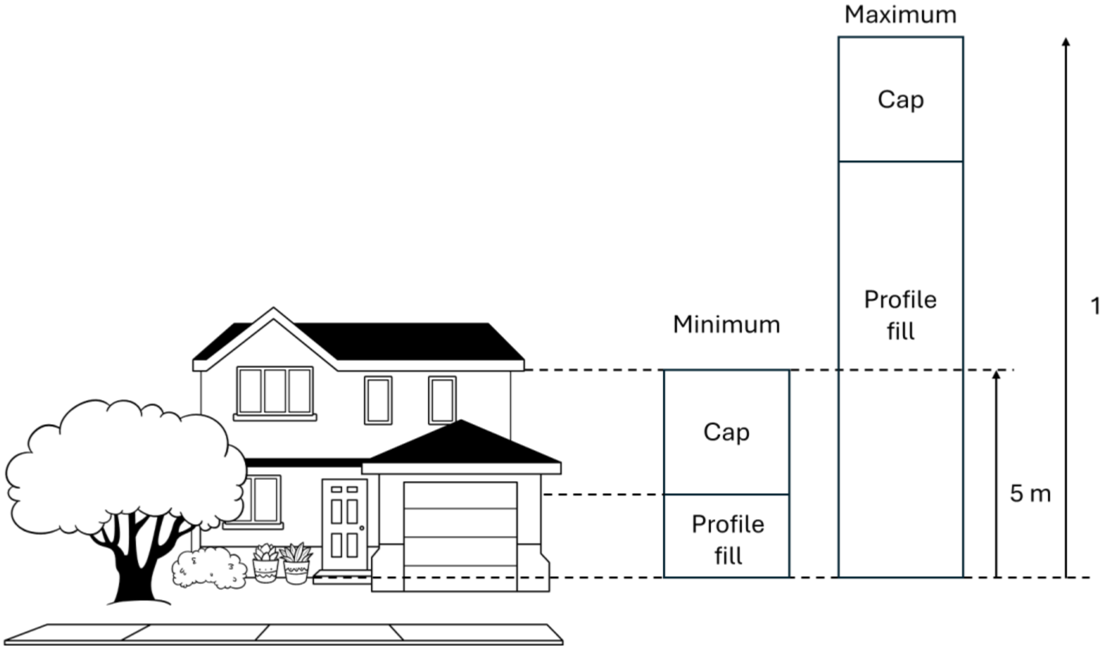

Figure 3.3: Thickness of material isolating the waste (typical house shown to provide context)

The cap will minimise infiltration into the repository. The cap will also isolate the trenches and vaults from the atmosphere, resulting in reducing geochemical conditions. The combination of low infiltration and reducing conditions will reduce degradation and corrosion rates. This will reduce release and leaching of contaminants from the waste, bulk gas generation, and settlement of the waste stacks. In the vaults, the grout will typically condition porewaters in the containers to high pH, reducing degradation and corrosion rates even further.

The final cap will be installed as a series of strips over the vaults and adjacent trenches, concurrent with completion of disposal operations in the associated area. The first strip of the final cap (Tranche 1) will be installed over Vault 8 and the adjacent areas of the trenches over the next decade. The leading edge of the cap will need to be sloped for stability. A temporary seal will be used to prevent infiltration through the leading edge and to help isolate the capped waste from the atmosphere.

Some water will infiltrate the final cap. In the vaults, the containerised waste form will help to direct infiltration away from the waste, down the gaps between the stacks. Passive drainage blankets will be installed below the bases of the future vaults. Water will be passively directed into these drainage blankets once water levels in the vaults rise to 1 m (Figure 3.4). This will help to reduce water contact with the waste. Keeping water levels in the repository low also provides a barrier to release of contaminants to surface soils and shallow groundwater.

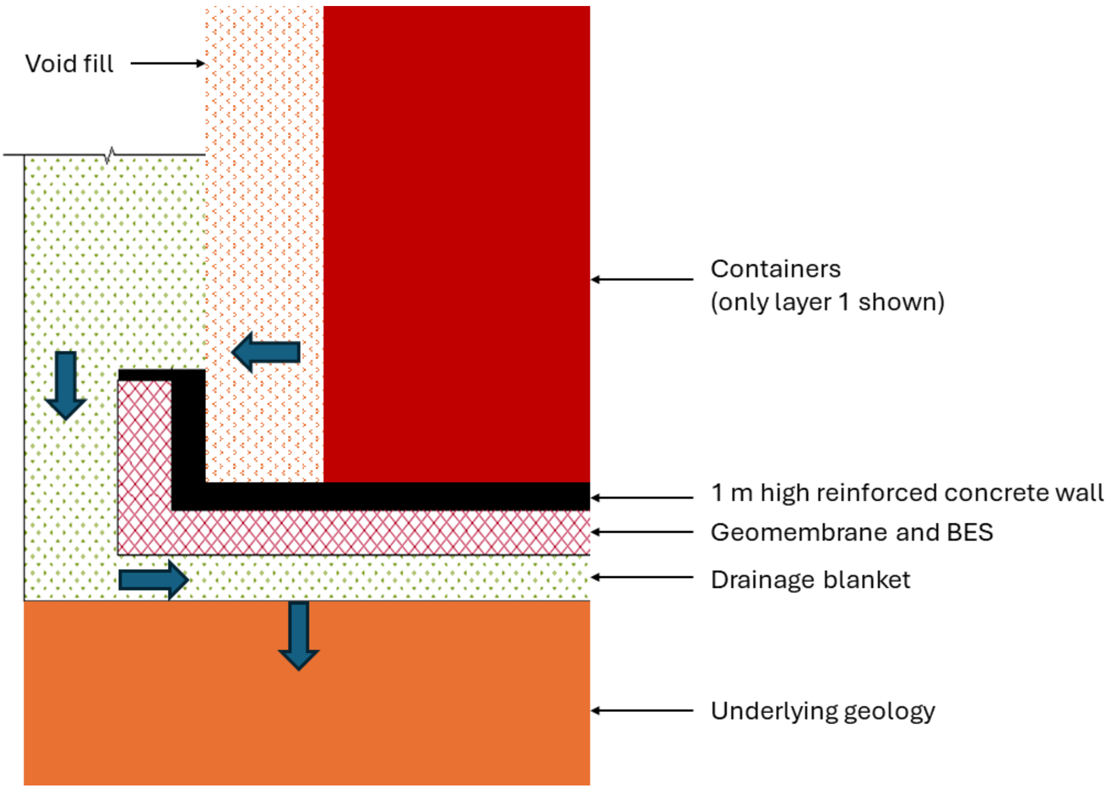

Figure 3.4: Passive drainage in future vaults

The existing cut-off wall will be progressively extended, concurrent with strip capping, to fully enclose the repository. The cut-off wall resists lateral flows of groundwater into and out of the repository. Resisting flow into the repository minimises potential for water contact with the waste and the volumes of groundwater entering the drainage blankets. Resisting flows out of the repository provides a barrier to release of contaminants to surface soils and shallow groundwater.

The main engineering components are therefore:

1) Final cap (including profile fill material).
2) Interim trench cap.
3) Trench wastes.
4) Vault waste container stacks.
5) Vault bases.
6) Vault side walls.
7) Cut-off wall.
8) Leachate management system.
9) Under-vault drainage and underlying geology.

Reference [36] demonstrates that these are the key engineering components for understanding performance.

3.2 Engineering Functions

This subsection describes the primary functions of the engineering as part of the optimised approach to isolating the waste from the environment and containing contaminants in the waste. The functions are illustrated in Figure 3.5.

This section does not describe the status of the engineering or future development plans. Some features of the engineering are already present, some will be improved or altered in the future, others will be constructed or extended in the future.

More detailed design information and development plans are summarised in the next subsection (3.3), and full details are provided in references [5] and [10]. New vaults will be constructed as they are needed, and closure engineering will be progressively installed once vaults have been filled.

Operations

During the operational phase, the interim trench cap reduces infiltration into the trenches, water levels in the trenches, and leaching of contaminants. The combination of low water levels in the trenches and a cut-off wall resists lateral flows to surface soils and waters. This includes resisting discharge to the drain in the base of the railway cutting that runs outside the eastern (inland) repository boundary.

The vault engineering limits leaching from the waste by rainwater and captures leachate and directs it to the marine pipeline for safe discharge. Containerisation of the vault waste, and void filling with cementitious grout, reduces leaching by limiting water contact with the waste and increasing the pH of the water inside the containers. Low permeability vault bases and walls capture clean rainwater and leachate from the containers, and direct both to the marine holding tank for discharge via the marine pipeline.

Recent optimisation work has identified additional approaches that could be used to improve protection of the containers from rainwater during the operational phase. These approaches would reduce generation of leachate. We intend to use removable warehouses to protect containers. The warehouses would not be in vaults that are accepting waste, for example there would not be a warehouse in Vault 9. Wastes destined for Vault 9 would be stored in a warehouse or warehouses in Vault 10, or on a suitable base slab outside the vaults. Once there are enough containers in the warehouses, they would be moved to their final disposal positions and then protected by constructing the next strip of the final cap over them. Other container protection options are described in Subsection 3.3.

ILW is divided into ILW that can be managed in the same way as LLW, and ILW that requires different management arrangements (i.e. operational shielding). If ILW is accepted for disposal, ILW that can be managed in the same way as LLW could also be protected using warehouses. Higher dose rate ILW requiring different management arrangements would be placed into concrete shielded modules, which provide operational shielding and weather protection. These modules would be constructed in the vaults. They would have thick reinforced concrete bases, walls and roofs.

Post-closure

The final cap is the key long-term barrier. The cap isolates the waste and provides containment of contaminants by minimising water contact with waste as much, and for as long as reasonably achievable. As noted previously, the cap will be constructed in several strips, so containers are covered and protected as early as possible. The size of the strips is determined by practicality considerations, for example limiting the number of joins between strips, efficiency of materials handling, space needed for working, and managing the sloping leading edge.

The final cap will have multiple layers that, together with the underlying profile fill, provide multiple barriers and provide the following functions:

- shielding from radiation;
- protection against biointrusion;
- reducing the potential for, and impacts arising from, inadvertent human intrusion;
- minimising infiltration of rainwater into the waste;
- managing bulk gases.

The layers act together to maximise performance and long-term durability of the cap.

The underlying profile fill gives the cap the correct shape and slopes and protects the cap from strains generated by settlement of the waste. Managing strains from settlement of the waste is a key factor in protecting the cap and keeping infiltration into the repository low.

The cap performance may start to decrease over the timescales to the start of disruption of the repository by coastal erosion. If the cap performance starts to decrease, infiltration into the repository will increase, and water levels in the repository can rise. A passive drainage system in the vaults is designed to direct waters into the deeper underlying geology. This helps to keep the waste dry, minimising contact with water, and prevents release of contaminants directly to the surface environment.

The vault wastes are containerised for operational handling and containment. The containers and grout provide an additional post-closure barrier to contaminant release. For example, the containers limit water contact with the waste in the event of localised cap failure or damage, by directing water down the gaps between container stacks.

The cut-off wall will minimise lateral flow of groundwater into the repository, including water that runs off the cap and infiltrates the ground around the repository once the cap surface water drains fail. This minimises groundwater contact with the waste and minimises use of the passive drainage capacity by lateral inflows. The cut-off wall works with the passive drains below the future vaults to minimise the potential for releases to the ground surface and shallow groundwater pathways e.g. to soils and streams.

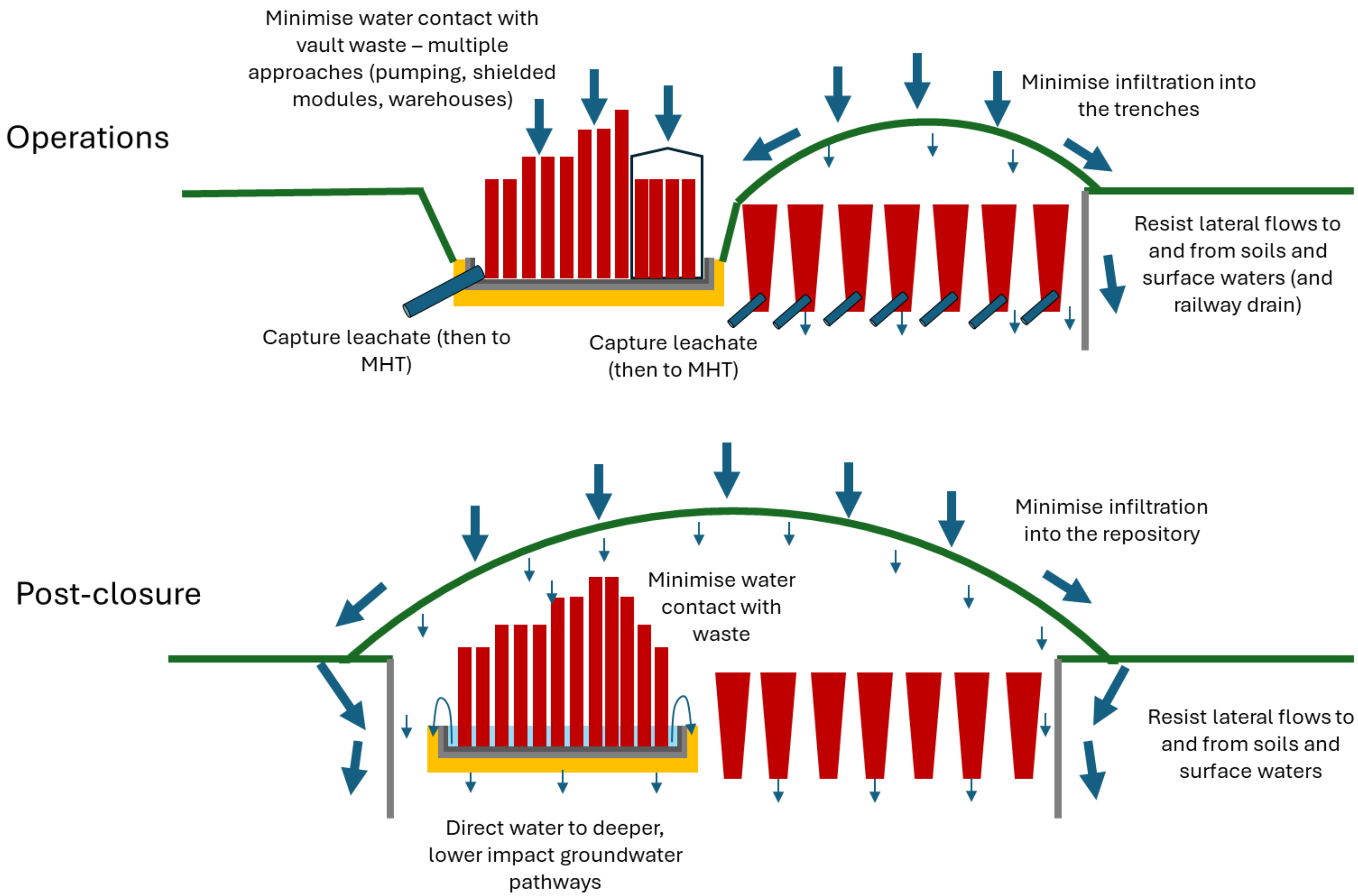

Figure 3.5: Engineering functions (vertically exaggerated schematic cross-section with vaults on the left, trenches on the right)

3.3 Design and Development Details

This subsection provides details of the optimised design [5] and repository development plans [10].

Replacement of the interim trench cap

The interim trench cap is constructed from ungraded site soils, with a 0.375 mm thick 'Blackline' low density polyethylene liner. Performance of the interim trench cap will be improved by covering the north end of the trenches with the first strip of the final cap, and work in progress (Spring 2026) to replace the interim cap over the southern end of the trenches with a geosynthetic clay layer (GCL) overlain by a geosynthetic drainage layer (GDL). The LDPE liner will not be removed but it will be punctured everywhere, so it no longer provides a barrier to infiltration. This provides predictability in hydrological performance and removes risks to construction of the final cap. The GCL, GDL and overlying material will be progressively removed as the interim trench cap is decommissioned and replaced by the final cap.

Vault 8 and Vault 9 closure

We identified that it would not be possible to install the closure engineering for the repository in the way described in the 2011 ESC without damaging the containers already in Vault 8 and Vault 9 or containers that are already committed to the current container design [10]. We concluded that the majority (potentially all) of the containers would deform from the loads on them, and some of the voidage present in the containers would be expressed. Some of the containers would deform during construction of the cap, likely damaging the cap by shearing and offsetting cap layers.

We developed and assessed options for closing Vault 8 and concluded the optimised closure approach is to surcharge[4] existing containers and those committed to the same designs (existing and committed containers) to ensure deformations and voidage expression occurs prior to final cap construction (references [5] and [10]). Deformation of the containers will reduce their contribution to the multibarrier system. However, surcharging is important to provide a stable base for cap construction, and it also provides additional benefits, including for example, reduced long-term settlement and maximum confidence strains from long-term waste settlement will not damage the cap. This is particularly beneficial for existing containers as many older containers have higher levels of voidage than recent disposals. (We have been successful in significantly reducing container voidage over the last decade to reduce potential waste settlements.) Also, existing containers have higher levels of organic waste that will degrade generating voidage compared with projections for future containers [4].

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[4] Material will be emplaced over relevant disposals to the equivalent height of the profile fill and the cap, to provide a load equivalent to the final cap. Once the surcharge is complete the top 3 m of the material will be removed prior to cap placement, with the remaining material retained as profile fill [5].

We further examined the optimal approach to vault closure for existing containers in Vault 9 and waste that is committed to arrive in existing container designs [10]. This work concluded the optimal approach for existing and committed containers in Vault 9 and 9a is to:

- provide early protection from the weather by extending the leading edge of the first strip of the final cap and the leading-edge seal over these containers; and subsequently
- surcharging these containers using the same approach as for Vault 8, during construction of the second strip of the final cap.

Future waste and vaults

We have also considered the optimal approaches for future wastes where the container design can be changed. We concluded the optimal approach for future LLW is to transition to a strengthened ISO container design, which would not deform under closure loads from the profile and cap, could be stacked higher, and would not require surcharge prior to final capping [10]. Stronger containers will reinstate the post-capping contribution of the containers to the multi-barrier system.

A conceptual design has been developed for a container protection unit (CPU) that would be placed on the top of each stack of containers (Figure 3.6). This consists of reinforced concrete with an outer steel frame. The CPU protects the lid of the top of stack container, so it is not damaged by loads from the profile fill and cap. The CPU directs the loads into the structural corner elements of the containers, and down the structural elements of the underlying containers into the vault base. The CPU will also help to direct infiltration down the gaps between the waste stacks.

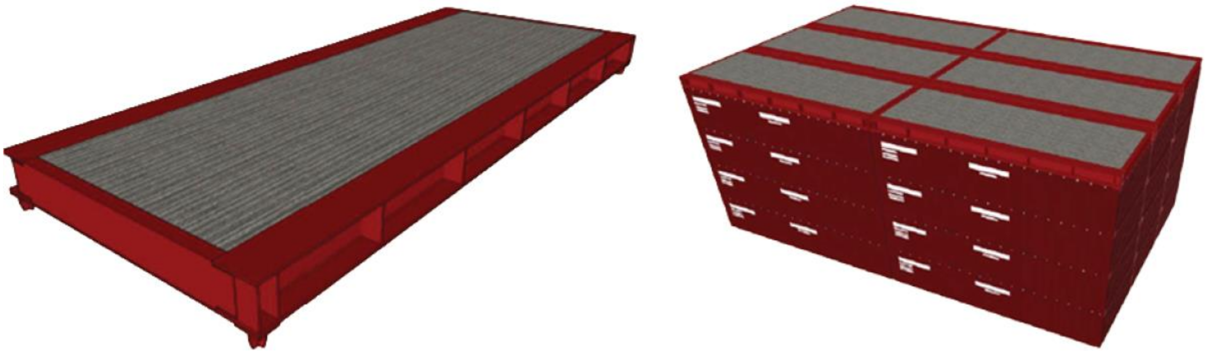


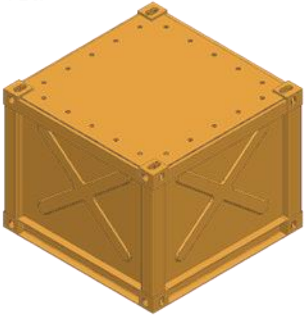
Figure 3.6: Conceptual container protection unit (CPU), left, and in position on top of waste stacks, right (illustrative design)

Optimised approaches were developed for potentially disposing ILW in the vaults that are integrated with the approach to future LLW disposal [10]. Conceptually it may be possible to dispose of some ILW in ISO containers. For the ESC, we have assumed ILW would be disposed in a small, strong, mild steel container which could be transported to the site in a Standard Waste Transport Container (SWTC) if required (Box 1). This assumption gives confidence in meeting transport regulations and increases the range of ILW that could potentially be disposed at the LLWR. Weight limits and handling practicalities preclude placing ISO containers within a shielded transport container.

Box 1: SWTC-compatible Strong Boxes

It is anticipated that most ILW would require overpacking in a reusable transport container for safe transport to the LLWR. The most advanced transport container design for packaged ILW is the Standard Waste Transport Container (SWTC). A new type of mild steel container is conceptualised that would fit into an SWTC. The SWTC design may be overengineered for the types of ILW that could potentially be disposed to the LLWR. Therefore, alternative transport container designs with less shielding, that can accommodate a larger disposal container, for the same total weight, may be plausible. However, they have not been considered at this stage.

The concept for the strong boxes is analogous to the concept for strengthened ISO containers. The container would be made from mild steel, so it would not be durable on the coast when exposed by coastal erosion. Vertical loads would be carried down structural elements. The containers would be designed to carry stack, profile and cap loads. Top of stack container protection units would transmit the profile and cap loads into the structural elements. Wastes would be encapsulated in cementitious grout by the waste producer, prior to transport to the LLWR.



Illustrative Schematic of a mild steel SWTC-compatible Strong Box

External dimensions assumed as 1700 mm(L) x 1700 mm(W) x 1350 mm(H)

Payload 2.6 m^3

ILW containers that can be managed in the same way as LLW would be stacked in the vaults with top of stack container protection units.

ILW containers that need different management arrangements (e.g. for dose management reasons) would be placed into shielded modules (Figure 3.7) constructed from steel reinforced concrete. We have developed a conceptual shielded module design for the ESC. If disposal of ILW in shielded modules is taken forward, the module design would be taken forward to detailed design. We anticipate the basic approach would be retained during detailed design, but aspects would evolve. Based on the conceptual design, for the ESC we assume the bases and roofs would be around 750 mm thick, and the walls would be around 600 mm thick. The walls would be tied into the base and the roof. Concrete internal walls also support the roof and divide the interior into corridors.

The waste may be disposed in SWTC-compatible strong boxes, as dose rates and, or specific activity considerations would most probably necessitate a transport container. The modules provide operational weather protection and shielding, protect the waste containers from vertical loads from the final cap and profile material, and direct any water infiltrating the final cap away from the waste inside. Passive drainage arrangements between and within the corridors would drain water away from the waste.

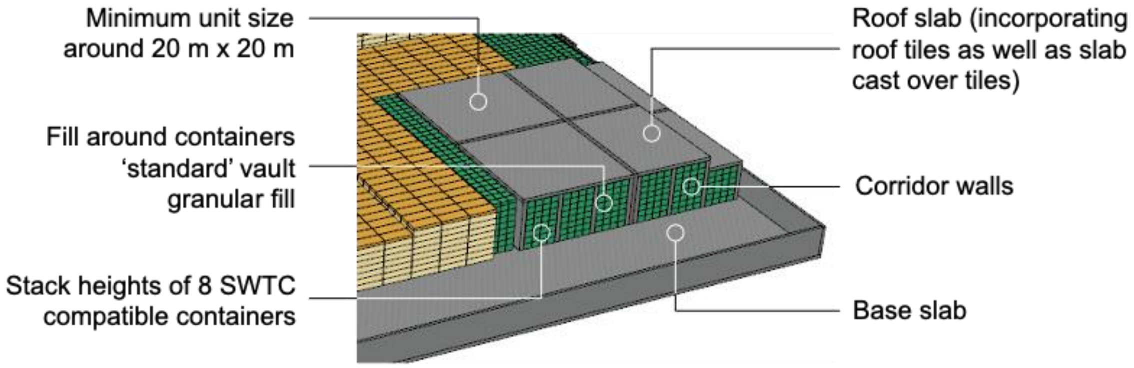


Figure 3.7: Illustration of a shielded module. Note that a 'cut-away' representation of the corridors is shown. The end of the corridors would be closed except during emplacement operations.

Final Cap

The final cap is a multi-layer, multi-barrier design. Important functions of the cap are to:

- isolate the waste from humans and the environment;
- reduce the risk of, and impacts arising from, biological and human intrusion;
- contain contaminants by minimising infiltration into the waste.

The cap layers are shown in Figure 3.8. Isolation is provided by the total thickness of the cap and underlying profile material. The total thickness and bio-intrusion layers reduce the risks of biological or human intrusion into the waste. The bentonite enhanced sand (BES) and overlying high-density polyethylene (HDPE) geomembrane are low permeability layers that resist infiltration of rainwater into the underlying waste. The drainage layer directs water sideways, over the low permeability layers, to the perimeter of the cap. The layers overlying the geomembrane, including the bio-intrusion layer, protect the geomembrane and BES.

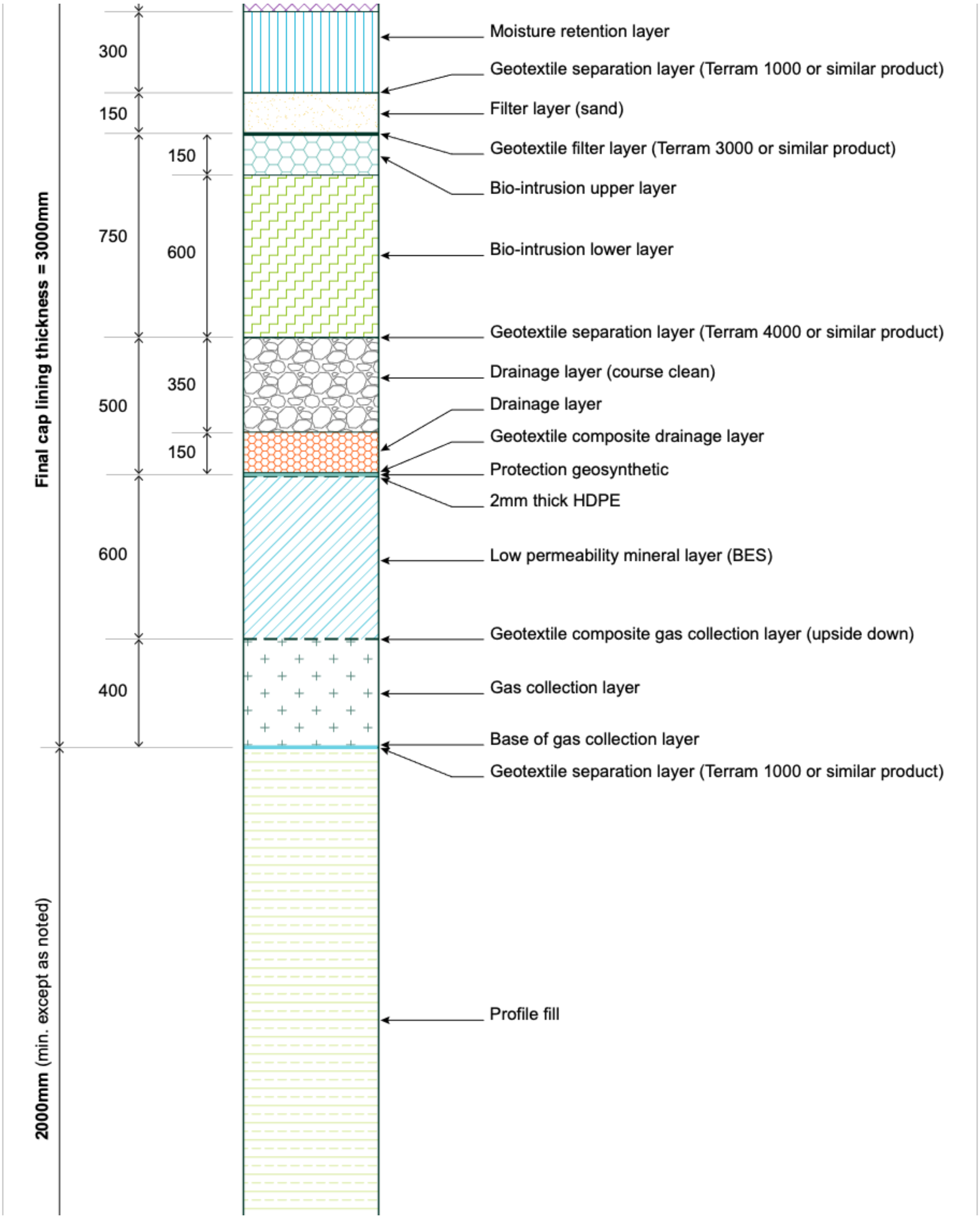


Figure 3.8: Final cap layers

The cap profile (Figure 3.9) has been optimised to balance the preference for lower gradients to minimise erosion and the risk of slope slip against the preference for higher gradients to promote lateral runoff of rainwater. The main area of the cap has a 1:25 gradient, while the shoulders have a maximum gradient of 1:5.

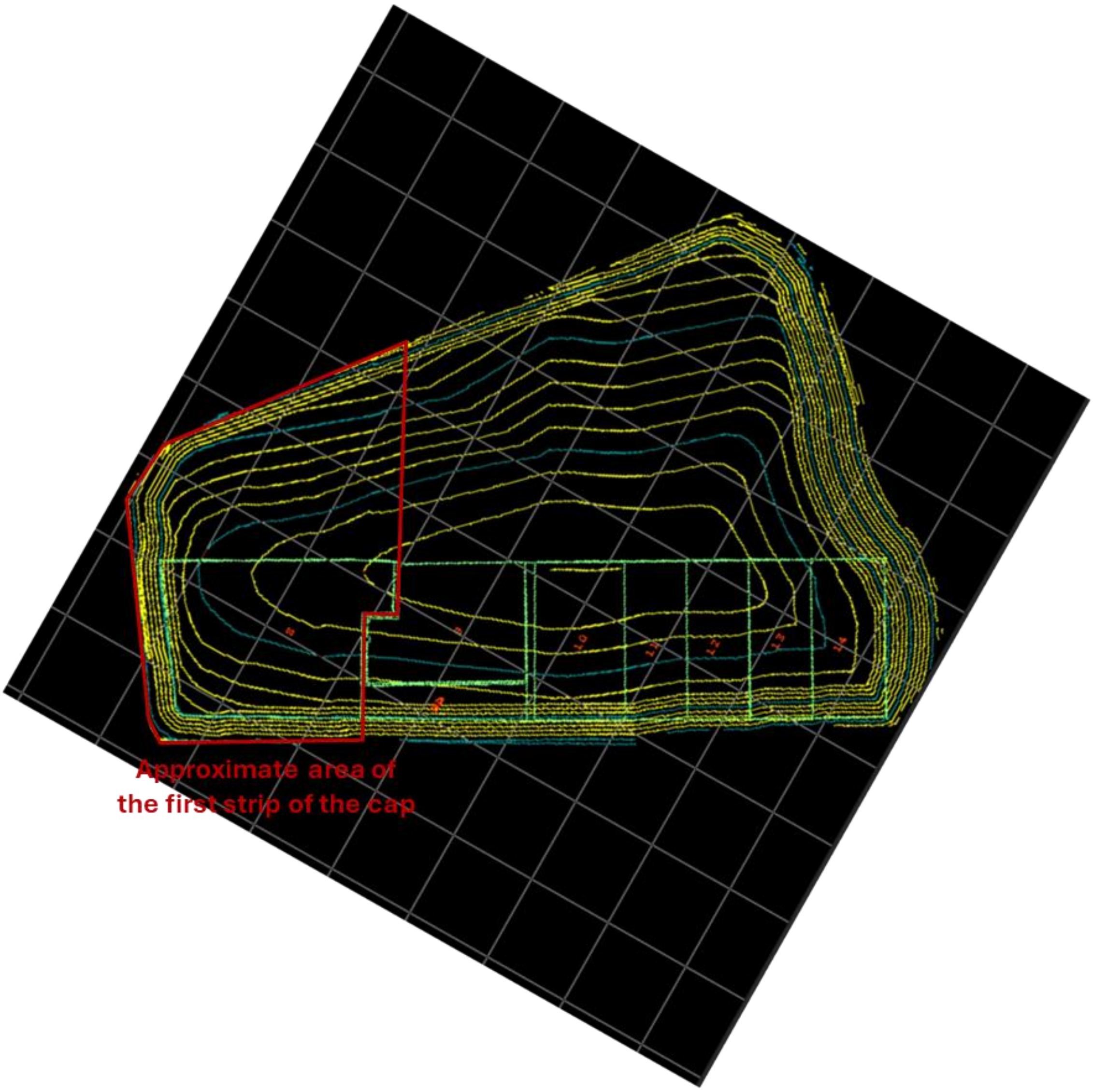


Figure 3.9: **Cap profile. Draft optimised profile for the first strip of the cap over Vault 8 and the adjacent trenches combined with a cap profile over the rest of the repository (up to Vault 14) which complies with the Requirements Management System [5].**

Implementation

Plans for development of Vault 9 and the future vaults are illustrated in Figure 3.10. Existing and committed LLW in existing container types will be present in Vault 8 and the adjacent (northern) area of Vault 9 and 9a[5]. LLW in new stronger containers and ILW that can be managed in the same way as LLW would be placed in the remaining area of Vaults 9 and 9a,

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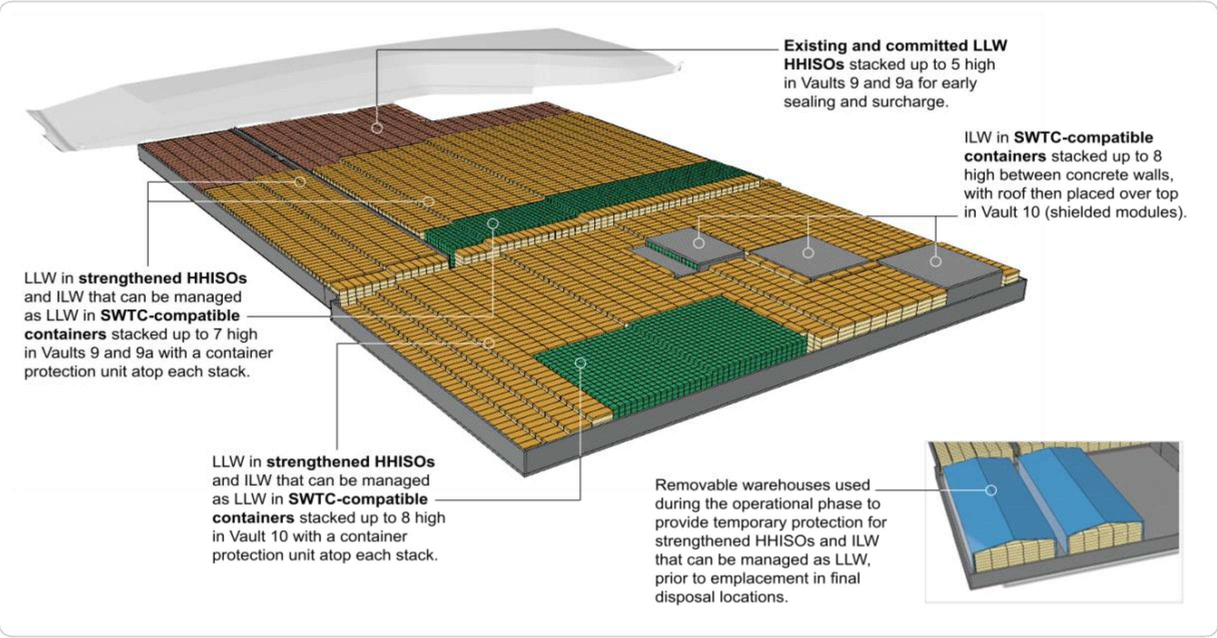
[5] This is the preferred approach. It assumes Vault 9a is available in time for construction of the first strip of the final cap. If Vault 9a is not available, existing and committed waste could be placed at the north end of Vault 9 only.

and in subsequent vaults. ILW that requires different management arrangements would be placed in concrete shielded modules in Vault 10 and subsequent vaults.



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 3.10: Illustrative representation of the preferred vault disposal options for existing and committed LLW containers (brown), future stronger LLW and ILW containers (yellow and green, respectively) and also including indicative concrete shielded modules for vault disposal of ILW requiring different management arrangements to LLW (grey). Note: illustration only shows disposals to Vaults 9/9a and 10.

Minimum practicable dimensions have been identified for the shielded modules. The layouts of the shielded modules have been developed to the extent needed to underpin assessments. The principles of the layout have been optimised to minimise the potential impacts during coastal erosion of the repository, capturing learning from our assessment models [37] [38].

Vault 8 and Vault 9 were constructed as single units. Future vaults will need to accommodate a range of waste types. Therefore, future vaults will be constructed using a modular approach, with different modules for different types of waste. The numbers and sizes of the modules will be governed by the amounts, rates and timings of arisings. The modular approach provides flexibility to respond to differences between projected future waste arisings and actual arisings. The '*Engineering Design'* [5] and '*Optimisation and Site Development Plan'* [10] reports provide more details on current plans.

The first strip of the final cap, Tranche 1, will be constructed over Vault 8 and the adjacent area of the trenches in the next decade (Figure 3.9). The trench wastes will be surcharged for a period prior to capping to provide a solid base for cap construction, with the additional benefit of reducing long-term settlements. Containers in Vault 8 will be surcharged using profile fill prior to construction of the cap. Voidage will be expressed immediately as the containers deform under the load.

Improvements to operational container protection

Due to the major improvements in waste treatment and diversion since 2011, LLW receipt rates are expected to be sufficiently low that there will be decades between construction of each strip of the final cap. Therefore, containers could be exposed to the weather in open vaults for decades, although there are many uncertainties. The implications for container protection have been considered.

As noted above, existing and committed containers in Vault 9 and Vault 9a will be protected by extending the leading edge of the final cap. The containers will be covered by profile fill and a temporary geomembrane. The geomembrane will be removed and the containers surcharged prior to construction of the next strip of the cap (Tranche 2).

Subsection 3.2 notes that removable warehouses will be used to provide container protection prior to moving containers into their final disposal positions prior to construction of the next strip of the final cap. Removable warehouses will be used if container receipt rates are sufficiently low that containers would be exposed in open vaults for more than a decade [10].

3.4 Engineering Materials and Degradation Processes

This subsection provides an overview of certain materials used to construct the key engineering components, and the process that degrade these materials. Specific details of the nature and degradation of each of the key engineering components is described in Section 5.

Geomembrane

Geomembranes are thin sheets that are impermeable to water. They are made from materials such as high-density polyethylene (HDPE). An HDPE geomembrane is used in the final cap to resist infiltration of rainwater, and HDPE geomembranes are used in the vault bases to resist leakage of leachate. The sheets are flexible and can withstand a level of strain without tearing. Geomembranes are delivered on rolls that are laid in strips and then welded together at their edges. Water can only pass through manufacturing defects (pinholes) or construction defects (small holes, tears, imperfect welds) in the material.

Oxidation of geomembranes leads to embrittlement and loss of strain tolerance. Small strains then result in extensive tearing, so the material is no longer an effective hydraulic barrier. Manufactures include antioxidants and other additives in their products to resist oxidation and other degradation processes, such as exposure to sunlight as the material is laid.

Bentonite-enhanced sand (BES)

BES is a mix of bentonite and sand. BES is a low permeability material that is used to resist infiltration through the cap and leakage from the vault bases. The main mineral in bentonite is montmorillonite, which is a clay mineral that swells when it is hydrated. The bentonite controls the hydraulic properties, while the sand controls the mechanical properties. The properties of BES are affected by the amount and type of bentonite used; sand grain size, shape and grading; and the chemistry of the water hydrating the BES. BES is laid with approximately optimal moisture content to maximise the as-placed density. Hydraulic conductivity decreases as the density increases.

Bentonite swells as it hydrates. Sodium bentonite exhibits greater swelling than calcium bentonite. For both types of bentonite, swelling decreases as the ionic strength of the water hydrating the BES increases. Swelling enables the BES to self-heal in response to minor movements. For a given wt% bentonite, sodium bentonite has lower hydraulic conductivity and greater self-healing capacity than calcium bentonite.

BES is degraded by cation exchange of the bentonite and washout of the bentonite by water flowing over the surface of the material, or through the material. Cation exchange of sodium for calcium reduces swelling potential, capacity for self-healing, and increases hydraulic conductivity. Washout of the bentonite has the same effects.

If the material dries, the bentonite shrinks, resulting in cracking and a substantial increase in hydraulic conductivity. However, if the material is subsequently exposed to water, the bentonite will quickly rehydrate and swell, closing the cracks and the reducing the hydraulic conductivity.

Structural concrete

Structural concrete is a strong material that has low permeability. It is used to construct the operating surfaces of the vault bases, the vault walls, and will be used to construct shielded modules if disposal of relevant ILW is taken forward. Structural concrete is formed from a mix of cement, sand and aggregate. Contact between the sand and aggregate grains provides high compressive strength. Steel reinforcing bars buried in the concrete increase tensile strength.

Degradation can occur through:

- cracking under operational or closure loads;
- leaching and chemical alteration of the cement;
- expansive corrosion of the rebar, leading to cracking of the concrete.

Leaching is expected to be the most important cement degradation process in the LLWR, but not necessarily the most important concrete degradation process. Leaching of cement minerals results in decrease in porewater pH, increasing in porosity and permeability, and reduction in strength. This is illustrated in Figure 3.11 which shows pH evolution, and the controlling mineral phases, against the number of pore flushes. Note the number of pore flushes is a log scale, so leaching of CSH takes many more pore flushes than leaching or $Ca(OH)_2$ which takes many more pore flushes than leaching of NaOH and KOH.

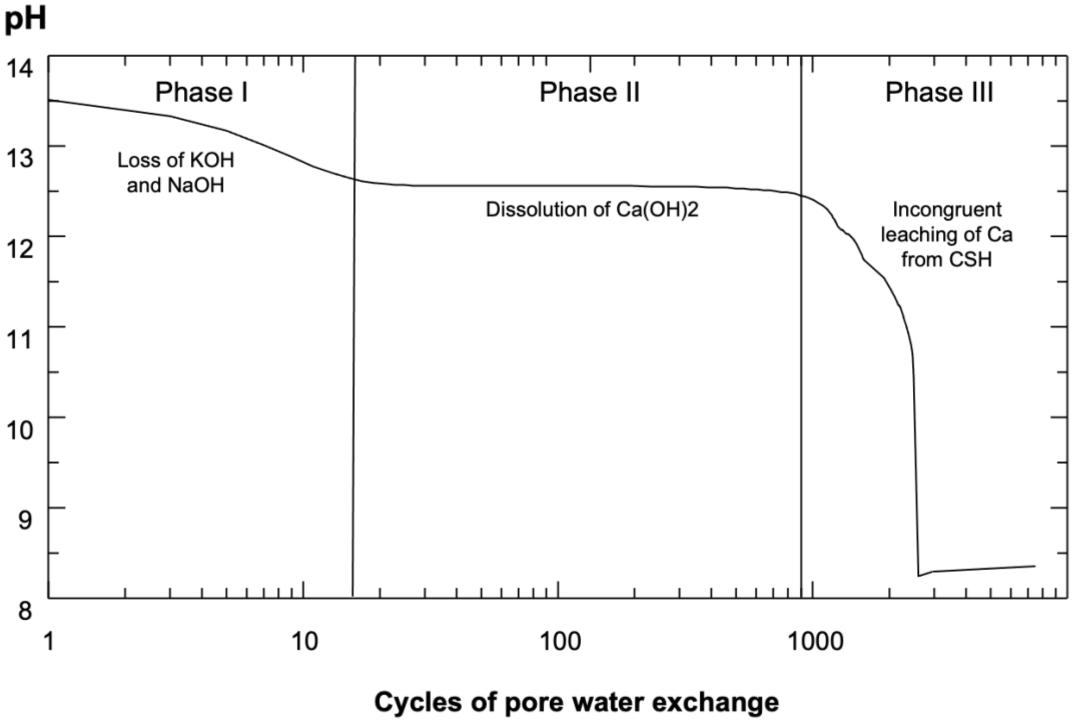


Figure 3.11: pH evolution of cement and controlling mineral phases [39]

Reaction of cement minerals with atmospheric carbon dioxide and carbon dioxide generated from the waste is expected to be the most important chemical degradation process in the LLWR. This results in precipitation of carbonates, a small porosity decrease and pH decrease.

Corrosion of the rebar results in volume increase and generates stresses which then crack the concrete. The rebar is buried in the concrete where the high pH cement porewaters and isolation from atmospheric oxygen result in low corrosion rates. Operational cracks, leaching and chemical alteration of the cement can affect the chemical conditions around the rebar, and therefore the corrosion rate, and cracking of the concrete.

Drainage materials

These are coarse granular materials which have high hydraulic conductivity. The grains are strong and chemically inert, so they do not degrade. Clogging of the pores reduces the hydraulic conductivity of the drainage material. Physical clogging can occur through transport of fine-grained material into the drainage material by water and gravity, chemical clogging can occur by precipitation, and biological clogging can occur by formation of biofilms. More than one clogging process can be active, and the processes may be coupled.

3.5 Natural Hazards

The likelihood of natural hazards and the resilience of the repository to natural hazards have been considered as part of the engineering design. Natural hazards could impact the engineering performance throughout the assessment timeframe, so they need to be considered as part of the EPA.

Coastal erosion

Coastal erosion is not included in this subsection as the EPA timeframe ends when the repository starts to be disrupted. The potential impacts of sea-level rise and coastal erosion on the hydrogeology and water levels in the repository are calculated by our groundwater flow models [7] and groundwater pathway assessment model [14] [40].

Seismic events

Engineering studies of seismic hazard at the site for the 2002 PCSC [29] [41] ensured application of the standard UK nuclear safety provisions, which require seismic assessments to assume ground accelerations of up to 0.25 g in the absence of more detailed specific site-specific data. This conservative assumption continues to underpin the engineering design [5] [42].

Seismic events are primarily a concern during the operational phase and are addressed in the relevant operational safety assessments. Their impact post-closure is considered minimal. This is largely due to the confined nature of the engineered barrier system, which limits the transmission of seismic energy and associated deformation.

The only notable post-closure consideration is cap stability. Previous assessments for the 2002 PCSC [29] [41] demonstrated that slopes of up to 1 in 4 remained stable under seismic loading. The current design incorporates considerably flatter slopes (maximum 1 in 5 on the shoulders, Figure 3.9), which further enhances stability.

In addition, recent geotechnical modelling and material strain assessments [42] confirm that the cap system is resilient to dynamic loading. Strain levels induced by seismic-like deformation remain well within the material tolerance thresholds [43] ensuring long-term integrity.

Overall, seismic loading post-closure is not considered a significant risk to cap performance, and the current design provides a robust solution aligned with long-term safety objectives

Other disruptive events

The 2002 PCSC Engineering Performance Assessment [29] included ‘exploration of the implications of the disruption of the facility by credible natural hazards that are relevant to the region’. This effectively screened out the need to further address disruptive events, such as meteorite impact and tsunamis. Following the tsunami of 2004 in Sumatra, the department for the environment, food and rural affairs (DEFRA) commissioned a study of the potential threat posed by tsunami to Britain [44]. While tsunami events cannot be ruled out for the north-west coast, modelled estimates of wave height, based on past events and postulated future events, do not exceed 1 m to 2 m (see, for example, Table 7.1 of reference [44]). Given that the ground elevation between the LLWR site and the coast exceeds 20 m AOD, it is unlikely that a wave would reach the site even if a tsunami occurred.

LLW Repository Ltd produced a paper on the application of the EU Fukushima stress test [45] which considered the site’s resilience to extreme external events. The paper concluded that the existing safety measures at LLWR are adequate. LLW that is being processed or stored may be damaged by extreme external events. If this happens, containers, buildings, vaults and trenches would continue to offer some degree of containment. Releases to the environment would be below criteria for significance and public safety would not be threatened. Once damage had occurred, the situation would have no further potential for deterioration as seen at Fukushima.

The ONR report on the implications of events at Fukushima for the UK nuclear industry [46] states that:

> *'Tsunami risk at LLWR is extremely low as a result of its distance from driving mechanisms. Given the clear margin available between the maximum predicted flood heights and the dune protection, flooding impacts are considered to be minimal.'*

The ONR statement is based on the understanding of the elevations given above. The ONR report states that:

> *'Modelling for a 1 in 50 year storm surge indicates that a 2m increase in sea level is probable and if such an increase was included, the maximum sea level with extreme tide could reach +10.9m AOD.'*

Even allowing for ingress from the Ravenglass Estuary, such a surge might only cause flooding of the southern part of the LLWR site and would not be high enough to affect the trenches or vaults.

4 EPA Approach

4.1 Approach

The introduction of this report (Subsection 1.1.1) described the systematic, five-step approach that was applied (with iteration at each step as needed) to develop the EPA (Figure 1.1). The following subsections align with the five steps of the approach.

Each step of the approach provides new information. Iteration is needed to feed new information into earlier steps when required, and to ensure the conceptual models for the individual components and conceptual models for the whole system (repository) are aligned (consistent). The focus of this report is on presenting the outputs from this iterative process. Details of its development are presented in reference [21] and supporting documents.

In parallel with development of the EPA there has been ongoing optimisation of the repository design and development plans. These updates have been fed into the EPA during the development process. As noted in Subsection 2.1, the history of interactions between the EPA, engineering design and optimisation, and assessments over the last decade is complex. The history is outlined in references [5] and [21] and is not described here.

Development of the EPA was co-ordinated by a small core team, but the full, wider EPA team included:

- key individuals from the ESC optimisation team, together with supporting engineers from NWS and contracting organisations bringing detailed knowledge of recent vault and closure engineering design and other optimisation and design programmes, and the RMS;
- wider experts from other aspects of the ESC programme, and in particular members of the near-field, groundwater and wider modelling teams who both provided key inputs and were also ‘customers’ of the EPA outputs and its data;
- independent engineering experts from outside the main team to provide wider inputs and challenge thinking.

Multi-disciplinary workshops have been a key tool to developing the conceptual models and quantifying performance. Regulatory observers from the Environment Agency and members of the ESC Peer Review Group attended selected performance quantification workshops.

4.2 Identification of Conceptual Models

This subsection describes step one of the EPA approach (Figure 1.1).

A 'top-down' approach was used to develop conceptual models of engineering evolution and performance. We considered the nature of each component and the factors that affect its performance. These include, but are not limited to, the quality of construction, uncertainty in material properties and general degradation processes. Conceptual models were also developed for low likelihood events, such as a major failure in a localised area, or to explain why certain outcomes are not possible. An example of a potentially important local event would be collapse of a stack (or stacks) of containers as they degrade, weaken, and cannot carry the vertical load.

It was essential to consider interactions between the key components to develop internally consistent conceptual models of the evolution and performance of the whole system (repository) and its individual components. Engineering judgement and logical arguments were used to help identify the key component interactions and develop conceptual models for the whole system. For example, while strains resulting from waste settlement are an obvious factor for inclusion in the assessment of cap performance, interactions between the cap and cut-off wall are much weaker. The interactions between the cap and cut-off wall are sufficiently weak that their evolution and performance do not need to be coupled.

The level of discussion and analysis of each of the components is proportionate to the importance of the functions they provide, their complexity, and the anticipated sensitivity of the overall system performance to uncertainties in their evolution. The final cap, as a multi-barrier (and multi-layer) structure that is fundamental to performance, is a key focus. Analyses for other components are in general less complex, but nevertheless also sufficiently detailed to underpin a robust understanding of performance.

A 'bottom up' audit of the conceptual models developed during the first iteration of the EPA was undertaken against the detailed EPA from the 2002 PCSC [29]. Although there have been some changes in engineering design since 2002, many of the main components and concepts are similar, so the audit builds confidence that no key events or processes have been omitted. The details of the audit are provided in reference [20].

4.3 Supporting Information

This subsection describes step two of the EPA approach (Figure 1.1).

As noted in Subsection 1.1.1, we have used the EPA to integrate understanding relevant to engineering performance from across the ESC in a single place. Iterative development of the EPA over more than a decade means that understanding from ongoing optimisation work and best available technology (BAT) studies, updates to engineering design and development plans, new literature information, and outputs from our near-field work were progressively integrated into the EPA.

Key inputs to developing the conceptual models include the following.

- Projections of climate change and sea level rise [8], changes in HER [47] [48] and the timescales for start of disruption of the repository by coastal erosion [8]. These are summarised in Table 2.1.

- Outputs from repository optimisation and engineering design, including the optimised design and development approach (Section 3) and assessments underpinning the design, such as cap resilience including settlement calculations [42].

- Outputs from our conceptualisation and modelling of the near field, including pH and Eh conditions, waste degradation rates and container corrosion rates [6].
- Literature data from conventional landfills, other analogous facilities, civil engineering and the construction industry. This includes publications from other radioactive waste management organisations, including their assessment assumptions, data and outputs.
- Learning from experience and good practice guide to understand the quality of construction that can be achieve and types of defects that might be present.

In addition, we have established links with other radioactive waste management organisations, supporting exchange of information, sharing learning from experience, and site visits to understand approaches and concepts. These links are described under the topic of learning from experience in reference [5].

The following subsections summarise learning from the sources listed above to underpin development of the conceptual models in Section 5.

4.3.1 Cap Resilience Assessments

Multiple iterations of cap settlement and wider resilience assessments have been undertaken since the 2002 PCSC. Each has represented a development in assessment approach and methodology leading to the most recent assessment reported in reference [42]. Assessments have been undertaken for the trenches, vaults containing existing and committed containers and vaults containing future stronger containers.

Settlement occurs as the waste and containers degrade. As the waste and containers degrade, they weaken and compact under the weight of the overlying waste, profile fill and cap. Compaction occurs through movement of material into void spaces and compression of materials, reducing porosity. Degradation of organic waste to aqueous and gaseous products generates void spaces, allowing settlements to occur. Settlement can potentially propagate into the cap, and the associated strains can potentially damage the cap layers. The profile material absorbs strains from settlement and protects the cap. The effectiveness of the profile material in absorbing strains is controlled by its nature and its thickness.

Two outcomes of settlement are of interest.

- General settlement that occurs across the repository in which the cap height decreases and the cap gradient decreases. As the cap height decreases, the distance from the toe of the cap, over the surface of the cap to the crest decreases, suggesting there must be some shortening and distortion of the cap layers. Flat areas or reverse gradients would affect the ability of the cap to shed water, leading to increased hydraulic heads on the cap low permeability layers, which would typically result in a small increase in infiltration.
- Differential settlement occurs where a material that degrades and compacts is next to a material that does not degrade and compact or degrades and compacts much

more slowly (e.g. over a hard point). The differential movement can result in strains and possibly shear in the materials above the interface between the hard and soft materials. Differential settlement is of greater concern than general settlement as shear of the cap layers could significantly reduce cap performance, e.g. creating tears in the cap geomembrane and possible displacement of cap layers.

General and differential settlement are expected to be much lower at the LLWR than at a conventional landfill. This is because of the following considerations.

- The LLWR contains much less degradable material than a conventional landfill, especially in the vaults.
- All the readily degradable material in the trench wastes will have degraded prior to final capping. Much of the voidage will have already been expressed through degradation, loading by the interim cap and then surcharging prior to final capping.
- Voidage will be driven out of existing containers in the vaults, and containers committed to the same designs, by surcharging.
- Future stronger containers and shielded modules are typically expected to carry the vertical loads throughout the assessment timeframe, with insufficient settlement to affect performance.
- After the 2011 ESC, we implemented more robust controls on voidage in containers. This has resulted in a notable increase in the amount of grout typically added to containers (Figure 4.1), showing the action has been effective in reducing ungrouted voids. Even if future stronger containers do corrode and weaken to the point where settlement occurs, the containers will have much lower voidage than the existing vault wastes. This will limit potential settlements so the resulting strains will not damage the cap.
- Future containers are projected to contain much less degradable material than existing containers [4]. Again, this will limit potential settlements if future containers degrade to the point settlement occurs.

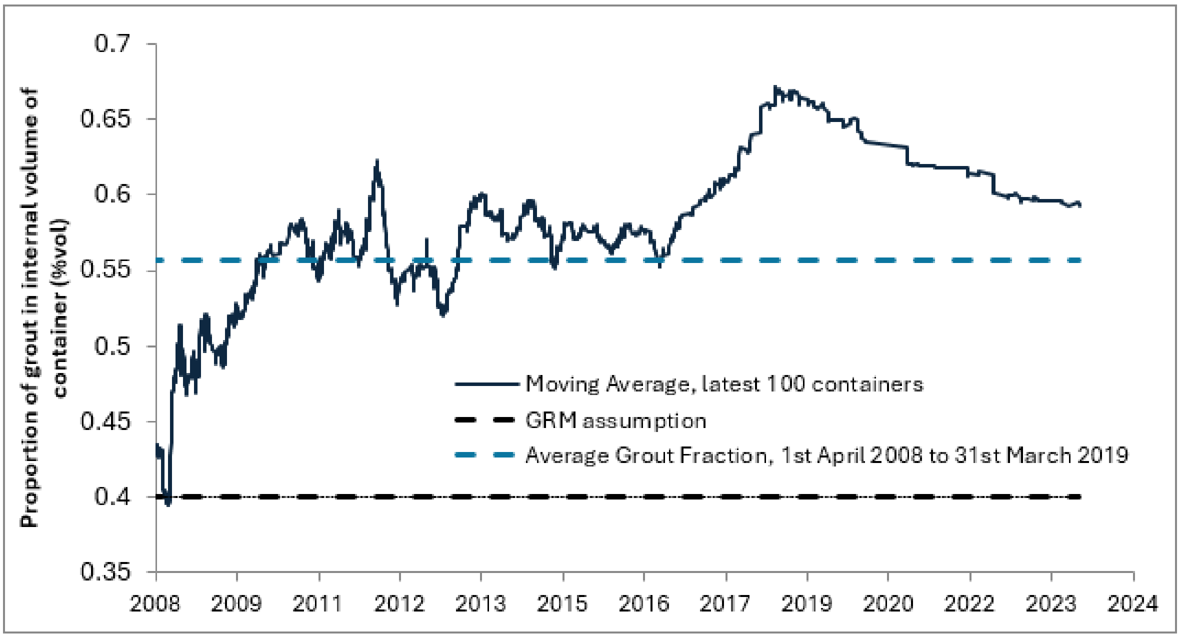


Figure 4.1: Amount of grout added to containers [49][6]

The assessment, including calculations and associated lines of reasoning, provides a high degree of confidence that the maximum possible strains are below the levels the cap BES and undegraded geomembrane are resilient to. However, once the cap geomembrane has lost its antioxidants and has oxidised, it will become brittle and stress cracks will form.

The assessment also provides confidence that the cap will retain its shape and gradients as general settlement occurs. As the waste degrades, different areas of the cap will settle more quickly than others. The main gradient of the cap is 1:25 (Figure 3.9). Even though differential settlement is not sufficient to cause unacceptable strains in the low permeability layers, some transitory local flattening of the profile, or even minor reverse gradients, could occur. The assessments provide confidence that such transitory changes will not significantly affect performance as the low permeability layers will remain intact.

A key overall outcome from our resilience assessments is confidence that degradation and settlement of the waste will not damage the cap. This means that the coupling between conditions in the waste, evolution of the waste, and performance of the cap is weaker than in systems where large amounts of waste settlement are expected.

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[6] At each date, the moving average is calculated using the 100 most recently received consignments. These data suggest a general upwards trend from 2008 to 2019, followed by a steady decrease associated with the containers grouted in the most recent campaign. Most of the decrease is associated with the increase in the assumed grout density. Assuming 1.8 t m^{-3}, the average volume fraction tends towards 59%, as shown in this figure. Assuming 1.7 t m^{-3}, the average tends towards 62%, which is only slightly lower than the values observed in 2019, at the time of the last grouting campaign. The small decrease may be taken as evidence that the waste packing fraction is beginning to improve.

4.4 Understanding of the Near Field

Our understanding of the evolution of biogeochemical conditions in the repository is coupled to the engineering performance. The EPA provides information on engineering performance and infiltration rates to our near-field work [6]. These are key inputs to understanding the biogeochemical evolution of the trenches and vaults. For example, the rate of infiltration affects leaching of cement from grout and concrete in the vaults. Leaching of cement affects the pH conditions, and therefore metal corrosion rates, the microbial processes that may be active and their rates. Corrosion rates affect the durability of containers in the vaults. Container durability affects water flows in the vaults and evolution of the biogeochemical conditions. Information on degradation of the waste and corrosion of the containers, and information relevant to the potential for clogging of drainage components by precipitation and biofilms, is fed back into the EPA.

Given this coupling and the associated feedbacks, the EPA and our near-field understanding have necessarily been developed iteratively, with the integrated understanding subsequently feeding into our assessments. A summary of our understanding of the conditions and flows in the trenches and vaults is provided below. Key evidence underpinning this understanding includes the cap infiltration rates, settlement calculations, biogeochemical models of the trenches and vaults, and the extensive data set underpinning our elicitation and expert review of corrosion rate data[7].

Conditions in the trenches are expected to be moderately reducing with slightly acidic to neutral pH [6]. Bulk gas is generated by microbial degradation of organic waste, especially cellulosic waste, and anaerobic corrosion of metals (mainly steels). Microbes in the trenches generate CO_2 and CH_4 gas, as they degrade organic (principally cellulosic) waste, and reduce CO_2 with H_2 generated by anaerobic corrosion of steels, forming CH_4 gas.

Biogeochemical conditions in the vaults are significantly different to the trenches. Although the Ordinary Portland Cement (OPC) content of the LLWR grout is low, the containers are expected to provide sufficient protection during the operational phase that alkali metal hydroxides are not flushed from the grout before closure. At closure, the typical pH in the waste containers is expected to be around pH 12.5 [6] [50].

The pH will typically be too high for microbial activity, although some activity in niches on the surfaces of cellulosic waste in super-compacted pucks cannot be ruled out with confidence (e.g. by analogy with reference [51]). Conditions inside the containers will be very reducing, due to metal corrosion and isolation from the atmosphere by the profile fill and cap. Given the lack of microbial activity, the main gas generated in the vaults will be H_2 from anaerobic corrosion of metals.

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[7] We have undertaken a detailed elicitation exercise and expert review to understand metal corrosion rates in the trenches and vaults under the range of conditions expected to be encountered throughout the lifetime of the repository. This includes conditions during the operational period, following installation of the closure engineering, throughout the post-PoA period, and following exposure by coastal erosion [6], [107], [108].

The LLWR grout is substantially water saturated when it has cured. There may be some drying during the operational phase, depending on weather protection. The exception is some top of stack existing and committed containers. Rainwater may enter through open grout ports in the container lids, fully saturating the grout. Ponded water may be present in containers that have an ullage space, but this will be expressed from the containers when they deform during closure.

The results of our EPA, presented in this report, show that once the repository has been capped, infiltration is expected to be very low. Infiltration will be focused on the top of stack containers immediately below defects (small holes) in the cap geomembrane. Most containers will not be exposed to infiltrating waters. Infiltration and water present in the containers at closure will be consumed by corrosion leading to gradual drying within the wastes. However, water present in the containers and other repository components at closure, and the ground, are assumed to generally maintain humidity at a level (60% to 70% [52]) at which metal corrosion can proceed.

Outside the containers the pH is expected to be significantly lower than inside the containers. Initially the pH is anticipated to be around 8 to 9, buffered by iron corrosion products on the surfaces of containers, and by carbonates on the surfaces of the concrete walls and floors, which form during the operational phase. The pH may be locally higher below defects (small holes) in the cap geomembrane, with the cap BES conditioning infiltrating water to around pH 10 [53]. The lower pH outside the containers compared with inside the containers would lead to faster corrosion of the outer surfaces of the containers compared with the inner surfaces (sufficient water being available).

Conditions outside the containers would be highly reducing, due to isolation from the atmosphere and hydrogen generated from anaerobic corrosion of the steel containers and metal waste. The conditions outside the containers would be amenable to microbial activity. However, while the cap geomembrane is intact, water flow and saturation would be too low for significant transport of organics from the containers into the gaps between the stacks where microbes could be active.

If humidity is low, microbes lose water and shrink. Microbial replication stops when the relative humidity is below about 60% [54]. Therefore, if humidity inside or outside the containers falls to a level where corrosion stops, microbial activity would also stop. Corrosion and microbial activity would restart as the engineering starts to degrade, and infiltration into the vaults increases. As noted above, the humidity in the repository generally expected to be greater than 60% to 70%, so we assume microbes will always be active.

Once the cap geomembrane fails, infiltration into the repository is expected to increase. However, infiltration will still be low, limited by the cap BES and other cap layers. Water will flow through existing and committed containers with damaged lids at the tops of stacks, and to a lesser extent through the underlying containers, resaturating the containers and transporting solutes (Figure 4 2). Water will flow down the gaps between stacks of future containers with CPUs (Figure 4 3). Capillary suction will imbibe water through small corrosion perforations in the containers, until the grout has resaturated. Solutes may diffuse out of the corrosion perforations into water in the gaps.

pH conditions inside and outside the containers will change little over the remainder of the assessment timeframe. Under the high pH conditions, general corrosion of the containers will be too slow for significant thinning and weakening of the containers. Only the existing and committed LLW containers (that have been surcharged, resulting in structural damage and deformation), are expected to allow significant interaction between grouted wastes and infiltrating water. The stronger containers for both LLW and ILW will be protected from structural damage by the container protection units placed on the top container of each stack. Localised perforation by corrosion may occur, but this may not affect all containers and the interaction with infiltration will still be restricted.

Standing water may start to develop on the vault bases. This is not expected to significantly affect the rate of corrosion of the bottom of stack containers compared with the humid, unsaturated conditions. There may be some additional leaching of hydroxide and alkali metals from the grout in these containers, but this will be a slow diffusive process, further limited by the largely intact containers and small contact area. Therefore, conditions in the bottom of stack containers are expected to be similar to the overlying containers.

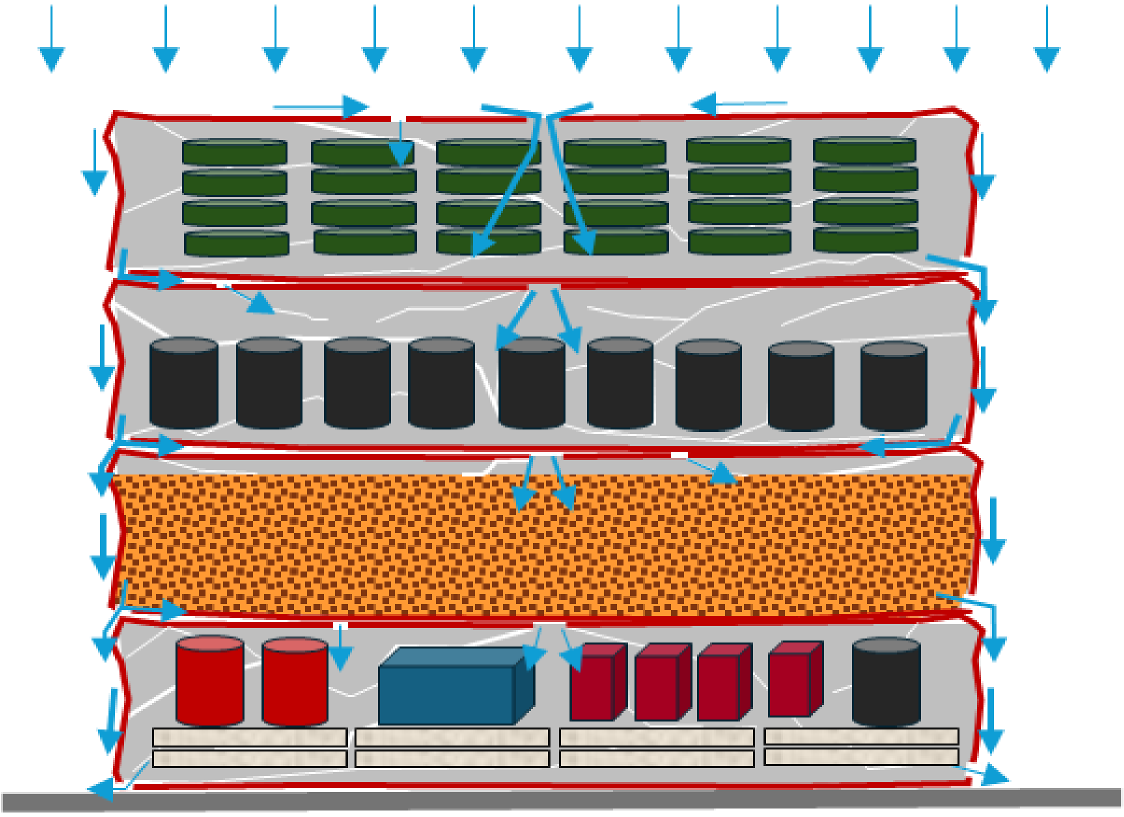

Figure 4.2: Conceptual model of post-closure water flows through stacks of deformed existing and committed ISO containers (red lines), illustrating variable waste types, unsealed grout ports, small tears, local corrosion perforations and extensively cracked grout (grey).

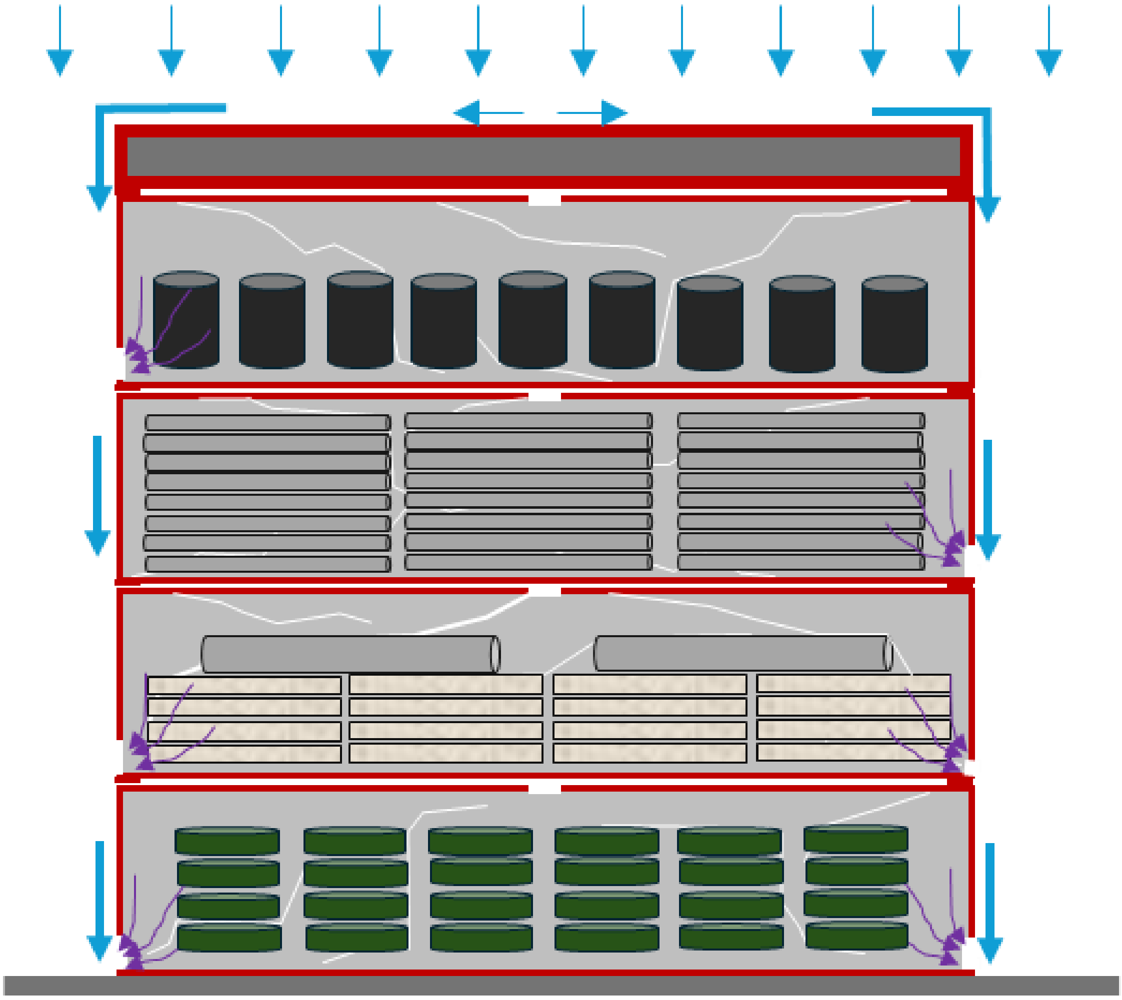

Figure 4.3: Conceptual model of post-closure water flows over a CPU and down the sides of future stronger ISO containers (red lines), and diffusion of aqueous species from variable waste types through the cracked grout (grey) and small perforations in the containers.

4.4.1 Literature Data

The EPA integrates literature information on a wide range of topics. Key topics are:

- geomembrane defects, degradation processes and rates;
- BES properties and degradation;
- performance and degradation of composite resistive layers, i.e. combined geomembrane and BES;
- structural concrete and grout properties and degradation, including the effects of leaching, chemical attack, and expansive rebar corrosion resulting in concrete cracking in structural concrete;
- physical and biogeochemical clogging in drainage systems, including in landfills and a much wider range of potential analogues.

Literature information has been used directly in development of the conceptual models and parameterisation of performance, and in workshops that supported development of the conceptual models and component properties. For each of the topics listed above, literature information was assembled into workshop data packs.

There is extensive research in the UK and internationally on the long-term evolution and performance of key repository materials including metals, concrete, grout and BES, e.g. references [55], [81], [56], [57]. We have used information from several radioactive waste management organisations, repository concepts and environmental safety assessments. Information from SKB's assessments for their existing SFR facility for disposal of L/ILW [58] is particularly relevant because the facility exists, the wastes are comparable to those that are or might be disposed at the LLWR, and extensive information is readily available.

We have taken care when using literature data to consider the applicability to the LLWR. For example, SFR is located at around 50 m to 100 m depth in fractured crystalline bedrock. Therefore, the groundwater and mechanical conditions are quite different to those at the LLWR. This may result in different rates and modes of degradation. Another example is literature data on clogging. The literature focuses on sites where extensive clogging has been observed. While all these sites have different physico-chemical conditions to the LLWR, our analysis of the literature has helped provide confidence that the passive drainage system at the LLWR will not clog significantly post-closure.

4.4.2 Construction Management and Construction Quality Assurance (CQA)

Good practice construction management processes, from design to procurement and implementation, and associated rigorous Construction Quality Assurance (CQA) approaches are essential for achieving the anticipated engineering performance. Learning from experience is being applied to build confidence in implementation. This includes learning from examples of bad practice associated with construction of the original interim trench cap, and good practice associated with construction of Vault 9.

Intrusive investigations and inspection of construction records [59] suggest the geomembrane in the interim trench cap over trenches 1 to 6 was laid in the wrong direction, i.e. across the slope rather than down the slope. Cover materials were then pushed downslope rather than being placed upslope. Combined with working in wet weather and use of poor cover soils, this resulted in tears and gaps in the geomembrane across the slope of the cap. These defects intercept substantial volumes of water flowing downslope and allow water to infiltrate through the cap. No such damage has been found in the later Trench 7 interim cap, where the geomembrane was laid down the slope. Possible better working practices were also used.

The procurement process for construction of Vault 9 demonstrated the importance of selecting a contractor with a demonstrable commitment to quality. Placement of one of the BES layers in the base of Vault 9 did not meet the contractor's quality requirements, so the contractor removed and relayed the material.

The current southern trench cap interim membrane replacement project (STIM) is being implemented incrementally. Learning from initial work on a small area is being applied across the wider southern trenches area and will feed into delivery of the first strip (Tranche 1) of the final cap.

Literature resources provide learning from other sites and describe good practice processes, (e.g. references [60], [61], [62] and underpinning references). These include resources developed by the Environment Agency. These resources have been reviewed as part of developing this EPA and have directly informed the performance that is expected to be achieved, e.g. reference [63].

The cap geomembrane and BES layers are important for minimising infiltration into the repository. The potential for construction defects in these layers is of particular concern. Reference [21] includes:

- literature data on the frequency of defects in real systems, e.g. reference [63];
- a review of installation faults and hazards that could lead to defects in the cap low permeability layers;
- a review of the cap design, construction management and CQA activities that could be used to minimise the frequency of defects;
- the risks of defects once cap design, construction management and CQA activities have been applied, and the types of defects that might still be present.

The EPA also reviewed latest information on the strain tolerance of the composite barrier materials identified in reference [42].

The review was used to underpin CQA assumptions in the EPA, especially the assumed types and frequency of defects in the cap geomembrane, including folds, wrinkles, pinholes, holes and tears which are key inputs to the cap infiltration calculations.

For the EPA, the reference assumption is that all future engineering components (including the cap) will be built with excellent, high-quality construction management and CQA processes [5]. The potential consequences of worse than expected CQA, leading to lower performance are captured in alternative engineering evolution cases, which then inform the cases we consider in our assessment calculations.

Further discussion of construction management and CQA is also provided in the '*Engineering Design*' report [5].

4.5 Component and Whole System Evolution and Performance

This subsection describes steps three and four of the EPA approach (Figure 1.1).

4.5.1 Reference and Alternative Evolution Cases

We have developed a suite of engineering evolution cases, which describe different conceptual models of the evolution and performance of the key engineering components and the repository (whole system). These include a REEC, which describes the best estimate evolution and performance, and AEECs which describe plausible, but less likely, alternative evolutions.

The suite of cases provides a structured exploration of conceptual model uncertainties in the engineering evolution and performance. The cases are also used to explore uncertainties in the properties of the key components. This subsection further describes the aims, structure and content of the cases.

The aim of the suite of cases is to bound the reasonable failure modes and timings for the key components, and therefore evolution and performance of the whole system. It is not necessary to describe all possible evolution paths within the performance envelope. The cases also aim to explore key situations of interest. Some of the AEECs capture low probability 'what-if' failure modes and events that are outside the bounds of the worst credible to best possible performance envelope or are implausible. The 'what-if' cases are used to record arguments why situations that are of interest or might cause concern are very unlikely or implausible.

The cases for individual key components are aligned with those for the whole repository. For example, in the REEC the conceptual model of evolution and performance of the vault bases is consistent with the conceptual model of the evolution and performance of the final cap, with the cap performance affecting infiltration and the rates of alteration of cement and bentonite in the bases. The approach used to construct the REEC and AEECs is described below.

These cases do not correspond on a one-to-one basis with ESC assessment calculation cases. They are engineering-focused analyses aiming to explore the range of potential modes of evolution of the engineered system. However, they inform the ESC assessment calculations, which also consider a wider range of factors.

Reference Engineering Evolution Case

The REEC lies within an envelope of possible closure system performances ranging from very good to very poor. The REEC lies approximately midway between the worst credible and best possible system behaviours. There are uncertainties within the bounds of the REEC that are of equal likelihood. Uncertainties within the bounds of the REEC are explored as variants to the REEC, for example REEC variant cases explore the consequences of uncertainty in the location of the first failure of the cap geomembrane and mineral layers.

Alternative Engineering Evolution Cases

AEECs describe evolutions of the system that clearly diverge from the REEC. These include markedly different timeframes for evolution of key components compared with the REEC, and different processes and modes of evolution. Like the REEC, there are uncertainties within the bounds of each AEEC that are of equal likelihood. Again, uncertainties within the bounds of a given AEEC are explored as variants to the AEEC.

Definitions of Key Terms Used in the Engineering Evolution Cases

The cases describe 'general degradation' and 'failure' of the engineering components. We define general degradation and failure as follows.

- General degradation – processes that do not result in sudden and large changes in the performance of a component. General degradation may be a precursor to failure.
- Failure – sudden and large change in performance resulting from an event. Note that a failed component might still provide some benefit. Failure could refer to the whole component or a local area.

A component, or the whole system, may be described as 'degraded' when performance has substantially changed from its initial ('as built') level. A component is fully degraded when its properties have reached long-term values that do not change on the timescales of interest. The system is fully degraded when all components are fully degraded.

Degradation is not always bad for performance. The context is important. For example, degradation of the vault bases during the operational phase would be negative as it could reduce the effectiveness of leachate capture. However, long-term (post-PoA) degradation of the vault bases is positive as this helps water to reach the passive drainage blankets keeping water levels in the vaults low.

4.5.2 Development of Cases

Development of the REEC and AEECs involved work and review undertaken in multidisciplinary workshops. We systematically identified REECs and AEECs for each key component. We iterated the REEC for the key components and the whole system so they were aligned (see explanation in Subsection 4.2) and then looked to see how we could combine the AEECs for individual components to explore the most important alternative evolutions of the whole system.

We have worked through this iterative process several times over the last decade as the engineering design and our understanding of component performance and interactions have developed [20] [36] [21].

AEECs for the whole system were systematically built up by considering various combinations of good and poor performance for different key components and by varying the time of onset of possible events. To keep the number of AEECs manageable, cases exploring similar aspects of performance were grouped. For each combination the conceptual models for each key component and the whole system were aligned. This enabled the sensitivity of the closure system to the performance of different components (both separately and in combinations) to be explored and to help understand the implications of the important feedback loops.

Judgements were made during the combination process to ensure the cases did not include unreasonable 'runaway' feedback loops. For example, while cap failure and waste settlement are strongly linked, cut-off wall evolution is not considered to be affected by changes to other components. Its evolution was therefore considered without much reference to the state of other key components. Similarly, although some quite extreme events were considered possible it was assumed that combinations of unrelated extreme events were very unlikely and therefore were not considered e.g. the simultaneous complete failure of the cap and the cut-off wall. Ten AEECs were identified for evolution and performance of the whole repository. The REEC and these AEECs are described in Subsection 4.5.4. However, first we describe how the timeframes for evolution were identified for each case to provide a 'storyboard' of evolution and performance over time.

4.5.3 Conceptual Model Storyboards

For each engineering evolution case we developed storyboards which describe the evolution and performance of the whole repository and the individual key components over time. The storyboards are presented in tabular format, with the condition and performance of each component described at times of interest.

The natural starting point for the EPA is when a component is constructed. Uncertainty in the performance of a component, and its contribution to the performance of the closure system is smallest at the time of construction. Information on the properties and performance of each component is (or will be) provided by design specifications, material and construction development tests, CQA including associated sampling and testing, and post-construction monitoring. Uncertainty in the performance of the component generally increases with the elapsed time since construction.

An end point for the assessment needs to be selected. This needs to be sufficiently far in the future to fully capture the period of interest. This judgement needs to recognise that uncertainty in performance increases significantly with time, and performance becomes increasingly difficult to project.

The start of repository disruption by coastal erosion was selected as an appropriate end point for the EPA. This is because, once the repository is breached by coastal erosion the behaviour of the facility is likely to be very different. To ensure this point is captured, the EPA chose 5,000 years as a suitable end point. This is well beyond the longest projected timescale for start of disruption of the repository by coastal erosion (Table 2.1) and is comparable to the timescales for the start of disruption assuming historical erosion rates, with no climate change or relative sea-level rise [8].

A set of timeframes were identified between 0 years and 5,000 years, which are relevant to key changes that would or could occur (e.g. waste degradation or engineering material evolution).

The timeframes adopted were:

- During completion and, or as-built.
- 0 to 100 years.
- 100 to 500 years.

- 500 to 1,000 years.
- 1,000 to 5,000 years.

These are appropriate periods to capture arguments on gradual evolution of the system and any events or step changes.

As uncertainties in component and system performance increase with time, the EPA focused on the first 1,000 years. Evolution from 1,000 years to 5,000 years is described in sufficient detail to provide an outline of the expected evolution over this timeframe.

4.5.4 Exploration of Uncertainties and Performance Envelopes

4.5.4.1 Exploration of Uncertainties

A REEC and ten AEECs were carried forward for assessment (Subsection 4.5.2). Variant cases have been identified for the REEC and some of the AEECs which explore uncertainties within the bounds of the case that are of equal likelihood. The cases and their variants are described in Table 4.1.

A key element of the REEC is the timescale for degradation of the cap. Given the expected durability of the cap geomembrane (Table 5.3), the results of settlement calculations [42], and the expected performance of the cap BES once the geomembrane has degraded, we anticipate the cap would remain largely functional for more than 2,000 years. The quality of the cap engineering, design and component selection, and the planned quality of the construction and CQA also support the expected performance and durability of the cap.

Table 4.1: Overview of the main engineering evolution cases

Case	Description	Variants
Reference Engineering Evolution Case (REEC)[8]	The reference case with no significant cap failure until around or after 2,000 years.	REEC 1.A - REEC 1.E: Variants exploring different potential locations of the first failure of the cap geomembrane and mineral layers, assuming this does not occur until around or after 2,000 years (although general degradation is in progress before then), and assuming a linear[9] failure initially. All other areas of the cap geomembrane fail subsequently, most likely within a few decades.
		REEC 1.F: Explores the less likely case that all evolution is gradual (i.e. there is no localised failure for a prolonged period beyond that for the REEC).
Alternative Engineering Evolution Case A (AEEC A) Accelerated Reduction in Cap Performance over the Vaults	A lower probability case exploring accelerated reduction in cap performance leading to cap failure, localised to over the vaults, before 1,000 years.	AEEC A.1.A - AEEC A.1.C: Variants exploring different potential locations of the first failure of the cap, between 500 to 1,000 years, assuming a linear initial failure (as in the REEC), with the geomembrane only failing.

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[8] Here 'combined' refers to evolution of the system as a whole, considering all relevant engineering components, rather than one component (e.g. the cap) on its own.

[9] A 'linear' failure is a tear or other discontinuity that is essentially linear in form.

Case	Description	Variants
		AEEC A.1.D: Assesses the implications if the first failure, over the same timeframes, involves the mineral layer as well as geomembrane failure.
		AEEC A.1.E: Explores the less likely case that the first failure is not a localised one, and that all evolution (although accelerated compared to the REEC) is gradual.
Alternative Engineering Evolution Case B (AEEC B) Accelerated Reduction in Cap Performance over the Trenches.	A lower probability case exploring accelerated reduction in cap performance leading to cap failure, localised to over the trenches, before 1,000 years.	AEEC B.1.A and AEEC B.1.B: Variants exploring different potential locations of the first failure of the cap, between 500 to 1,000 years, assuming a linear failure (as in the REEC), with the geomembrane only failing.
		AEEC B.1.C: Assesses the implications if the first failure, over the same timeframes, involves the mineral layer as well as geomembrane failure.
		AEEC B.1.D:

Case	Description	Variants
		Explores the less likely case that the first failure is not a localised one, and that all evolution (although accelerated compared to the REEC) is gradual.
Alternative Engineering Evolution Case C (AEEC C) Major Failure of the Cap.	A further, much lower probability case exploring more significantly accelerated reduction in cap performance leading to a full failure of the cap, involving significant general degradation in performance plus failure of the geomembrane and the mineral layer, before 1,000 years.	AEEC C.1.A - AEEC C.1.E: Variants exploring different potential locations of the first full failure of the cap, between 500 to 1,000 years, assuming a linear failure (as in the REEC). All other areas fail by 1,000 years.
		AEEC C.1.F: Variant exploring full simultaneous failure across the cap, between 500 to 1,000 years, with no single first location of failure.
Alternative Engineering Evolution Case D (AEEC D) Enhanced Cap Performance.	A lower probability case where the cap performance lasts for longer than assumed in the REEC, with all evolution gradual; no further variants considered necessary.	No variants.
Alternative Engineering Evolution Case E (AEEC E) Interim trench cap not punctured	This case was included in early EPA studies in advance of recent optimisation studies. It is now redundant. We have decided the existing LDPE geomembrane in the interim trench cap will be punctured, and the replacement GCL/GDL over the	No variants.

Case	Description	Variants
	southern trenches will be removed prior to final capping.	
Alternative Engineering Evolution Case F (AEEC F) Faster than expected deterioration and/or more extensive failure of one or more sub-areas of the vault base and walls.	A lower probability case exploring early deterioration of the bases and walls, based on considering the potential for complete corrosion of reinforcement bars in one or more of the vaults after PoA+100 years, with the effect of prolonging the period for which the vaults remain at low saturation below the level of the 1 m walls. Variant cases explore failures in specific locations within the vault system.	AEEC F.4.A: Failure in HHISO Surcharge (existing and committed LLW) Vault Area
		AEEC F.4.B: Failure in Strengthened Containers (Future LLW and potential ILW) Vault Area
		AEEC F.4.C: Failure in Shielded Modules (ILW) Vault Area
Alternative Engineering Evolution Case G (AEEC G) Slower than expected deterioration of the vault base and walls.	A lower probability case exploring later deterioration of the bases and walls, essentially characterised by the performance of the vault bases and walls continuing at PoA levels beyond 500 years, thus increases the likelihood of the vaults becoming saturated to the top of the 1 m walls within that timeframe.	No variants

Case	Description	Variants
Alternative Engineering Evolution Case H (AEEC H) Faster or more extensive failure of one or more sub-areas of the cut-off wall.	A lower probability case exploring cut-off wall failure.	No variants.
Alternative Engineering Evolution Case I - Slower than expected progressive failure of the cut-off wall.	Explores the potential for slower deterioration in performance of the cut-off wall; as the REEC assumes performance into the longer term, this is better performance e.g. by cation exchange processes not completing by the time of evolution.	No variants.
Alternative Engineering Evolution Case J - Earlier than expected clogging of the under-vault drainage blanket.	Considers the possibility that the under-vault drainage experiences earlier than expected clogging – decreasing the permeability contrast with the surrounding geology (by an order of magnitude) by around 250 years.	No variants.
Alternative Engineering Evolution Case K - Greater than expected clogging of the under-vault drainage blanket.	A less likely case considering that the level of clogging is greater than for the REEC. Once clogging commences, permeability is rapidly decreased compared with REEC.	No variants.

4.5.4.2 Performance Envelopes

AEECs, and variants of these cases, were used to understand the worst credible to best possible system performance. Together these cases help us understand the envelope of system performance. None of the AEECs describe the worst credible or best possible system performance throughout the assessment timeframe, as this might involve unlikely or impossible combinations of component evolution. However, an AEEC might describe worst credible or best possible system performance for part of the assessment timeframe. This is shown schematically in Figure 4.4.

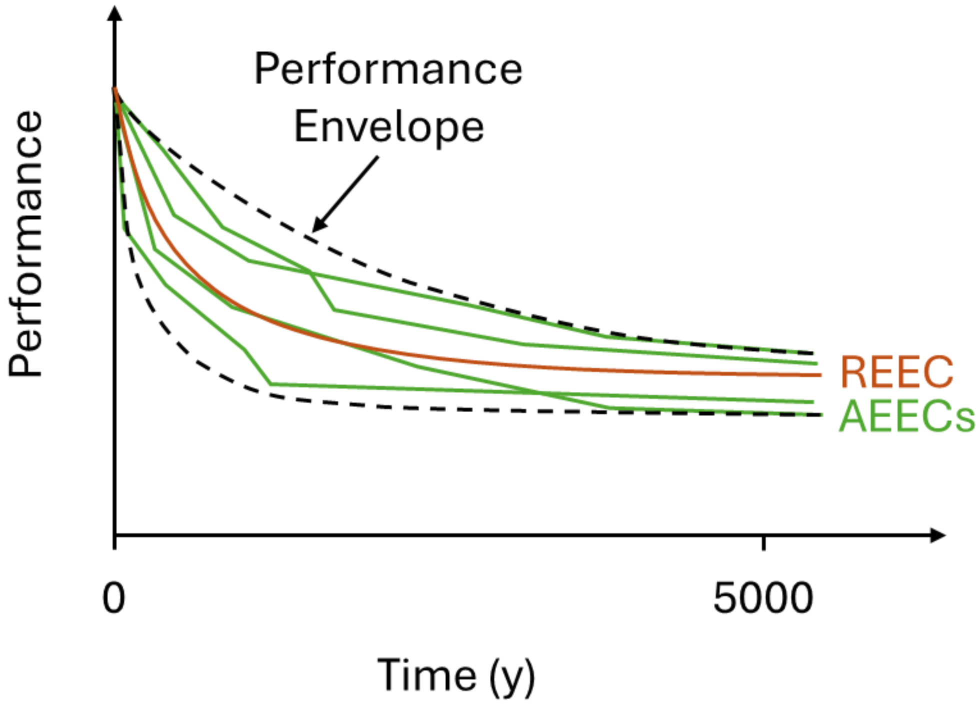

Figure 4.4: Schematic description of the performance envelope explored by the REEC and AEECs, excluding 'what-if' cases

Upper and lower bound performance were considered when parameterising the properties of the components for use in assessment calculations. Selection of parameter values for upper and lower bound performance was guided by the REECs and AEECs and understanding from those cases, i.e. component interactions and feedback loops, were considered when selecting parameter values for individual components to ensure they are consistent with the overall repository evolution and performance. 'What-if' cases lie outside the envelope described by lower and upper bound performance and are not shown in Figure 4.4.

4.5.4.3 Exploration of Upper Bound Performance

With upper bound performance the engineering performs better than expected for longer than expected. Therefore, the hydraulic conductivities of resistive components are lower than in the reference case and remain low for longer, while the hydraulic conductivities of drainage components are higher than in the reference case and remain higher for longer.

The following cases help to describe the upper bound of the performance envelope:

- Case D – Enhanced cap performance.
- Case G - Slower than expected deterioration of the vault base and walls.
- Case I - Slower than expected progressive failure of the cut-off wall.

There are arguments for associating Case G with upper bound performance and with lower bound performance. Here we associate Case G with upper bound performance for the following reasons.

- Slower degradation of the vault bases means they are closer to their design specification for longer, and arguably performance can be calculated with greater confidence.
- The difference between Case G and the reference case is expected to be limited as water will be directed over the 1 m high walls in the future vaults into the drainage blankets. Over topping of the 1 m high walls will start a little earlier than in the reference case and the flow rates over the walls will be a little higher. However, cap performance is expected to exert greater control on the timing than differences in the permeability of the bases. In both cases overtopping of the 1 m higher walls is likely to start reasonably soon after failure of the cap geomembrane, and an associated step increase in infiltration into the vaults. Assuming no loss of water through the vault base, a simple scoping calculation shows it will take around 13 years for water to rise to the 1 m level (Table 1.1).

Table 4.2: Scoping calculation of the time for water levels in the vault to rise 1 m

	Value	Notes
Infiltration rate	30 mm y^{-1}	Around the 50th percentile value when the cap geomembrane fails [64]
Porosity	0.4	Approximate average of the vault waste and drainage media between stacks
Time for water level to rise 1 m	1,000 mm x 0.4 / 30 mm y^{-1} = 13 years	Assume no loss of water through the vault base

4.5.4.4 Exploration of Lower Bound Performance

With lower bound performance the engineering performs worse than expected and degrades faster than expected. Therefore, the hydraulic conductivities of resistive components are higher than in the reference case and increase more quickly, while the hydraulic conductivities of drainage components are lower than in the reference case and decrease more quickly.

The following cases help to describe the lower bound of the performance envelope:

- Case A – an accelerated reduction in cap performance over the vaults;
- Case B - accelerated reduction in cap performance over the trenches;
- Case F - faster than expected deterioration and, or more extensive failure of one or more sub-areas of the vault base and walls;
- Case H - faster or more extensive failure of one or more sub-areas of the cut-off wall;
- Case J - earlier than expected clogging of the under-vault drainage blanket;
- Case K - greater than expected clogging of the under-vault drainage blanket.

There are arguments for associating Case F with upper bound performance and with lower bound performance. Here Case F is associated with lower bound performance for the opposite reasons described in the previous subsection in relation to Case G.

4.5.4.5 'What-if' Cases

The most important 'what-if' case is:

- Case C – major failure of the cap.

We think it is very unlikely that there will be a major failure of the cap. This case is used to present the arguments. The key arguments against a major failure are:

- the low cap gradients, especially over the waste, which minimise the risk of erosion or slipping of the layers;
- the waste characteristics and design choices minimise the potential for settlement (Subsection 4.3.1, and later in subsections 5.2 and 5.3);
- the cap includes multiple layers that provide different functions, have redundancy in their design, and support each other providing stability and further redundancy;
- the chemical and physical environment within the cap is benign (this is described later, in Subsection 5.2.2);
- the risk of damage from natural hazards, such as seismic activity, is low (Subsection 2.3).

4.6 Quantification of Performance

This subsection describes step five of the EPA approach (Figure 1.1).

4.6.1 Probability Density Functions Quantifying Performance

The properties of the engineering were quantified for use in assessment calculations based on their conceptualised performance and underpinning evidence. The properties quantified within the EPA were:

- Probability density functions (PDFs) describing the frequency of classes of defects in the cap geomembrane (pinholes, holes, wrinkles, and tears including stress cracks). PDFs were developed for the cap geomembrane 'as built' and for future times. Key evidence included research undertaken by the Environment Agency [63], as used in their own landfill assessments [65], and multiple lines of evidence from recent research in Canada and the US [66] [67] [68].
- PDFs for the time when the antioxidants in the cap geomembrane have been depleted and subsequent oxidation has completed, and the time when widespread brittle failure of the geomembrane begins. Key evidence was provided by research undertaken in Canada, including long-term experiments in support of the liner and capping system for CNL's proposed Near Surface Disposal Facility (NSDF) for LLW.
- PDFs for the hydraulic conductivities of the cap BES layer and drainage layer, and for the other key components 'as built' and for future times. Some of the key components are constructed from several elements. For each key component, the properties of all the main elements were quantified. Key evidence was provided by collations of literature data and supporting calculations, e.g. timescales for rebar corrosion and cracking in structural concrete [21].

The PDFs for the cap layers (drainage, geomembrane and BES) were used within the EPA to calculate PDFs for infiltration rates through the cap 'as built' and for future times. The approach to calculating cap infiltration rates is described in Subsection 4.6.4. The final PDFs supplied to assessment calculations were infiltration through the final cap and the hydraulic conductivities of the other key components.

The PDFs describe the reasonable envelope of performance and evolution of the system and reflect the REEC and AEECs. 'What-if' cases are very low likelihood or implausible. Very low likelihood 'what-if' cases that are plausible lie outside the distributions.

4.6.2 Approach to Developing PDFs

For each engineering component, parameter values have been identified that reflect the conceptual models. Parameter values have been identified for each component 'as built' and for key times in the future, except for vault wastes and container stacks. The behaviours of the trench waste, and the vault waste and container stacks are strongly dependent on the geochemical conditions in the repository. Therefore, properties of the trench waste, and the vault wastes and container stacks have been developed within our near-field work and assessments, informed by our understanding of the inventory, vault engineering and evolution of the near field [6]. The properties of the trench waste, and the vault waste and container stacks developed by these other areas of the ESC are summarised in Subsection 5.3.5.

Development of parameter values within the EPA included the following steps.

- Identifying key parameters and options for the derivation of PDFs, including identifying any EPA-specific modelling that might be required. Review and agreement of the approach for each component through appropriate workshops.
- Literature reviews, analysis, and calculations as required.
- Production of workshop briefing material, including relevant contextual information and proposed PDFs and their justification. Examples of contextual information include:
    - outcomes of discussions with assessment modellers on their requirements;
    - assumed approaches to construction quality management and CQA;
    - intended use of the PDFs;
    - guidance on use of the conceptual models, including using alternative evolution cases to inform development of PDFs.
- Review of the briefing information in at least two and, in general, several iterations of workshops to identify an agreed set of outcomes and underpinning rationale. This included several iterations of the EPA over several years, as well as workshops held as part of the final iteration of the EPA. Additional work was undertaken between iterations as required.
- An ‘integration’ workshop to ensure that the outcomes across all components are aligned and correlated.

A proportionate approach has been taken to parameterising engineering performance. This included different classes of workshop (Table 4.3) and activities providing inputs to the workshop. The most resource intensive approach is 'full elicitation'. Full elicitation involves production of workshop briefing materials and datapacks, extensive discussion of conceptual and numerical models, and then elicitation of parameter values. We have developed an elicitation approach [69], which captures learning from previous elicitations for the LLWR, the UK Geological Disposal Facility (GDF) programme, and good practice guidance.

Table 4.3: Classes of review workshop

Title	Description
‘Standard’ documentation review	Review of past documentation and any updated information on component performance. Recommendation of changes (or no changes) to parameter values and the supporting evidence. This approach was relevant where there was already good confidence in the understanding of a system component and the ability to

Title	Description
	translate that into parameter values. Outcomes of the review were presented at a multidisciplinary workshop where they were endorsed or alternatives values agreed.
‘Enhanced review’	Data packs were developed which included component design and specification information, literature performance data, and the results of EPA team analyses and calculations. The core EPA team used these packs to review the parameter values used in the 2011 ESC and propose updates or no change. Some components were not present for the 2011 ESC, e.g. shielded modules. For these components completely new parameter values were proposed, making sure they aligned with the values for other similar components. The data packs and proposed parameter values were reviewed in multi-disciplinary workshops involving appropriate sets of industry experts.
Full elicitation	This is a resource-intensive process that goes beyond the ‘Enhanced review’ approach to actively identify parameter distributions through expert elicitation meetings. The meetings are underpinned by data packs and are conducted using structured good practice approaches [69]. They involve industry experts developing and agreeing parameter values and supporting arguments within the workshops.

Effort has been focussed on the engineering components that are expected to be most important for isolation and containment. For example, parameterisation of cap performance included a trial full elicitation of parameter values, enhanced review of the outcomes of the trial elicitation, and enhanced review of the outcomes of cap infiltration calculations using the elicited parameter values. In this case, the enhanced review was effectively a continuation of the elicitation process.

Drainage media and the potential for clogging were also subject to iterations of elicitation and enhanced review, supported by the outcomes of an extensive literature review and clogging calculations.

Data packs were developed for structural concrete and grout, and for BES, to support enhanced reviews of other components. The approach involved review and update of the parameter values proposed for the 2011 ESC [23], considering the updated conceptual models and data pack information, followed by workshop review of the parameter values proposed for the 2026 ESC. Most trench and vault components were subject to 'enhanced review' but 'standard review' was considered sufficient for the profile fill and cut-off wall.

The parameterisation workshops were attended by experts drawn from NWS and contractors. These included experts in the ESC, assessment and mathematical modellers, materials science and conditions in the near field, and repository and landfill engineers. Some workshops were observed by representatives from the Environment Agency, and the ESC independent Peer Review Group, providing opportunities for information provision, and to highlight gaps and approaches undertaken by others.

Our parameterisation process reflects the aims of the ESC, that the outcomes should be an evidence-based analysis of the distribution of parameter values. Modal PDF values reflect our best estimate of performance. Modal values and parameter distributions do not aim to be 'cautious'. The concept of a ‘cautious’ distribution negates the value of describing distributions and using them to underpin probabilistic performance or risk calculations. The distributions and calculation outputs should reflect a true assessment of probability based on the available evidence and arguments.

Also, it is often not clear in multi-pathway assessments what is cautious. A parameter value that is cautious in one context may not be cautious in another context. Therefore, it is good practice to minimise the use of cautious arguments, as far as is practical, in the parameter distributions and underpinning arguments.

A summary of the workshops undertaken for each component is provided in Appendix E of reference [21]. The outcomes of the workshops were fed back to the conceptual models to ensure the conceptual models and parameter values are aligned.

4.6.3 Parameter Correlations

The conceptual models describe interactions within the key engineering components, for example the layers in the final cap, or rebar and concrete in reinforced concrete, and interactions between the key components. The conceptual models for each component and the repository have been 'aligned' to ensure they are internally and cross consistent.

Interactions within components are captured in the parameter distributions. It is important that interactions between the components are considered when using the parameter distributions in calculations. Correlations can be represented mathematically through the sampling of parameter distributions for different components. For example, if the performance of two components is very strongly coupled, the same properties of each component should always be based on the same percentiles of the parameter distributions.

A detailed overview on the identification and representation of correlations in assessments is available in good practice guidance, e.g. references [70] [69]. It can be difficult to express correlations mathematically, unless there is a very strong and direct (or inverse) correlation. Good practice guidance is to address correlations by using consistent and integrated conceptual models. We have followed this guidance, so correlations are implicitly included in the component PDFs. Correlations do not need to be specified mathematically when using the PDFs in assessment calculations, so long as the assessment calculation cases remain consistent with the EPA engineering evolution cases. Further detail is provided in reference [21].

4.6.4 Calculating Cap Infiltration Rates

The current iteration of the EPA has involved a detailed, systematic and iterative analysis of the performance of the optimised design for the final cap. The analysis has considered the design approach and understanding developed for the LLWR system, together with the evidence from wider literature, noting differences in context such as the location of the composite layers within the design, and in-situ temperature. It has involved evidence review, analysis and calculations, and expert elicitation including challenge and debate from engineering experts.

This rigorous approach has ensured the outcomes of the EPA for the final cap are robust and underpinned. This approach has improved our understanding of performance and reduced uncertainties and cautious assumptions compared with the 2011 ESC [23].

A key development compared with the 2011 ESC is that instead of eliciting cap infiltration rates, we have elicited the properties of the cap and then used the elicited properties to calculate infiltration rates. Defects in the cap geomembrane and the properties of the BES can be elicited more robustly than infiltration rates, so we expect that this change in approach will lead to more robust estimates of cap infiltration.

The major steps followed in the current iteration of the EPA can be summarised as:

- Workshops to elicit the properties of the cap geomembrane (types and numbers of defects) and BES (hydraulic conductivity). These were initially undertaken as a trial of the 2026 ESC elicitation process but were then subject to enhanced review.
- Literature review and development of datapacks on the properties and evolution of geomembranes and BES to underpin the workshops.
- Standard review of the properties of the cap drainage layer. This was informed by extensive work on the properties and performance of passive drainage in the vaults, including the drainage blankets.
- Calculation of cap infiltration rates using the outcomes of the above.
- In parallel with the above, collection of additional supporting evidence, including informal interaction with internationally recognised experts, and capture of the results of long-term performance experiments undertaken for CNL's Near Surface Disposal Facility (NSDF) for LLW.
- Enhanced review of the calculations, assumptions and results.
- Update of the calculations and further enhanced review of the results.

The aim of the approach is to provide systematic assessment underpinned by evidence, not to 'prove' high levels of performance of the final cap. As the iterations of elicitation and assessment have included input and challenge from experts in landfill engineering throughout, the outcomes are a consensus view based on the evidence obtained. The calculated infiltration rates are found to be comparable to those calculated by CNL for their

Near Surface Disposal Facility, noting the differences in the designs and environmental conditions. For example, the environmental conditions affect both construction (e.g. propensity for wrinkles in the cap geomembrane) and long-term performance.

4.7 Outputs from the EPA to the Wider ESC and Feedbacks

The EPA interacts with our work to optimise the repository development and the engineering design, our work to understand the evolving biogeochemical conditions in the near field and our assessments. The EPA has been developed iteratively in parallel with these other work areas. Outputs from the EPA to these other areas, and information fed back into the EPA are summarised in Table 4.4.

Table 4.4: EPA Interactions

Recipient	Outputs from the EPA	Feedbacks to the EPA
Repository optimisation and engineering design [5] [10]	Engineering evolution conceptual models, including key issues for performance. Understanding of geomembrane evolution and specifications. Planned updates to the Requirements Management System (RMS). CQA assumptions and requirements.	Updates to the optimised concept, development plans and engineering design.
Near field [6]	Rates of infiltration into the repository. Engineering evolution conceptual models.	Conditions in the repository, including pH inside and outside containers, Eh, humidity, container corrosion rates, rates of alteration of the grout and degradation of organic waste, microbial activity. Our near field work and assessments use these outputs to described evolution of the waste form and containers, which also feedback into the EPA.
Groundwater modelling [7]	Rates of infiltration into the repository. Hydraulic conductivities of key components.	Our site-scale groundwater model includes a simplified representation of the repository. This provides quantification of water levels and flows in the repository for feedback to the EPA and for comparison with the results of our groundwater pathway assessment model (below).

Recipient	Outputs from the EPA	Feedbacks to the EPA
Groundwater pathway [14] (and Hydrogeological Risk Assessment, HRA [15])	Rates of infiltration into the repository. Hydraulic conductivities of key components. Engineering evolution conceptual models.	Quantification of water levels and flows in the repository (using a simplified compartmental flow model).
Gas pathway [14]	Properties of the cap and cut-off wall which affect the locations of releases of bulk and trace radioactive gases. Engineering evolution conceptual models, including evolution of the cap layers as a barrier to radon gas.	The gas pathway assessment results will be used (after submission of the 2026 ESC) to inform optimisation of the gas management strategy and vent design. Updates to the optimised management strategy and vent design will then feed into the EPA.
Human Intrusion [14]	Engineering evolution conceptual models, including resistance of the cap to erosion, stability of the cap, and long-term isolation of the waste by the cap. The HI assessment takes information on the condition of the cap and then considers the further damage to the cap and damage to other barriers that could arise from human actions.	Future human actions are outside the scope of the EPA because they are too uncertain to be included in the engineering evolution conceptual models. However, feedback from the HI assessment into the EPA provides a conduit for optimisation of the engineering design, e.g. the 'as built' isolation barrier thickness needed to prevent intrusion by different types of events accounting for anticipated cap erosion.
Coastal Erosion pathway [14]	In combination with our work on near-field evolution, the EPA informs the anticipated condition of the waste and engineering components when the repository starts to be disrupted by coastal erosion.	Conclusion that containers should not be durable in the coastal environment [17] fed back into optimisation, engineering design and the EPA.

Recipient	Outputs from the EPA	Feedbacks to the EPA
Criticality [13] [14]	Water flows, waste and container degradation and settlement, and biogeochemical conditions in the near field input to the criticality assessment. These are directly informed by the EPA and indirectly via our near-field work.	None.
Non-Human Biota [16]	No direct inputs from the EPA. However, the non-human biota assessment uses environmental concentration results from our other assessments, which are informed by the EPA.	None.
Period of Authorisation (PoA) [13]	Engineering evolution conceptual models. Groundwater pathway assessment for the PoA uses cap infiltration rates from the EPA.	No direct feedback. PoA outputs may lead to changes to the optimised repository design and development, for example any measures to provide additional protection from direct and indirect (scattered) radiation. These then feed into the EPA.

5 Component Evolution, Performance and Properties

5.1 Introduction

This section describes the evolution, performance and properties of each of the key components. Each key component is considered in turn, broadly following the five-step EPA approach (Figure 1.1):

- the conceptual model of the evolution and performance of the component, including:
    - the nature of the component;
    - factors affecting performance of the component;
    - evolution of the component;
- the storyboard for the REEC;
- the properties of the component, at times corresponding to the storyboard.

The conceptual models describe the most important processes affecting the evolution of each key component. This approach is repeated for different component behaviours and external influences to understand the range in closure system performances that might be expected. Component storyboards for the REEC are presented in this report and storyboards for the AEECs are presented in reference [21].

Section 6 combines the REEC conceptual model storyboards for the key components into a conceptual model storyboard for the whole repository. Storyboards describing the conceptualised evolution and performance of the whole repository for the AEECs are presented in reference [21].

Nine key components are identified in Subsection 3.4. Some of these key components are made from several sub-components (e.g. layers), each formed from a different material. Many of these materials have been (or will be) brought to the site from different locations and environments or manufactured from a range of raw materials. When located together in the LLWR each of these materials will change or evolve over time as they equilibrate to their new environment. Changes in the properties of some materials can occur over a few decades, while for other materials the timescales may extend to geological timeframes. The combined effects of these changes can affect the engineering performance of the components.

The key components considered in this section are:

- final cap (including profile fill material) and for the purposes of this section the interim trench cap;
- trench and vault waste;

- trench and vault bases;
- vault side walls;
- cut-off wall;
- leachate management system;
- under-vault drainage and underlying geology.

The components are presented in this order as it reflects the priorities in concept optimisation [10] which considered the cap first, and then other components below it in approximately vertical order, reflecting system water flows.

The following subsections are supported by extensive and much more detailed documentation in reference [21] and supporting references.

5.2 Final Cap (Including Profile Fill Material and Interim Trench Cap)

5.2.1 Nature of the Final Cap

The multi-layer final cap (Figure 3.8) is based on orthodox and well-tested designs, although it provides more barriers and redundancy than a typical landfill design. It is the most complex component within the closure system. There are eleven layers (including the supporting profile fill) plus additional geotextile and geosynthetic drainage layers. Each layer is included for at least one, and often more, specific reasons. The layer functions and material specifications, and key processes that can potentially degrade performance, are described in Table 5.1. All the layers are required to use non-calcareous materials to minimise the risk of chemical clogging of the cap drainage layers and the passive drainage system in the vaults.

Key features of the layering approach are summarised below.

- Use of a composite low permeability barrier to reduce infiltration.
- Placement of layers above the composite barrier to:
    - reduce heads on the barrier (achieved via evapotranspiration and drainage of water to the perimeter of the cap);
    - enhance stability (for example, through plant rooting zones and balancing lower gradients for runoff performance against upper gradients for slope stability and erosion resistance);
    - protect the most sensitive cap layers and waste from intrusion (achieved by the inclusion of biointrusion barriers, and the overall thickness of overlying material).
- Protection of the cap from gas pressurisation by directing gases through a collection layer to the cap vent.
- Use of profile fill to provide an appropriate geometry and stable formation for the placement of the cap.

Important functions of the cap are to:

- isolate the waste from humans and the environment;
- reduce the risk of, and impacts arising from, biological and human intrusion;
- contain contaminants by minimising infiltration into the waste.

The cap needs to achieve these functions in a dynamic environment, exposed to daily weather, seasonal and long-term climate changes, low frequency extreme weather events, and evolution of the underlying wastes. The layers that are included in the final cap are all designed to work together to achieve the required functions in this dynamic environment, both in the years immediately following construction and into the future, significantly beyond normal assumed engineering design lifespans. Further detail on the functions of the cap relevant to the EPA are provided below.

Table 5.1: Final cap layer functions, specifications and potential degradation processes

Layer	Function and specification	Potential degradation processes
Surface soil	Provides a good growing medium for vegetation. Selected site soils and imported soil, sand dominated, with lesser amounts of silt and clay, and a small organic content (4% to 8%) [71].	Erosion by wind and water. Greatly enhanced by loss of vegetation.
Moisture retention layer	Provides water for surface vegetation during dry period to resist loss of vegetation. Selected site soils and imported soils. Low organic content and higher silt and clay content than surface soil [72]. Wet cohesive material, class 2X1	Erosion by wind and water if exposed through loss of surface soil.
Filter layer	Resists downwards transport of silt and clay from the moisture retention layer that could clog underlying drainage layers. Well sorted fine to just medium sand [72].	Erosion by wind and water if exposed through loss of overlying layers. Over very long timescales the pore spaces between sand grains may be filled with silt and clay particles, so fine material starts to pass through the layer.

Layer	Function and specification	Potential degradation processes
Biointrusion layer	Resists intrusion of plant roots, burrowing animals and excavation by humans. Difficult to maintain an open excavation. In combination with the total thickness of cover materials, the biointrusion layer protects the underlying low permeability layers. Large, hard, durable stone cobbles [5].	None. Resistant to erosion even if overlying layers are removed. Large pore spaces and high total pore volume mean that substantial clogging is unlikely, so they layer will always contribute to the cap drainage capacity.
Drainage layer	Directs water over the underlying low permeability layers to the perimeter of the cap. Minimises heads on the low permeability layers. Mixed gravel, including fine, medium and coarse grain sizes [72].	Physical, chemical and biological clogging, leading to reduction in hydraulic conductivity.
Geomembrane	Impermeable material that resists infiltration into the underlying waste. Works with the BES as a composite barrier which has properties superior to the summed contributions of the geomembrane and BES. 2 mm thick sheet made from high-density polyethylene (HDPE). It is supplied in rolls, so the layer is formed by strips which are welded together at their edges.	Loss of antioxidants, followed by oxidation initiation and then oxidation resulting in embrittlement and loss of strain tolerance. Expected small strains in the cap are sufficient to result in stress fractures and failure.
BES layer	Low permeability material that resists infiltration into the underlying waste. Works with the geomembrane as a composite barrier which has properties superior to the summed contributions of the geomembrane and BES. Mixed onsite and then laid in three layers of overlapping panels. Compacted to high density during emplacement. Mix specification to be developed but expected to contain around 5 wt% to	Cation exchange of sodium for calcium reduces swelling potential, capacity for self-healing, and increases hydraulic conductivity. Washout of the bentonite has the same effects. Drying resulting in shrinkage of the bentonite, cracking of the BES and increase in hydraulic conductivity. When

Layer	Function and specification	Potential degradation processes
	10 wt% sodium bentonite. Bentonite swells as it hydrates. This enables the BES to self-heal in response to minor movements.	subsequently exposed to water the dry material will rehydrate, swell and cracks will close (self-heal).
Gas collection layer	Collects gases generated from the degrading waste and corroding containers and directs it to the cap vent. Protects the cap from gas pressurisation. Similar to the drainage layer but without the fine-grained material and a narrower grain size range [72].	Physical, chemical and biological clogging, leading to reduction in hydraulic conductivity.
Profile fill	Gives the cap the desired shape and gradients. Protects the overlying cap layers from strains generated by waste settlement. Vault profile - specification as drainage layer [72]. Trench profile - mixed site won soils, including cohesive materials, and retained parts of the interim trench cap. A layer of granular material, with the same specification as the vault profile, will be placed over the retained parts of the interim trench cap before being covered with mixed soils.	Physical, chemical and biological clogging, leading to reduction in hydraulic conductivity.

Evapotranspiration of rainwater

The vegetation, and top and sub-soil layers reduce infiltration into the cap. Under present climate conditions, with grass vegetation about 35% of total incident rainfall is returned to the atmosphere through evapotranspiration. Vegetation is also important for binding the surface soil and slowing surface runoff, which both act to reduce erosion. The topsoil and sub-soil also have an important role in storing water from rainfall events This 'buffers' flow to the underlying cap layers helping them to maintain a more consistent moisture content. This is important as the cap is sensitive both to saturation (e.g. affecting cap slope stability) and to desiccation (causing shrinkage cracks in clay-rich materials).

Buffering of rainfall is illustrated by Figure 5.1, which shows the outputs from a simple cap performance model from early[10] in development of the EPA [36]. The figure shows the high variability of rainfall and evapotranspiration (AE). However, interflow (runoff) in the cap layers is much less variable, largely showing seasonal changes, and infiltration through the cap is nearly constant.

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[10] Note this early work has been superseded by the most recent cap infiltration calculations presented in this report, which only consider annual rates [64]. Understanding from this early work supports the approaches applied in the latest calculations. This early work uses example input parameters, not those elicited for the 2026 ESC.

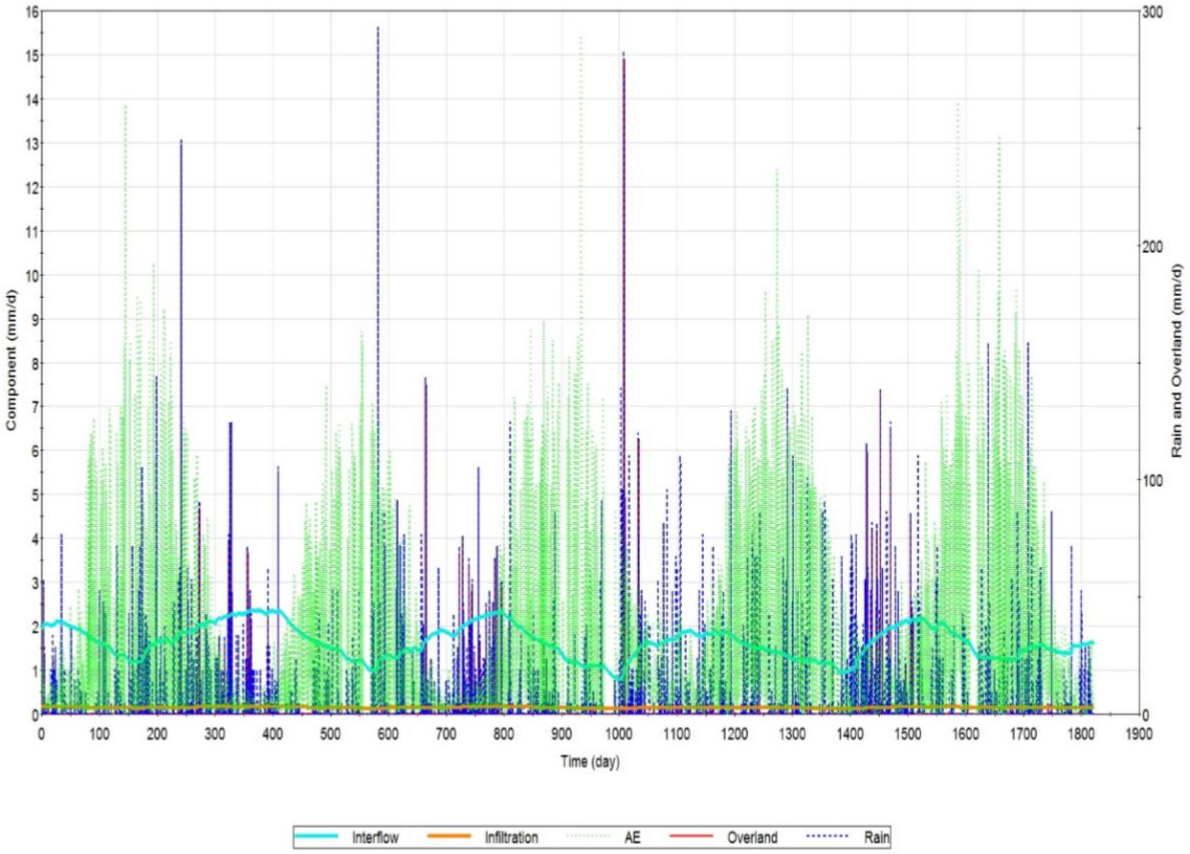

Figure 5.1: Example results from EPA modelling of cap performance [36]

The vegetation will evolve in response to changes in climate, availability of moisture and soil nutrients. Evolution of the species comprising the cap can be anticipated immediately following seeding and planting, and in the longer term in response to climate change. Sensitivity studies to assess change in evapotranspiration for climates such as Oporto in Portugal or Reykjavik in Iceland demonstrated that provided good grassland vegetative cover is maintained, the change in evapotranspiration performance from these layers over time will be limited [29]. Surface vegetation that binds the surface soils, slows runoff and helps to return rainwater to the atmosphere is expected to be sustained given the emissions and climate change scenarios developed for the 2026 ESC (Table 2.1), even if the species change [21].

Physical stability

The cap has been designed within lower and upper gradient limits to minimise the risks of slope instability, waterlogging of the upper layers, and erosion and gullying by overland flow. These processes are coupled, so there is an optimal gradient range. Too shallow and water logging will occur, potentially damaging vegetation and the surface soils, and increasing infiltration. To steep risks slope instability, erosion and gullying by runoff.

It is also important that the final cap is resilient to plausible general and differential settlements. Settlement could damage the cap low permeability layers or alter the cap gradients. Potential settlements have been a key focus of iterations of cap and profile fill optimisation and design as set out in references [10] and [5] and supporting references. These iterations have been undertaken alongside, and integrated with, development of the EPA and key supporting resources such as cap resilience assessments (see Subsection 4.3.1 and reference [42]). The cap resilience and slope stability assessments provide high levels of confidence that the cap will be physically stable for a prolonged period, including being resilient to remaining uncertainties in repository and climate evolution.

Resist intrusion

The intrusion barrier is intended to protect the underlying resistive layers from animal and plant intrusion and to reduce the likelihood of inadvertent human intrusion. The barrier comprises a layer of cobbles. This will be clearly recognisable as a construction layer that will help inform people who might inadvertently attempt to intrude into the repository. The cobbles will also provide a physical barrier. Unbound cobbles are very difficult to penetrate, and it is very difficult to maintain an open excavation because the sides will easily collapse into the hole.

The intrusion barrier cannot guard against all possible inadvertent human intrusion events. However, the intrusion barrier, and the total thickness of the cap and profile fill, provide significant barriers to many common intrusion events, limiting the depth of intrusion or preventing exposure of waste. They also reduce the amount of waste that might be exposed by the more extreme (and determined) events [25].

The intrusion barrier and total thickness of the upper cap layers provide a substantial bio-intrusion barrier protecting the composite low permeability layers. However, it is possible that intrusion by the deepest tree roots, localised slope failures or other minor intrusions could occur over the longer term. Although these are considered remote possibilities, over thousands of years such impacts cannot be fully discounted. Any such minor defects have been included in the EPA as part of the evolution the of the cap and associated defects.

The cobble layer is underlain by the drainage layer. This layer combination is an important element of the internal cap drainage system providing layer stability and significant drainage redundancy. In addition, the cobbles provide a layer that is very difficult to erode in the unlikely event of erosion gullies forming on the cap from runoff or high winds.

Drain rainwater

Some of the rainwater incident on the cap will be returned to the atmosphere by evapotranspiration, some will flow laterally to the cap perimeter via interflow and at times overland flow, and some will drain through the surface soils into the underlying layers. Good internal cap drainage and appropriate gradients are essential to encourage water that drains through the surface soil layers to flow laterally to the perimeter of the cap. This is important in managing slope stability but also, critically, managing the total heads and the duration that those heads remain on the resistive layers during and after periods of rainfall.

The magnitude of the head and its duration are likely to be affected by processes such as clogging (including physical, biological and chemical) of the drainage layers. The cap has been designed to reduce the potential for clogging, for example by including filter layers and geotextiles to resist downwards movement of fine-grained material (Figure 3.8). However, the potential for clogging of the drainage layers cannot be ignored and the possible effects of clogging have been included within the expected general reduction in performance of the cap over time.

Resist infiltration

The upper layers of the cap and their gradients offer controls on the rate and volume of water reaching the cap low permeability layers and the duration of any heads that form on the low permeability layers. These layers are the most critical components of the cap from the perspective of water management and are intended to significantly reduce the potential infiltration through the cap to very low values for a prolonged period.

For improved performance and redundancy, a composite resistive layer is included in the design. The upper layer comprises a geomembrane that will be placed over the top of, and will be in intimate contact with, a lower BES layer. Both components are excellent resistive layers in their own rights and have very low target hydraulic conductivities. Together these layers act as a composite barrier which has been demonstrated in testing and through experience to perform significantly better than the summed performance of its individual elements ([73] [74] [67]). For example, the geomembrane will help slow desiccation and cation exchange in the BES (Table 5.1). The BES will provide an excellent formation for the geomembrane and will help to limit infiltration through any defects (small holes) in the geomembrane.

The overburden load on the BES layer, the thickness of the BES layer, and the swelling properties of the BES, mean that an open crack cannot be maintained in the BES. If the resistive layers are ruptured by an event such as settlement or minor intrusion, the BES will tend to self-heal, maintaining a low permeability barrier to infiltration. The resistive layers can be damaged by:

- high strains (see physical stability);
- desiccation (relevant for the BES layer);
- construction damage and intrusion events;
- oxidation (relevant for the geomembrane);
- weathering and cation exchange (relevant for the BES layer).

The inert characteristics of the upper layers of the cap make relative changes in the performance of the two resistive layers over time one of the most important factors affecting long closure system performance. For example, even with good construction quality management, the as-placed cap geomembrane will have minor defects such as small holes. The evolution of these defects, together with the long-term degradation of the material, are key factors controlling the long-term performance of the geomembrane as a barrier to infiltration.

Provide gas pathways

Together, the profile fill and gas collection layer are intended to provide gas storage and gas pathways out of the facility. In the current design the gas collection layer connects to a 'mushroom' vent at the crest of the cap. Our reference assumption is that the vent will be closed at the end of the period of active institutional control, but it is possible the vent could be left open at the end of the PoA for long-term management of gas pressures [5] [10]. We are further considering the approach to managing bulk and trace gases generated in the repository, and design of gas management features (Subsection 1.2). Arguments on safety in the 2026 ESC are not contingent on the outcomes of this work, so it is scheduled as a continuing ESC activity consistent with the principles of ongoing optimisation. The final decision whether to close the vent (or possibly vents, if the optimised design changes) will be underpinned by ongoing monitoring and modelling of gas evolution as strips of the final cap are emplaced.

Closing the vent has the benefit of removing uncertainty in long-term performance associated with the evolution of the vent and management of gases, including avoiding concentrating releases of radon and C-14 gas into a small area. However, we need to be confident this could not lead to gas pressures that could damage the cap. For example, the cap geomembrane is expected to be a significant barrier to the release of gas and could trap gas leading to pressurisation. We have undertaken some multiphase modelling work which indicates peak gas pressures should be a little below the level where damage to the cap could occur [6], but there are uncertainties. One of the key uncertainties is the bulk gas generation rate. Sensitivity calculations with higher bulk gas generation rates have similar peak gas pressures, with more gas migrating under the cut-off wall. These sensitivity calculations provide some confidence the design is robust to uncertainty in the bulk gas generation rates. This work will be one input to future optimisation of gas management and the vent design.

When gas meets the base of the BES it is likely to spread out laterally through the gas collection layer and upper layers of the profile fill before exiting the cap through the vent, while it is open. Some gas is also likely to diffuse vertically through the capping system through defects (small holes) in the geomembrane, especially if the cap vent is sealed at the end of the period of active institutional control. This could have beneficial effects on rates of infiltration passing in the opposite direction. We also acknowledge that the gas could potentially locally desiccate the underside of the BES, but these effects are difficult to quantify and are unlikely to be important and under real conditions [75]. Therefore, they have been excluded from the expected evolution [21].

The EPA assumes that the gas management strategy and the vent included in the cap design will prevent overpressures developing that could potentially damage the cap. Damage could include dilation of the interface between the BES and overlying geomembrane. Dilation would increase the area for gas flow to each defect (small hole) in the geomembrane and reduce the quality of contact between the geomembrane and BES.

However, as noted above, the latest multiphase flow modelling work indicates peak gas pressures should be a little below the level where damage to the cap could occur.

Resist strains from waste settlement

The profile fill is an important component of the multilayer cap. It will be constructed in layers. Over the vaults the fill will be physically and chemically inert, free-draining, granular, material. Over the trenches similar materials may be used, but the profile fill will also include material used as part of the interim trench cap as well as substantial volumes of processed material excavated during future vault construction. In both cases a primary purpose of the profile fill is to provide a good foundation for the multilayer cap and to establish and maintain the shape of the multilayer cap. Its other important function is to help distribute strains that may arise from settlement of the underlying waste to minimise stresses on the geomembrane and BES.

The choice of inert, low-fines material is preferred for the vaults to minimise the potential for clogging of passive drainage within and below the vaults by downwards transport of fines (there are no passive drains in the trenches to clog). Granular profile fill, and the void fill between vault waste stacks, will encourage cap infiltration to flow around the containers and drain downwards of the bottom of the vaults, while also providing an easy pathway for gas to move in the other direction.

The thickness of the profile fill is an important variable as greater thicknesses help distribute strains from settlement over larger areas. Strains above the tolerances of the resistive layers can lead to rupture or damage, a general increase in holes and tears, and associated increases in infiltration. A key change in the current design, compared to the 2011 ESC, is the increase in the minimum thickness of the profile fill from one to two metres over the waste. This can be achieved everywhere for the first strip of the final cap, except for a few small areas above the Vault 8 perimeter walls where the thickness is between one and two metres. Over the centre of the cap the profile fill thicknesses are substantially larger. The decision to increase the minimum thickness of profile fill was initially in response to evidence that older wastes in Vault 8, near the periphery of the cap, are the most likely to be associated with higher levels of voidage that could be translated into settlements with time [10] [42]. However, it also provides additional confidence in resilience to settlements in other areas.

The bulk volume and the inert characteristics of the fill material mean that its stability and hydraulic characteristics are unlikely to degrade. Its thickness and aerial extent provide redundancy in its required properties. Although localised clogging of the profile fill is a realistic possibility in areas of concentrated flow, this is very unlikely to significantly affect the role of the profile fill in supporting the multilayer cap or in acting as a conduit for flows of gas and infiltration. Infiltration is therefore assumed to pass vertically downwards unimpeded through the layer, while gases produced by the waste are expected to travel vertically upwards.

5.2.1.1 Incorporation of Interim Trench Cap Materials

The interim trench cap is a key component of the closure system prior to the placement of the final cap because of its water shedding capability and the role it plays during the continued operation of the vaults and the early phases of final cap construction.

The interim trench cap is being replaced over the southern area of the trenches. The existing geomembrane is being rendered ineffective prior to installation of a replacement GCL and overlying GDL. These replacement layers and those above them will be removed prior to final capping. When this occurs, the component will cease to have any effect on future hydrogeological or gas performance of the closure system and so is not considered relevant to the long-term performance of the closure system. This is because the retained parts of the former interim trench cap will just form part of the profile fill. The existing geomembrane will also be rendered ineffective over the northern area of the trenches, before they are covered by the first strip of the final cap.

The evolution and performance of the interim trench cap prior to final capping is further described in reference [21].

5.2.1.2 Effects of Surcharge

The proposed surcharging of the trench waste and vault waste in current container designs, before placement of the final cap, is an important feature of the design (see reference [5]). Surcharging is intended to help drive out available waste settlement and container movements prior to cap construction. This is needed to provide a stable formation to facilitate cap construction with the additional benefit of reducing long-term settlement. The effects of surcharge are implicitly addressed in the EPA through the confidence in cap construction quality and in subsequent cap stability, which provide the starting point for assumptions on the reference evolution of the cap.

5.2.2 Factors Affecting Final Cap Performance

Many of the factors noted in Subsection 5.2.1 are likely to affect the layers over timescales ranging from a few years to millennia. The most important factors that can affect cap performance are summarised below.

Constructability

The cap design has been optimised to give confidence in constructability and its subsequent performance. Design factors that influence constructability include the cap slopes, the number of layers, the nature of layer materials and thicknesses, interactions between the layers, and how the layers are placed including the use of man-made materials such as geotextiles as foundation layers.

The current cap design is an evolution of that included in the 2011 ESC. The main changes to the design are intended to improve constructability. These changes are the amalgamation of the bio-intrusion and drainage layers into a single layer, and inclusion of additional man-made layers to further aid construction whilst including functionality. The man-made layers are geotextiles, drainage, and gas collection layers to support the main equivalent functional layers constructed with natural materials.

The approach to laying the BES is designed to minimise the potential for construction defects, such as poor compaction. The BES layer will be placed as several layers of overlapping compacted panels. This means that defects should be identified during placement of successive layers. If any hidden defects occur within an isolated BES layer, these would be mitigated by the self-healing properties of the BES, and it is unlikely that spatially overlapping defects would persist in separate BES layers.

Damage during construction and from other site closure activities

Any construction defects, damage that occurs during construction, or damage from other site closure activities may affect the 'as built' and long-term performance of the cap. This is why construction management and CQA are such an important element of cap construction. However, even with the highest quality source materials and with excellent construction management, defects and damage will be present following cap construction. The nature and frequency of the defects and damage will then evolve with the cap materials. Damage to the geomembrane is the main concern, because water is only able to permeate through small holes in the geomembrane, and it is the layer most vulnerable to construction damage.

The EPA assumes there will be defects in and damage to the geomembrane, although these will be minimised to a level consistent with very good cap performance. Defects and damage will evolve with time and affect the combined performance of the composite including the underlying BES. The nature and extent of defects and damage is examined with the engineering evolution cases, including the REEC and alternatives which are described in reference [21] and supporting references. The types of defects that might be present in the geomembrane include manufacturing pinholes, holes and tears (collectively small holes), folds and wrinkles. Stress fractures will develop once the geomembrane has aged and become brittle. The types and numbers of defects that could be present in the geomembrane have been elicited by experts in landfill capping and civil engineering (Subsection 4.6.4) using literature data (e.g. Environment Agency data [63]), and judgements on their extrapolation to the LLWR and its evolution.

The current southern trench cap interim membrane replacement project is being implemented incrementally. Learning from initial work on a small area is being applied across the wider southern trenches area and will feed into delivery of Tranche 1 of the final cap. A construction trial for the final cap will also provide important information on constructability and CQA. We will also periodically retrieve samples of the geomembrane, for example from an area of the cap outside the cut-off wall tie-in, to allow testing for aging [9].

Climate

Climate will affect the upper layers of the cap throughout the assessment timeframe. Climate effects include:

- rainfall and runoff;

- the risk of waterlogging;
- risk of desiccation;
- water and wind erosion of the cap;
- temperature (and its impact on the above);
- the effects of the above on the HER i.e. the water reaching the resistive layers.

Repeated assessments (e.g. references [29] [23] [36] [64]) have all concluded that annual measures of rainfall and HER (rather than daily or other frequencies) of rainfall are the most appropriate basis from which to start calculating infiltration, although the effects of changes in seasonal weather and short-term storm events on the cap are considered in the EPA. These are most significant for the cap vegetation, soil and sub-soil layers. Assessments provide confidence the cap will be resilient to plausible future climate change (Subsection 5.2.1).

Physicochemical conditions in the cap

The average temperature at the LLWR is 10 °C [6]. This may increase by a few degrees in the future in response to climate change [8]. The cap vegetation and surface layers will be exposed to higher temperatures in the summer and lower temperatures in the winter, including freezing. However, temperatures will be increasingly moderated with depth below the surface of the cap, so the temperature in the most sensitive cap layers is expected to remain within a few degrees of the annual average. Even in cold winters, freezing is not expected to result in significant damage to the cap surface soils. The coastal location of the LLWR will help moderate temperatures, so freezing does not extend significantly into the cap, and drying and cracking of the surface soil layers is limited in summer.

The cap layers are made from chemically benign materials. The most active material expected to be present is gypsum (calcium sulphate), which may be present as an accessory mineral in the bentonite component of the cap BES. As the cap BES is expected to contain around 5 wt% to 10 wt% bentonite, and gypsum will only be present in small quantities in the bentonite, the amount of gypsum in the cap will be small.

Rainwater (pH 5.6) will be chemically conditioned in the cap. Reaction with silicate minerals in the cap will buffer the pH closer to neutral. Reaction of infiltrating water with the BES will further increase the pH of the water to around pH 10 [53]. Microbes in the soil and sub-soil layers will degrade organic matter, consuming oxygen, so conditions become more anoxic below the upper cap layers.

Gypsum in the BES will dissolve in water infiltrating the cap. In the gas collection layer and profile fill, microbes may use sulphate from the gypsum to oxidise hydrogen gas generated by anaerobic corrosion of metals in the repository. This may generate small amounts of H_2S gas. Much of the H_2S gas will dissolve in the infiltrating water and then be transported downwards into the repository where it may corrode metal containers and waste. If the cap vents are closed at the end of active institutional control, a small amount of H_2S may be advected through the BES and defects (small holes) in the geomembrane by bulk gas generated from the waste. The H_2S might chemically attack the geomembrane, however the impacts would be small because the amount of H_2S would be small, and attack would mainly occur adjacent to existing small holes.

Degradation

Over time the cap layers will degrade, and the cap's performance will decrease. The upper cap layers will be most vulnerable to degradation. Degradation will be caused by:

- the impacts of atmospheric processes, temperature, infiltration, and sunlight on the cap (collectively termed weathering);
- chemical processes within the cap including leaching, oxidation, and cation exchange (of the BES).

Probably the greatest single change in understanding in cap performance from the 2002 EPA and 2011 engineering elicitation has been the significant improvement in the evidence for, and experts' confidence in, the performance of the geomembrane hundreds of years. Understanding of geomembrane susceptibility to oxidation and stress cracking, the importance of geomembrane resin formulation, and evidence from longevity testing, have improved. International research [74] [67] has significantly improved understanding of the fundamental mechanisms that underly degradation of these components, notably influencing understanding of the possible timings and effects of processes. This understanding, coupled with better and more rigorous testing regimes at point of manufacture and longer testing times, has extended confidence in the durability of geomembranes in low stress, mild temperature, well-designed environments. Expected timescales to failure of the geomembrane have increased from decades to centuries and even millennia.

This increased confidence in the durability of the geomembrane together with the protective effect the geomembrane provides the underlying BES are significant. Given the confidence in cap resilience over long timeframes, these developments have resulted in significantly greater confidence in the time the cap will remain functional.

Waste evolution and settlement

Settlement of the underlying waste is expected prior to and after cap completion. Settlement rates will depend upon the nature of the containers and the waste material and their evolution. In broad terms, settlement rates are expected to reduce over the life of the facility, and the most significant changes will be in the first few hundred years. If uncontrolled, potential effects of settlement could include impacts on cap integrity, slope stability, surface runoff and the risk of surface gullying by water, waterlogging and the potential for pond development. However, our optimised design, understanding of the disposed inventory, waste acceptance criteria, and grouting procedures, together provide the controls needed to limit settlement and mitigate its effects.

The trench wastes and vault wastes in existing and committed containers that have deformed under surcharge loads are most likely to experience ongoing settlement after cap construction, although the amounts of settlement are expected to be limited. There is expected to be less settlement of waste in future stronger containers and shielded modules. There will also be limited settlement of the cap layers and profile fill across the whole repository under their self-weight. Both the likelihood and impact from general settlement (i.e. over large areas of the cap) and differential settlement (more localised settlement over smaller areas) have been considered.

Storyboards developed for the EPA, and for linked assessments in the cap resilience report [42], have considered the timescales over which settlements might occur, the locations that are most sensitive to differential settlements, and have assessed how settlements related to voidage evolution may lead to strains in the cap functional layers. The most sensitive locations include hard points at the repository edge, over areas of containers with the highest voidage, and over areas with the lowest thickness of profile. Even with cautious assumptions (Subsection 4.3.1), the calculated strains on the BES and cap geomembrane are within the tolerances of these layers.

We have also considered the possibility of a related process, heave, which could result in the upward movement of areas of the cap and its damage, particularly over the vaults. The driving mechanism for this would be the formation of expansive degradation products, e.g. metal corrosion products. The risk of significant heave affecting the capping layers has mostly been discounted noting that expansion will in part act to fill voids (e.g. within the waste form, and between vault container stacks), corrosion rates will be low, especially in the vaults, and due to the overburden pressures. Therefore, heave does not need to be recognised in the cap resilience calculations.

Composite resistive layer

Our design includes a composite resistive layer (i.e. geomembrane and BES) that is expected to perform better than the simpler barriers (e.g. clay or BES only, or geomembrane only) installed in many landfills. This is consistent with international experience and the associated literature [76] [77] [68] [66] [67]. The international literature is clear that, with good construction management and CQA, composite systems typically out-perform simpler systems in both the short and longer term. The geomembrane and BES complement each other, so the composite barrier is better than the sum of its parts. This is because of the following considerations.

- The BES provides an excellent foundation for the geomembrane.
- The BES resists flow through any defects that penetrate the geomembrane.
- Flow through any defects can be further minimised by ensuring good quality contact between the geomembrane and BES. A good contact resists flow along the interface between the geomembrane and BES, limiting flow through the low permeability BES to a small area. The swelling properties of the BES help to ensure good quality contact.

- The geomembrane will bridge over any defects that might develop in the BES. It also protects the BES by helping to conserve saturation levels in the BES. In combination with the intrinsic moisture retaining properties of the BES, this assists in maximising the performance of the BES, including minimising desiccation and cracking.
- Minimisation of flows through the BES reduces the rate of cation exchange in the bentonite. A fully cation-exchanged (Na to Ca) BES would still offer a good barrier on its own, but performance is reduced a little compared to pure Na-bentonite in the BES.
- Use of good construction management and CQA will minimise defects in the geomembrane and the BES, ensure good contact between the two layers, and ensure other requirements for performance and durability are met.
- In general, the geomembrane and BES comprise dissimilar materials with different strain characteristics, tolerances and performance. These attributes complement each other as they reduce the likelihood of unintentional damage to both the geomembrane and BES occurring at the same location, resulting in better overall performance.

The final cap optimisation process (see references [73] and [10]) sets out the above considerations as reasons for preferring a composite resistive layer compared with the simpler systems used or proposed for conventional landfills and other facilities receiving or proposed to receive VLLW or LA-LLW. In addition, we note that:

- Other systems (e.g. landfill caps) are typically designed with much shorter timeframes for performance in mind, rather than the long-term focus required for the LLWR. Use of a composite resistive layer provides confidence that long-term infiltration into the repository will be as low as reasonably achievable.
- Other systems have lower specifications and requirements. These lead to, for example, the acceptability of thinner caps and profile material (increasing the potential for settlement damage), higher cap gradients (increasing the risk of long-term slope instability, e.g. as geotextiles fail), use of a natural clay rather than taking advantage of the enhanced characteristics of BES, and use of one resistive layer rather than two. All these alternatives have been considered for the LLWR but were not taken forward as part of the optimised design (see references [78], [79] and [33]).

5.2.3 Evolution of the Final Cap

The cap will remain intact and form a prominent feature in the landscape until the repository is disrupted by coastal erosion. As the repository starts to be disrupted by coastal erosion the dominant radiological release mechanism changes and the closure system slowly ceases to influence radiological risk.

Good hydrogeological performance of the cap is expected to be retained over a prolonged period. The system will evolve, for example with surface water drains failing relatively early after end of the PoA, some slow long-term clogging of drainage layers, minor settlements within tolerances, and the balance of vegetation changing with evolution of climate. Some minor intrusions into upper cap layers may occur through plant root development. However, the resistive layers will be protected from deep roots by the thickness of the overlying layers, including the biointrusion layer, which is not amenable to root growth. Performance will be controlled by the evolution of the low permeability layers.

The frequency and size of holes and tears in the geomembrane will increase with time as strains on the geomembrane gradually increase. A step-change in performance will occur when the geomembrane fails relatively quickly following antioxidant depletion and subsequent oxidation and embrittlement. The BES will slowly degrade through cation exchange and leaching of bentonite. For a long time, this will be limited to very small areas immediately below defects (small holes) in the geomembrane. Once the geomembrane has failed, these processes will slowly degrade the BES across the whole cap.

Within this broader picture of cap evolution, it is important to remember that areas of the cap may respond differently, including some areas of the cap potentially performing better than expected. Prior to widespread degradation of the geomembrane, there may be localised degradation leading to locally increased infiltration, but this may not significantly affect performance at the repository scale. The overall performance of the cap therefore reflects a balance in the frequency and impact of localised minor events with the overall performance of the whole cap over time.

As the geomembrane reaches the end of its life, the first failures may be localised. For example, the cap will be constructed over a period of over 100 years, so the cap strips will have different ages and are likely to use different manufacturer products. Also, there will be localised variations in construction related defects and damage, and localised variations in strains. However, the localised first failures will be swiftly followed by general degradation and failure.

Cap resilience

We have undertaken iterations of cap resilience assessments and optimisation of the design of the final cap (Subsection 4.3.1). The resilience assessments include quantitative calculations and supporting arguments including arguments resulting from optimisation decisions.

We have used good practice approaches to assess general and differential settlements that might arise from evolution of the system under the cap (in particular, related to expression of voidage associated with the wastes and containers), as described in Subsection 5.2.2. Following these iterations of assessments, we have concluded the cap will be resilient to plausible settlements [42].

The resilience assessments provide high levels of confidence that the strain tolerance of the geomembrane will typically not be exceeded until antioxidant depletion is complete and subsequent oxidation and embrittlement are advanced. They also show that the BES layer is very likely to persist into the longer term, retaining its resilience to settlements.

The following arguments and controls together ensure settlements will be minimised as far as practicable.

- The most degradable of the trench wastes will have broken down, and the resulting voidage expressed through settlement, prior to final capping. The trench waste will have been degrading for 30 to 70 years before the first strip of the final cap is installed, with around another 100 years of further degradation before the last strip of the final cap is installed. The trench wastes already occupy a reduced volume compared to their as-disposed volume [5] due to degradation and compaction under self-weight and the mass of the interim trench cap. Surcharge will be used to minimise remaining mechanical settlements that will occur after final capping.
- The amount of voidage in containers, disposed to the vaults, is a key control on potential settlement once vertical loads exceeds the strength of the container. Void spaces in the containers are filled with cementitious grout to minimise potential settlements. We have successfully implemented more robust controls on voidage to reduce potential waste settlements and the associated strains on the final cap (Subsection 4.3.1).
- Surcharge will also be used for vault containers of existing designs to express any container deformations (and associated settlements) that could otherwise occur during cap construction.
- We have added 1 m of profile fill compared to the 2011 ESC design (giving a minimum thickness of 2 m), which will therefore better distribute stains from waste settlements.
- We have selected granular profile material for use above the vaults to enhance strain distribution compared with finer grained, more cohesive materials, such as site soils.
- Improvements to understanding of the strain tolerance of geomembranes and BES since the 2011 ESC shows that these layers will have higher strain tolerances that previously assumed [33].
- Selection of a geomembrane with good strain resilience, underpinned by the latest understanding from the literature. Learning from the EPA has fed back into the specifications for the geomembrane [19]. Learning from the EPA has also reinforced arguments on the self-healing response of the BES if subjected to strain.
- Plans to develop new stronger containers for LLW and a similarly strong new container for ILW, protected by CPUs or shielded models (ILW requiring shielding). The CPUs will direct cap and profile loads into the container structural elements, which will be sufficiently strong that deformation will be negligible until they substantially degrade. Similarly, shielded modules will carry cap and profile loads with negligible deformation whilst intact.

Further arguments supporting resilience of the cap (Subsection 5.2.1) are as follows.

- The cap gradients have been optimised to maximise resistance to erosion and slip.
- The soil layers have been designed to provide good conditions for vegetation, including draining during wet weather while retaining moisture during dry weather. Vegetation binds and stabilises the soil layers and therefore the surface of the cap.
- The cap gradients and layer structure are consistent with ensuring resilience to plausible seismic events.

Overall, we expect the cap to be more resilient than a conventional landfill cap because:

- the cap contains additional layers which are designed to improve constructability and durability;
- the cap includes a composite resistive layer, which is well protected by the overlying cap layers;
- the design includes tightly controlled gradients which are lower than slopes often found in landfills;
- we expect settlement and strains on the cap layers to be far lower than a conventional landfill, and within the tolerances of the resistive layers.

In addition, the cap geomembrane will be exposed to more benign physico-chemical conditions compared with conventional landfills. The benign environment supports cap resilience by minimising the rate of loss of antioxidants from the geomembrane which maintains the strain tolerance. The durability of the cap geomembrane is further discussed below.

Durability of the geomembrane

An important contributor to cap performance is the geomembrane that forms part of the resistive layer. The nature and frequency of defects will evolve with time, however the key control on overall performance is the slow but progressive loss of the antioxidants in the formulation resulting in embrittlement [21] [64] [63] (Table 5.2). Embrittlement makes the geomembrane much more sensitive to strain resulting in stress cracks. Eventually, following complete loss of antioxidants followed by oxidation induction the geomembrane will start to rupture, and over a relatively short timescale [64] [63] will cease to be effective and will provide no resistance to water ingress.

Table 5.2: Geomembrane degradation stages

Stage [63]	Condition	Timescales
Antioxidant depletion	Stress cracks are expected to develop in the geomembrane during the antioxidant depletion and oxidation induction stage, but they would be small and widely spaced. Their impact on performance would be limited.	Varies significantly with temperature and chemical conditions. Of the order of 2,000 years or more for low temperature 2mm HDPE systems with appropriate activation energies.
Oxidation induction		Up to around 30 y depending on temperature (e.g. reference [63])
Oxidative degradation	Defect prevalence will increase, and new tears will develop, until the geomembrane completely fails.	Around 50 y (e.g. reference [63])
Further degradation		Around 100 y (e.g. reference [63])

Most of the literature data on the performance of geomembranes are for landfill liners rather than cap applications. Geomembranes in landfill liners are exposed to higher temperatures and more chemically aggressive conditions than geomembranes in cap applications. Also, geomembranes in landfill liners are more at risk of damage or local penetration by sharp objects, especially as settlement occurs. Depending on the liner geometry and foundation layers, some may be under higher strain than the geomembrane in the LLWR cap.

The rate of evolution of geomembranes is very sensitive to temperature (Figure 5.2). Therefore, temperature has a very significant influence on durability. The average ambient temperature at the LLWR site is around 10 °C, although this could increase by a few degrees in the future due to climate change (Subsection 5.2.2). The LLWR waste is expected to generate little heat as it degrades, and much less heat than a conventional landfill. The cap geomembrane will be separated from the waste by several metres of material. Therefore, average temperature experienced by the LLWR cap geomembrane is expected to be around 10 °C. This may be a few tens of degrees cooler than experienced by a geomembrane lining a conventional landfill. A temperature difference of this magnitude can have orders of magnitude impacts on the timeframes for antioxidant depletion, and therefore durability of the geomembrane (Figure 5.2).

In addition, temperatures at landfill sites are often heterogeneous. This can cause further challenges to geomembrane longevity as sections of the geomembrane will evolve differently. This is different to the LLWR which is expected to have a more unform temperature and hence a more uniform evolution.

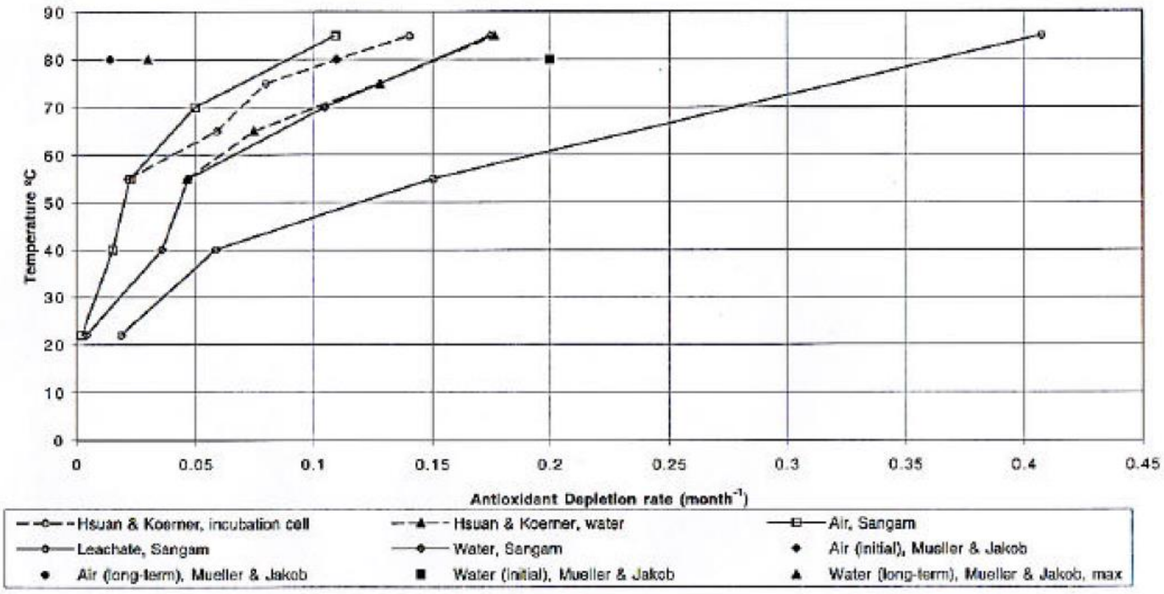

Figure 5.2: Illustration of the effect of temperature on antioxidant depletion rates, complied by the Environment Agency [63]

The thickness of a geomembrane is another consideration. Antioxidant depletion is essentially a diffusive process with timescales for evolution therefore approximately proportional to the square of the thickness for geomembranes of the same type and in similar conditions. A 2 mm thick geomembrane is optimal for the LLWR cap. All other factors being equal, it should provide greater longevity than thinner geomembranes that have often been used for other systems, while being thin enough to provide confidence in constructability.

Example literature data on the durability of geomembranes show that under field conditions, when used as part of a composite resistive layer, antioxidant depletion is expected to take one thousand to many thousands of years. The time is sensitive to the product and the antioxidant package it contains. This learning is being fed back into the specification for the cap geomembrane and testing requirements [19].

For example, the durability of three commercially available geomembranes was investigated in long-term immersion experiments at 10 °C [66]. The time to antioxidant depletion is summarised in Table 5.3. Experience indicates the time to antioxidant depletion for a composite resistive layer in the field (i.e. in a built system) is around a factor of 3.4 longer than immersion tests, which are more aggressive than field conditions [66]. The tests were conducted with leachates which are more chemically aggressive than the LLWR cap environment, resulting in faster antioxidant depletion than would be expected for the LLWR cap.

Table 5.3: Antioxidant depletion times (years) from long-term immersion tests in landfill leachate at 10 °C, from reference [66]

Geomembrane manufacturer	Municipal solid waste (MSW) leachate		CNL near surface disposal facility (NSDF) leachate	
	Test	Field[11]	Test	Field[14]
1	>2,000 y	>6,800 y	>2,000 y	>6,800 y
2	>2,000 y	>6,800 y	>2,000 y	>6,800 y
3	300 y	1,000 y	1,750 y	6,000 y

Overall, our view is consistent with the current international consensus based on models and arguments that have been matched to field observations (principally in the USA and Canada) on the longevity of geomembranes. This consensus has developed since the 2011 ESC and is now generally accepted [76] [77] [68] [66] [67]. Our view is consistent with CNL's view on the durability of cap geomembranes in their recent (2020) post-closure safety assessment for their near surface disposal facility (NSDF) facility [80], albeit drawing on similar sources.

BES

While the geomembrane is intact, the BES is protected from cation exchange and leaching which would reduce its performance, except for small areas below defects (small holes) in the geomembrane. The BES reduces flows through these defects to very small amounts.

The loss of geomembrane performance will be a significant point in the evolution of the cap, but the underlying BES will still retain its performance and will still significantly limit infiltration through the cap. The properties and placement of the BES will exploit the ability of the BES to self-heal minor defects such as cracking, brought about through waste settlement. Provided the estimates of settlement remain within the calculated bounds, the BES layer should be capable of maintaining good cap performance for a significant time after failure of the geomembrane. However, with more focus on a single component it is assumed that the infiltration performance of the cap will further reduce. Over the long term, BES is susceptible to cation exchange by Ca^{2+} ions which increases the hydraulic conductivity of the layer. Eventually, the effects of cation exchange, washout of bentonite, settlement, and related processes over extended timescales are likely to reduce further the infiltration performance of the cap to an ‘at rest’ condition when it has more fully equilibrated with its environment. This is likely to occur over timescales of millennia. It is important to note that this at-rest condition will still maintain a significant permeability contrast with the surrounding area,

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[11] On the basis of the factor of 3.4 for test vs field data.

hence the cap is always likely to be a hydrogeological feature in the landscape until it is disrupted by coastal erosion.

Protection of the resistive layers

The multi-layer cap design is intended to maximise the performance of the low-permeability, resistive layers. The upper layers protect the resistive layers from different forms of intrusion (plant roots, burrowing animals, shallow human intrusion events). The rooting systems that develop with the vegetation in the top and subsoil layers help stabilise the upper layers of the cap and reduce infiltration reaching the low permeability layers. The drainage layers beneath the surface layers further reduce possible heads that can develop on the resistive layer by facilitating lateral flow. Beneath the resistive layers, the gas collection layer helps reduce gas pressures, and the gas collection layer and the profile fill provide a stable substrate for placement of the resistive layers and help distribute strains from any settlement of the underlying waste. The planned surcharging operations over the trenches and existing and committed vault containers are also an import part of the design to reduce subsequent settlement and to provide a stable substrate for placement of the resistive layers, particularly the BES.

The cap materials in contact with and above the geomembrane are selected to be physically and chemically benign, eliminating point contacts and stress concentration, and chemical attack.

An important consideration during construction is protecting materials from damage during the process of adding successive layers. This applies to all layers but is especially important for the resistive layers. Man-made geotextile and drainage composite layers, combined with the specification for the main drainage material above the geomembrane (granular material that will not be sharp or angular), will protect the geomembrane from damage during placement of the main drainage layer.

5.2.4 REEC Storyboard for the Final Cap

The reference or best estimate conceptual model of evolution of the cap with time is described by the storyboard shown in Figure 5.3. In the storyboard, timeframes have been assigned to the processes and events described in the preceding subsection. In the next subsection, the storyboard for the REEC and storyboards for the AEECs (described in reference [21]) inform parameterisation of the components' properties.

Figure 5.3: **Storyboard for evolution of the cap in the REEC**

Component	Reference Engineering Evolution Case			
	During completion / as built	**100 years (to end PoA)**	**500 years**	**1,000 years**
Final cap (1)	As built performance.	Some settlement of vaults and trenches, but differential settlement limited. Further development of minor defects in the geomembrane and BES allow small increases in infiltration. Cap surface water drains clogged.		To c.1,000 years: Further clogging of drainage layers, localised wind erosion and a slight thinning of parts of the cap. Geomembrane still functioning, BES layer showing some (limited) increase in permeability, principally through cation exchange and washout below defects in the geomembrane.
Interim trench cap (2)	Northern area covered by first strip of the final cap, southern area replaced. Existing soils retained and existing geomembrane extensively punctured prior to final capping or replacement. Replacement includes, GCL and overlying GDL, with new	Replacement GCL and GDL layers removed from southern area, final cap complete. No change to interim trench cap. Original geomembrane still present and degrading but no impact on flows as extensively punctured.	Drainage layers in the cap and geotextiles start to lose some performance. Vault settlements lead to increased strains on the cap geomembrane. Strains are within the tolerance of the geomembrane but result in increases in small defects	>1,000 years: All settlement complete, all drainage layers above the low permeability layers have some clogging but drainage capacity still good.

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
	cover soils. GCL and GDL removed prior to final capping. Interim cap will be surcharged prior to final capping, expressing short-term settlements from the waste underneath, possibly with some damage and changes to geometry.		and an increase in infiltration. Both geomembrane and BES remain effective over the whole cap. Nearer 500 years, settlement of vault waste and trench wastes near complete. Antioxidant depletion of the geomembrane is in progress but the geomembrane still performs well. Slight head increase on the resistive layer through clogging, minor localised cracking of BES resistive layer, some cation exchange of BES and minor loss of performance. Overall small increase in permeability of cap.	

5.2.5 Properties and Calculated Infiltration Rates

5.2.5.1 EPA Outcomes Informing Parameter Elicitation and Review of Calculated Infiltration Rates

The approach to calculating cap infiltration rates is described in Subsection 4.6.4. The EPA outcomes that underpin the parameter values elicited for the infiltration calculations, and underpin review of the calculated infiltration rates, are described in Subsection 5.2.3.

Construction management and CQA assumptions are an important input to eliciting the properties of cap, which are used to calculate infiltration rates. We will deploy high standards of construction management and CQA [5]. As described in Subsection 4.4.2, we are capturing learning from experience and literature good practice guides. We have reviewed potential installation faults and hazards that could lead to defects in the cap low permeability layers and identified how they can be mitigated [21]. This provides confidence that it should be possible to achieve high standards of construction management and CQA. This is reflected in the parameter distributions elicited for the cap layers, particularly the central values. However, the distributions also address uncertainties including the potential for poorer CQA than expected.

5.2.5.2 Elicitation of Cap Properties

Calculations of infiltration through the cap are described in reference [64]. The calculations are based on good practice approaches from the literature. These include the empirical infiltration models developed by Giroud [81], as implemented in the Environment Agency's LandSim software [65], and updates to the models [82] [83]. Key EPA inputs to the calculations are the types and numbers of defects in the cap geomembrane, the hydraulic conductivities of the other cap layers, the quality of the contact between the geomembrane and the underlying BES, and evolution of these properties over time.

Distributions of the prevalence of different types of defects with time were identified based on literature data, including literature produced by the Environment Agency [63], and the experience of the experts contributing to the elicitation. This included experts currently involved in construction of landfill liner and capping systems, and experts with a long history of involvement in such systems, including reviewing system designs on behalf of the Environment Agency. The elicited numbers of defects are summarised in Table 5.4.

The basis for the number of defects is described in references [21] [64] [84]. The elicitation noted that literature data on the numbers of defects per area of the geomembrane are likely to be cautious in the context of the LLWR cap. The literature considers a wide range of systems (principally for hazardous wastes), with varying designs, roles of the geomembranes in the designs (including basal liners), and levels of CQA. This was reflected in the elicited number of defects.

Table 5.4: Elicited number of defects in the cap geomembrane [21] [64] [84] The total number of defects was elicited and distributed according to the 'good' case at the end of Stage 2 of reference [63].

Defect type (area in mm^2)	Areal density of penetrations (ha^{-1}) and wrinkles (areal %) after installation			Areal density of penetrations (ha^{-1}) and wrinkles (areal %) at the end of oxidation induction		
	Lower bound	Best estimate	Upper bound	Lower bound	Best estimate	Upper bound
Pinholes (circular, 0.1 to 5)	5	5	10	5	5	10
Holes (circular, 5 to 100)	0	2	7	2	2	7
Tears (circular, 100 to 10,000)	0		3	0		3
Small stress cracks (linear, 10)	0	0	0	10	55	100
Large stress cracks (linear, 1,000)	0	0	0	10	25	400
Wrinkles	0.3	1.65	3	0.3	1.65	3

The durability of the geomembrane was elicited based on Environment Agency literature [63], extensive recent literature data (references [67], [76], [77], [68], [66]) and considering the LLWR-specific conditions described in Subsection 5.2.3. The timescales for complete loss of antioxidants and subsequent oxidation induction were elicited.

The probability of the geomembrane having commenced degradation is based on a log triangular distribution (references [85] and [84]) with lower bound, central and lower bound values of 375, 1,800 and 5,000 years, respectively. This distribution is somewhat weighted towards shorter timescales than can be inferred from recent literature, which are indicative of confidence in performance beyond 2,000 years for relevant categories of geomembranes under LLWR conditions. However, the central value identified, plus the elicited uncertainty, was considered appropriate prior to final selection, procurement and testing of the geomembrane for the first strip of the final cap.

We anticipate that the geomembrane will degrade quickly once antioxidant depletion and oxidation induction are complete, and oxidation has commenced. A single best estimate value of 150 years was chosen (Table 5.2). Initially this will be over areas of higher strain, and then (within a few decades) more generally across the cap, leading to a step-change decrease in performance.

In principle, variability in the manufactured properties of materials (and associated antioxidant depletion activation energies), local characteristics such as minor changes in temperature and quality of welds, could lead to some local variations in the rates of geomembrane evolution. These are accounted for the in the engineering evolution cases. Experts considered this to be an uncertain and minor second order effect, primarily related to local deviations from the area-averaged mean performance. It was not considered proportionate to address such effects in the infiltration calculations.

Reference [86] explains that greenhouse gas emissions are expected to lead to ice melting, sea-level rise and faster rates of coastal erosion. Although the relationships are complex and non-linear, in general terms, higher emissions lead to faster coastal erosion. Considering multiple lines of evidence, reference [86] concluded that with low future greenhouse gas emissions and low relative sea-level rise, we expect that the repository will be disrupted by coastal erosion over a timescale of a few thousand years. Although the probability of different greenhouse gas emissions scenarios cannot be determined, and future rates of coastal erosion are uncertain, this implies there is a substantial probability the cap geomembrane would still be intact when the repository starts to be disrupted by coastal erosion.

A key consideration while the geomembrane performance persists is the quality of contact between the geomembrane and the BES. Reference [81] defines poor, good and excellent contact conditions. Our reference assumption is that there will be good quality contact given the confidence that it should be possible to achieve high standards of construction management and CQA. However, if high standards of construction management and CQA are not achieved the quality of the contact may be poor. Wrinkles in the geomembrane reduce the quality of the contact. Wrinkles increase infiltration if they intersect a defect that penetrates the geomembrane. Therefore, the aerial density of wrinkles in the geomembrane was elicited (Table 5.4) and the probability of wrinkles intercepting defects that penetrate the geomembrane was included in the infiltration calculations.

The BES layer was characterised by the experts at the elicitation in terms of its hydraulic conductivity. The elicited hydraulic conductivity values are given in Table 5.5. The basis for the elicited values is described in reference [84]. Note the upper bound hydraulic conductivity values exclude 'what-if' engineering evolution cases which explore disruption of the geomembrane and the BES layer from major differential settlements.

Table 5.5: **Elicited hydraulic conductivity of the cap BES**

Time	Hydraulic conductivity (m s^{-1})		
	Lower bound	Best estimate	Upper bound
After installation	2 10^{-11}	6.3 10^{-11}	2.0 10^{-10}
150 y (approximate time difference between first and last strip of the cap)	1 10^{-11}	1 10^{-10}	1 10^{-9}
Immediately following failure of the geomembrane	1 10^{-11}	1 10^{-9}	3 10^{-8}
3,000 y after geomembrane failure	3 10^{-11}	3 10^{-9}	1 10^{-7}

5.2.5.3 Calculated Cap Infiltration Rates

Calculation of cap infiltration is described in reference [64]. A full probability distribution for the infiltration through the cap was developed by combining all the relevant probabilities (including the prevalence of defects and the probability of degradation) in a Monte Carlo approach.

The resulting probability distribution (Figure 5.4) is bimodal. This is expected because the condition of the geomembrane dominates performance. Infiltration is substantially lower with the geomembrane intact than degraded. The modal infiltration rates reflect both the probability of the geomembrane being intact at that time and the best estimates of the numbers and types of defects present at that time, consistent with the underpinning REEC description.

For each condition there is a distribution of infiltration rates reflecting other uncertainties such as the types and numbers of defects in the geomembrane (only relevant when the geomembrane is intact) and the hydraulic conductivity of the BES (relevant when the geomembrane is intact and degraded). The uncertainty represented in the PDFs provides coverage of the AEECs (excluding 'what-if' cases).

Probability distributions of the type shown in Figure 5.4 were calculated for several future times. At early times the probability is weighted towards the geomembrane being intact. As time increases the probability increasingly becomes weighted towards the geomembrane being degraded, as shown in Figure 5.5.

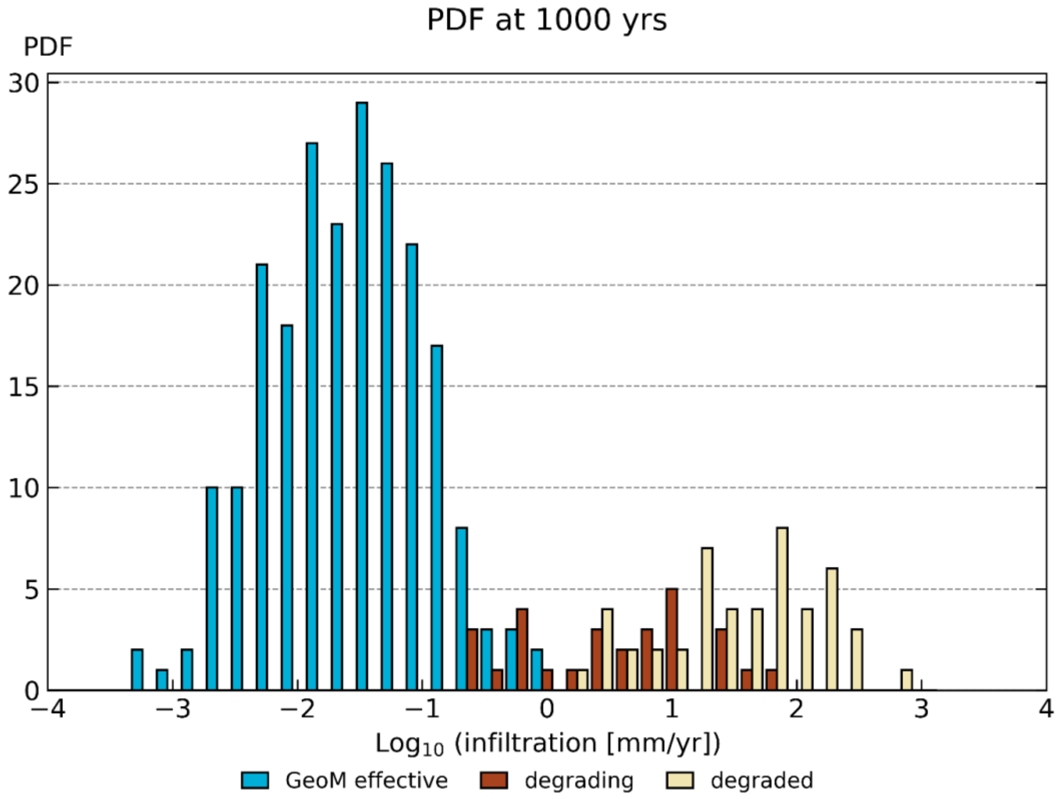

Figure 5.4: Cap infiltration PDF at 1,000 years

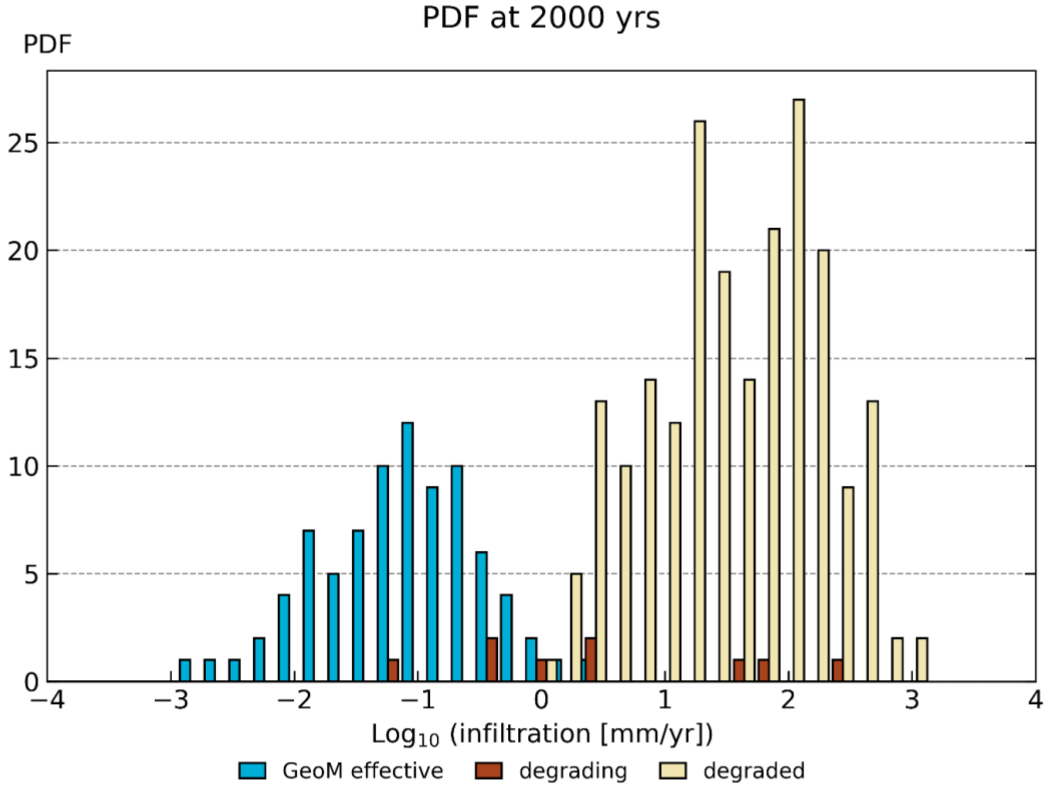

Figure 5.5: Cap infiltration PDF at 2,000 years

The time evolving distributions of the cap infiltration rates are summarised in Figure 5.6. Unlike the previous figures, this figure provides no information on the probability of the geomembrane being intact.

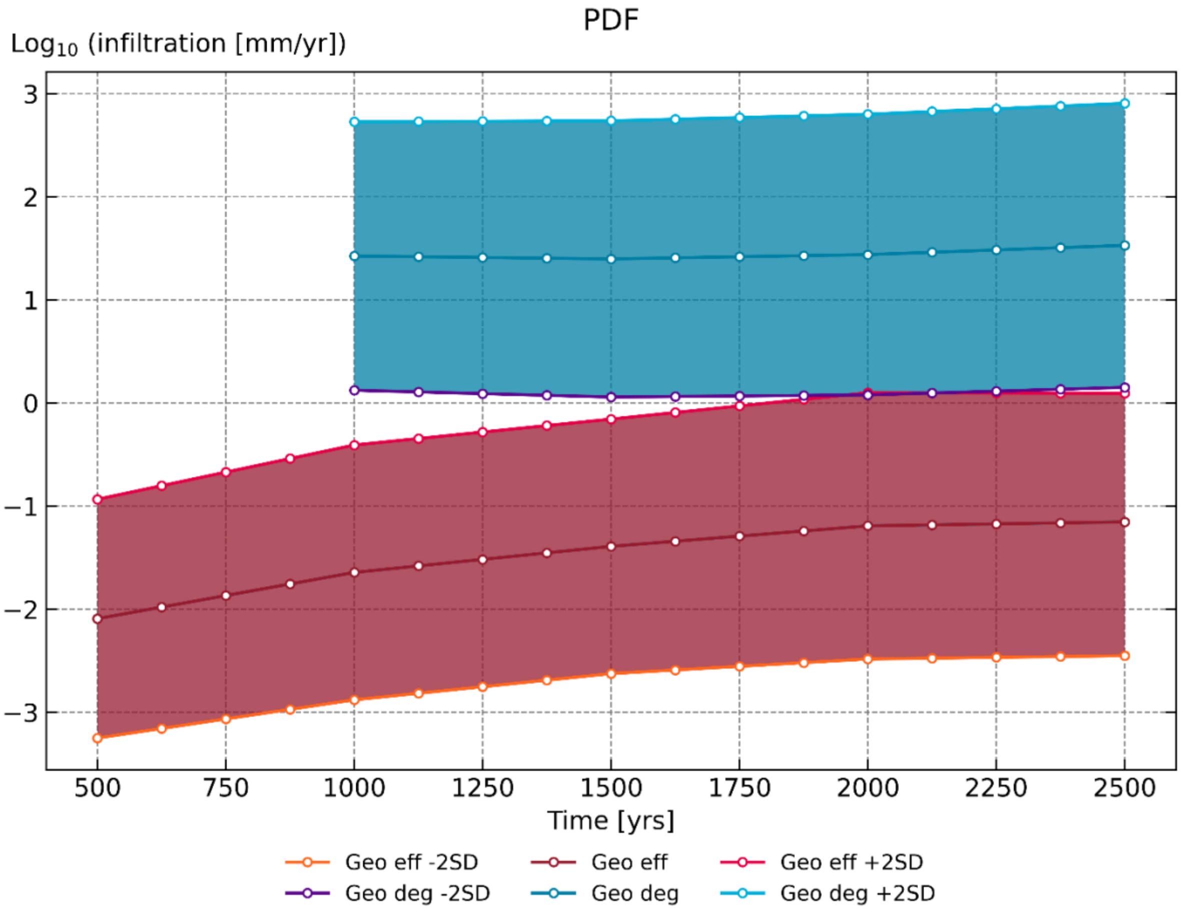

Figure 5.6: Evolving cap infiltration rates from Monte Carlo calculations exploring uncertainty in cap properties. Lower (red) distribution with the geomembrane intact. Upper (blue) distribution with the geomembrane degraded.

The different modes of the distribution (shaded in red and blue) reflect different situations. These different situations are represented in our assessment models. The mean and two standard deviation numbers for each mode of the bimodal distribution provide a good indication of the ranges of performance involved. The distributions capture the performance across the range of credible AEECs as well as uncertainty in the REEC, and so can be used to inform parameterisation of pathway assessment calculations exploring the related conceptual uncertainties.

The maximum infiltration rate with the geomembrane failed, which is approaching 1,000 mm y^{-1} represents a situation where there is no runoff from the cap, i.e. it is close to the calculated HER. This is implausibly high, as erosion and settlement of the cap is expected to be limited, and the water balance for other areas of the site show that there is significant runoff from site soils to streams and land drains [48]. Overland flow and interflow were not included in the cap infiltration calculations. However, they are accounted for when applying the calculated infiltration rates in the assessment calculations [40].

5.3 Trench and Vault Waste

Understanding of the evolution of the trench and vault waste is described in the Near Field report [6]. Evolution of the trench and vault waste is not detailed in the underpinning EPA reports (e.g. reference [21]). In this report, understanding of the near field is fed back into the EPA to provide a complete story of evolution of the repository engineering, including interactions between the waste and other components. Naturally there is a degree of overlap with the discussion of waste settlement, and the resulting strains on the final cap, in Subsection 5.2, above.

5.3.1 Nature of Trench and Vault Waste

Trench waste

Waste was disposed into the trenches between 1959 and 1995 using conventional tumble tipping techniques (Figure 3.1) with daily soil cover [5]. On completion of tipping activities, the trenches were capped, in two phases, with an interim cap. This was constructed from site soils with a low permeability geomembrane. The capping operations were undertaken in 1989 (Trenches 1 to 6) and 1995 (Trench 7).

The trench waste includes a heterogeneous mixture of soils, cellulosic materials and metals in a wide range of shapes and forms. The trenches have earthen walls (except for a reinforced concrete wall that divides Trench 7 in two along its length), and a basal gravity drainage system (Figure 5.7). Tenches 2 to 6 have earthen firebreaks.

Substantial settlement and degradation of the trench waste have already occurred, and some further degradation and settlement is expected. The highly heterogeneous nature of the waste and the variable time since its deposition make projections of the magnitude and timing of future settlement uncertain. This is further complicated by historic and anticipated future changes in water saturation level and oxygen content in the wastes as repository closure progresses.

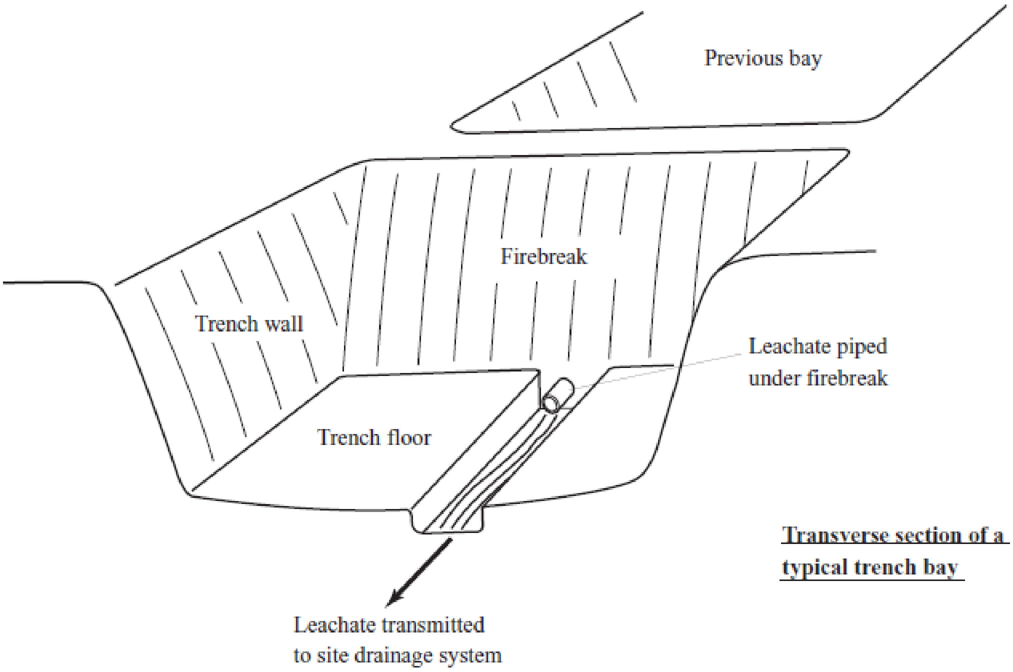

Figure 5.7: Trench features [35]

We have undertaken substantial work to understand the expected waste evolution and future settlement (for example references [6], [42]). To reduce uncertainties in the extent of settlement and to facilitate the construction of the final cap, the interim trench cap will be surcharged to the level of the final cap to drive out as much existing voidage as possible. This may result in a slight transient increase in leachate discharge from the waste [33].

For the purposes of the EPA, the highly heterogeneous nature of the waste is assumed to average out over a wide area with ‘conventional’ settlement characteristics (i.e. similar to those observed at conventional landfills). We expect that the trench wastes will pass from a partially oxic, saturated state into a drier, fully anoxic degradation state shortly following improvements to the interim trench cap and final capping, as applicable. This is expected to reduce the rates of degradation and continued settlement.

The uncertainty in waste properties and evolution is represented in the EPA through storyboards for different engineering evolution cases, which together capture the range of uncertainty in the estimated magnitude and timing of settlement. For example, biodegradation of different categories of cellulosic waste will operate on different timeframes, with wood degrading over much longer timeframes than paper. Similarly, the mechanical response of the wastes to surcharge and then final closure loads will operate on a further set of timeframes.

These uncertainties have been assessed and bracketed in successive iterations of the cap resilience report [42]. Aspects such as cellulose degradation have been informed by detailed geochemical modelling [6]. The impact of surcharge and final capping and the mechanical response have been explored in further underpinning assessments (e.g. reference [87]).

Vault waste

Waste was first disposed in Vault 8 in 1988. Like the trench waste, the vault waste comprises a heterogeneous mixture of cellulosic material, rubbers, plastics, soils, metals and other materials in a wide variety of forms. Waste is placed in mild steel containers and void spaces filled using a fluidic cementitious grout. Most of the containerised waste is in half-height ISO containers, but other size containers also exist.

The grout comprises PFA and OPC in a nominal 3:1 ratio (range 8:2 to 7:3), with a water to cement ratio that can range between 0.26 and 0.42 [88]. The grout includes a superplasticiser (Sikament 10, between 0.6 % and 1.0 %) that enables lower water contents to be used while achieving the desired fluidity [88]. Lower water content improves cured strength and minimises generation of bleed water, which may be contaminated.

The grout has lower strength than a typical concrete and is expected to contain cracks once cured. However, this does not affect its primary role in filling voids and reducing potential settlements. In the LLWR near field, the main process that is expected to chemically degrade the grout is leaching leading to loss of hydroxide, porosity increase, pH decrease, and strength decrease. Increases in loads on the grout may lead to further cracking. These includes loads from the profile fill and cap on waste and stresses generated by waste degradation and expansive corrosion.

'Soft' waste from Sellafield is super-compacted into pucks before being placed into containers, but the major portion of the waste is not compacted. Although the grouting procedures followed attempted to completely fill the containers, many of the containers, particularly the older ones, are known to have some residual voidage between the grout fill level and the container lid (ullage voidage). For some containers this may partially be due to degradation and self-compaction of the waste after grouting. In addition, voidage also remains within the waste, in areas inaccessible to the grout, such as the insides of pipes, wrapped or bagged wastes, and inaccessible cavities within plant components. Considerable effort has been made to successfully improve the extent of container grouting (Figure 4.1). Waste diversion and treatment have also contributed to voidage reduction as well as broader changes to the materials disposal profile.

There is evidence of some rusting and deterioration of the container steel, particularly in the containers placed in the 1980s. Prior to capping, the gaps between the container stacks, and any residual void spaces in the vaults, will be infilled with free-draining inert drainage materials. The drainage material is not expected to enter very narrow gaps, but these do not need to be filled.

In operational vaults, the waste and inner surfaces of the LLW and ILW containers are expected to be in a largely anoxic environment, while the outsides of the containers are in an oxic environment. Shortly after capping the waste and containers will fully pass into a fully anoxic state with degradation processes, notably steel corrosion, slowing.

Infiltration through the cap is expected to be low. Infiltration will largely enter surcharged top of stack containers through the damaged lids (Figure 4.2). Infiltration will mostly flow over

CPUs protecting stacks of future, stronger LLW containers and ILW containers, and drain between the container stacks (Figure 4.3), due to the large permeability contrast between the CPUs and intact containers, and the drainage material. Shielded modules and granular backfill inside the modules will similarly act to divert infiltration around ILW containers that require operational shielding.

Uncertainty in degradation of the waste, the effectiveness of drainage and continued container integrity, and impact of these small-scale variations on settlement is represented in the EPA by considering the range of uncertainty in the extent, estimated magnitude and timing of settlement that might be expected in the storyboards for the engineering evolution cases. This is similar in approach to the treatment of the trench waste and accommodates heterogeneity in vault waste evolution and the potential for different amounts of settlement in different waste stacks, and associated effects of differential settlement and uncertainty in timing.

Like the trenches, the effects of degradation and settlement on the overlying cap and on infiltration are mitigated by surcharging existing containers and containers committed to the same designs, and the reductions in container voidage already achieved over the last decade (Figure 4.1). Proposed improvements to the strength of future containers will also provide benefits for reduced settlement. However, settlement calculations show that taking no credit for support by the containers, and assuming all voidage in a stack is expressed as settlements at the same time, the cap will be resilient to plausible settlements (Subsection 5.2.2). The main benefit of stronger containers is to reinstate the full contribution of the containers to the multi-barrier system.

5.3.2 Factors Affecting the Trench and Vault Waste

The most important factors affecting the trench and vault waste over timescales ranging from a few years to centuries are described below.

Degradation of waste

Degradation and corrosion are mainly driven by the availability of moisture and oxygen and are significantly affected by the pH conditions and microbiological environments that develop. Most degradation processes require moisture, and to varying degrees oxygen, to operate and usually require the removal of reaction by-products to continue. These by-products are usually removed either through solution or suspension in water or through migration of gas. Under dry conditions most degradation processes cease, and degradation processes can also be severely restricted in anoxic conditions. Limiting moisture and oxygen access to the wastes is therefore one of the main objectives of the closure system, recognising that any delay in degradation that can be achieved has a significant impact on the timing and rates of associated settlement.

The outcomes of the large amount of work that has been undertaken to assess the response of the cap to settlement (Subsection 5.2.2) build confidence the cap will be resilient to all plausible settlements. Therefore, uncertainty in the degradation and settlement behaviour of the waste does not affect the expected performance of the cap.

Ground movements from waste degradation

Ground surface monitoring of domestic and industrial landfill sites have shown that settlement typically progresses following a relationship where the highest rates of vertical settlement are recorded immediately after loading. These progressively reduce with elapsed time as materials consolidate and waste degradation rates decrease. Eventually settlement will cease unless additional load is added [42] [20]. The magnitude of settlement varies for different wastes and materials over different time periods. Storyboards for the engineering evolution cases are based on from the settlement behaviour of conventional landfills, combined with site-specific arguments, site observations (especially for the trenches), and near-field modelling of future evolution.

The opposite effect, resulting in ground heave, can also occur. This is possible where the wastes are well compacted, with few internal voids, and degradation could generate potentially expansive by-products, and where processes to remove the by-products are restricted. For the trench and vault wastes, heave resulting in damage to the capping layers was considered [21] [42]. Heave is arguably most likely in vaults due to expansive corrosion of the metal waste and containers. We have concluded heave is very unlikely to affect the cap (Subsection 5.2.2) as the volume expansion which could occur is more likely to be accommodated within the containers themselves and laterally by the gaps between container stacks, rather than vertically. The potential for damage to the vault walls was discussed in workshops. There is not expected to be sufficient heave to result in damage to the vault walls. Even if minor, localised damage from heave occurs, it will not significantly affect the engineering functions relevant post-PoA.

5.3.3 Evolution of Trench and Vault Waste

Trench waste

The composition and age of the bulk of the trench waste mean that the settlement characteristics of the waste under the surcharge loadings are expected to follow a decreasing relationship with a rapid period of initial settlement (expected to be of the order of a few months) followed by a longer period of secondary settlement. The current design assumes that the surcharge will not be removed until after completion of the primary settlement (over a period of a few months [87]). Surface profiling and capping operations are then expected to continue in different areas of the cap for many years, so by the time the final cap is fully complete it is expected that the amount of secondary settlement still available in the system will be significantly reduced. Given the nature and compositional characteristics of the waste it is expected that trench settlements will continue and in general are likely to reach completion faster than the vault waste.

This pattern is expected to be disrupted locally by small amounts of differential settlement resulting from hard or incompressible features in the trenches, for example firebreaks (Figure 5.7) and the Trench 7 concrete wall [5], or from localised collapse or accelerated degradation of large items or groups or items (e.g. pipe bundles).

The trench drains, which are simple channels cut into the trench bases (Figure 5.7), are filled with waste and in the long term, are expected to clog. Because of their characteristics, their long-term impact is subsumed within the general waste performance and is not considered further.

The uncertainty in predicting future waste settlement comes from several factors, described previously. Alternative engineering evolution cases [5] therefore explore the potential for greater than expected settlements and describe the implications of greater saturation linked to worse cap performance (Subsection 4.5.2), to explore different possible performance envelopes into the future.

Vault waste in existing container designs

The containerised and isolated nature of the vault wastes mean that they will evolve differently to the trench wastes, although there will again be heterogeneous expression of waste degradation and mechanical settlements with time.

Under surcharge, existing containers, and those committed to the same design, are expected to deform immediately, expressing available settlements, and together with the profile fill, providing a stable platform for final cap construction. After the containers have been surcharged and capped, rates of container degradation will decrease as the exterior surfaces and vaults dry, and conditions become anoxic. The waste and grout will still contain significant amounts of water, the pH in the waste and grout will be high, and conditions inside the container will largely be anoxic prior to capping [6]. Therefore, rates of waste degradation will already be low prior to capping, so degradation rates will decrease by a relatively smaller amount following capping, compared with the trenches. Slow degradation of the waste, grout and containers will result in low rates of post-surcharge settlement.

Surcharging the existing and committed containers (and the trenches) will help reduce uncertainty in the amount of long-term settlement. The remaining uncertainty in describing future vault waste settlement comes from uncertainty in long-term performance of the waste and containers including the rate of expression of inaccessible voids and rates of biodegradation, the variety of container types, variability in the extent of container internal grouting, and localised spatial variations in water content and chemical conditions in the vault. The latter impacts metal corrosion rates and waste degradation.

We have developed storyboards for evolution of the vaults, which explore different degradation rates for different materials, to underpin our cap resilience assessments [42]. Overall, the total expression of voidage is likely to take longer than for the trenches, given the presence of large quantities of metals and grout. Given the characteristics of the existing and committed vault waste, waste degradation will be incomplete by the time the repository starts to be disrupted by coastal erosion.

Low rates of long-term secondary settlement are likely to be locally disrupted by occasional intervals of localised differential settlement driven by further structural collapse of stacks of ISO containers. Differential settlements are most likely in areas termed 'sensitive locations', e.g. over ‘hard edges’ such as the vault edges and dividing walls, or at steps in the heights of container stacks. The results of settlement calculations [42] provide confidence that these types of events will not have a significant impact on cap performance.

Vault waste in future stronger containers

Future stronger containers, including containers for LLW and ILW will not be surcharged. They will be designed to resist closure loads and are generally expected to maintain their structural integrity throughout the assessment timeframe. Best estimate general corrosion rates under vault conditions (Table 5.6) are sufficiently low that reduction in the strength of the containers could be within the factor of safety in the design. Disruption of the repository by coastal erosion is expected to begin several hundred to a few thousand years after present. A reference value of 1,250 years, and a range of 750 years to 1,750 years, is assumed for assessment models [8]. Only 0.4 mm thickness of steel would be corroded in 1,250 years at the rates given in Table 5.6. Some of the most highly loaded containers at the base of waste stacks may be subject to minor load-induced deflections in the load-bearing elements of the containers, but these are expected to be exceptions rather than the norm. There may be localised corrosion perforations of the containers, for example due to galvanic corrosion, or small areas where specific conditions result in faster general corrosion rates.

Table 5.6: Best estimate general corrosion rates and timescales for corrosion of containers of current designs

Container component	Thickness (mm)	Corrosion rate (mm y^{-1})	Corrosion time (y)
Wall	3	Outside $3\ 10^{-4}$ Inside $5\ 10^{-6}$	9,800
Structural elements[12]	8	Outside $3\ 10^{-4}$ Inside $5\ 10^{-6}$	26,200

Similarly, there is expected to be limited corrosion of the metal frames of CPUs. There will be some degradation of the reinforced concrete element of the CPUs, however this is expected to be limited by the small amount of infiltration through the cap. The reinforced concrete will be around 60-70 cm thick, so even if the top few centimetres of the concrete are altered, there will only be limited reduction in strength. Depending on the detailed design, alteration of the surface concrete may not penetrate to the rebar, reducing the potential for expansive rebar corrosion resulting in concrete cracking.

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[12] Note there are variations in the designs and thicknesses of the structural elements of the existing ISO container types. Future strengthened ISO containers might have thicker structural elements and, or they could have stronger geometry, e.g. ‘L’ section corner elements replaced with rectangular or square section corner posts, or bracing arrangements, optimised alongside consideration of the vault bases and stacking arrangements.

Small amounts of hydrogen sulphide may be dissolved in infiltration (see Subsection 5.2.2). However, conditions in the repository will be too reducing for sulphide to be oxidised to sulphate, forming sulphuric acid that could attack the concrete.

Waste and grout inside the containers will degrade during the assessment timeframe. However, because the containers and CPUs are typically expected to maintain their structural performance, waste and grout degradation will only contribute to settlement for the small numbers of containers that weaken to the point they deform.

5.3.4 REEC Storyboard for the Waste

The best estimate conceptual model of evolution of the waste with time is described by the storyboard shown in Figure 5.8. In the storyboard, timeframes have been assigned to the processes and events described in the preceding subsection. In the next subsection, the storyboard for the REEC and storyboards for the AEECs [21] inform parameterisation of the components' properties.

Figure 5.8: Storyboard for evolution of the waste in the REEC

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
Trench wastes (3)	The wastes will continue to degrade, especially cellulosics. They will generate some bulk gas during this process. Loading during interim cap upgrades and then surcharging and final cap emplacement is expected to release some water from the waste.	Continued degradation of wastes.	Around this time, it is expected that cellulosic degradation rates will be falling, not least as the faster degrading cellulosics will have degraded leaving slower degrading cellulosic materials such as wood. In central projections 50% or more of the total degradation of cellulosics will have occurred in most trenches [6].	Continued waste degradation. >1,000 years: Waste degradation substantially complete. Assumption at 5,000 years: Degradation complete.
Vault waste container stacks (4a) Existing and Committed LLW	Containers deformed by surcharging, with the majority of HHISOs undergoing deformation of load-bearing elements leading to available voidage being expressed, and some (limited) damage to the multi-barrier concept. Upper containers in stacks suffer lid damage and wastes are compressed by profile	A small number of containers may have undergone substantial further loss of integrity by this time, but probably this will apply to very few.	Between around 300 to 500 years the majority of disposed cellulosic and other easily degradable organics will have degraded. Most of the containers may have further deformed, as the surcharged containers will not resist voidage expression on waste degradation. There will be some associated container stack	There will still be limited mixing of container contents and parts of some wastes (especially thick metals and grouts) will still be intact. Waste degradation will continue with corrosion also influencing evolution, although the impacts of corrosion will continue to be a longer-term process.

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
	fill which fills available voidage in top of stack containers. Some degradation of the containers, e.g. due to corrosion during the operational phase. Some limited damage to upper containers from closure operations, e.g. placement of vault void fill.		movements (but the impacts of this on the cap will be substantially limited by the presence of adjacent stacks, void fill and profiling fill), and the vertical drainage channels will remain intact. It is expected that for many of these containers the grouted waste matrix will still provide some support, and not all voids within the containers and wastes will be expressed as stack settlement. Corrosion will not contribute significantly to stack evolution on this timeframe.	>1,000 years: Container and waste degradation will continue leading to eventual complete degradation. Assumption at 5,000 years: Degradation substantially complete. Most likely the repository will be disrupted by coastal erosion prior to degradation being complete.
Vault waste container stacks (4b) Future LLW and ILW that can be	Minor degradation of containers in Vaults following placement but functionally operating as designed. Container protection units prevent damage to top of stack containers and provide an	A small number of containers may have structurally deformed by this time. The majority of disposed cellulosic and other easily degradable organics will have degraded by this time. Container protection units continue to be largely intact and will divert	Beyond around 500 years it is cautiously assumed a small minority of the containers may have failed structurally with some container stack deformation (but the impacts of this on the cap will be limited by the presence of adjacent stacks and profiling fill).	Some additional containers have failed but the majority remain intact. Container protection units degrade more slowly than the containers with the majority remaining intact.

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
managed as LLW	additional protective barrier to infiltration into stacks.	infiltration down the sides of waste stacks.	It is expected that most of the container protection units will still be intact and preventing ingress of water into waste stacks. It is expected that for the small subset of containers that have failed, the grouted waste matrix will still provide some support and so not all voids within the containers and wastes will be expressed as settlement. Voidage will in any case be lower than for the existing and committed LLW.	>1,000 years: Container and waste degradation will continue, with the rate of waste degradation reducing, leading to eventual complete degradation. There will still be limited mixing of container contents and parts of some wastes (especially thick metals and grouts) will still be intact. Corrosion rates will be slow and so most containers and CPUs will retain integrity for most of this time period. Some residual settlement but not enough to challenge performance. Assumption at 5,000 years: Degradation substantially complete including container protection units. Most likely the repository will be disrupted by coastal erosion prior to degradation being complete.

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
Vault waste container stacks (4c) Future ILW disposed in external concrete structures	Shielded modules operating as designed and protecting containers by successfully carrying all capping loads and diverting all infiltration away from the waste. Only minor degradation of containers in shielded modules.	Some deformation and cracking of concrete in shielded modules, Structure still effective in protecting the containers from infiltration, loads, and crushing. Negligible settlement seen above shielded modules.	A small fraction of shielded module roofs assumed to have structurally failed and only partially preventing loads being passed to waste. A minority of loaded containers below roof failures are assumed to have failed structurally and excess voidage in wastes expressed. The resulting strains on the cap are within tolerance. However, across the shielded modules, the combined effect of residual shielded module structures, containers and the grouted waste matrix will provide support, such that only very limited voids within the containers and wastes will be expressed as settlement. Overall shielded modules intact.	Shielded modules units likely to persist significantly beyond 1,000 years and protect against settlements. Assumption at 5,000 years: Shielded module, container and waste degradation will continue leading to eventual substantial degradation by around 5,000 years. No notable performance difference remaining between different categories of vault disposals. Most likely the repository will be disrupted by coastal erosion prior to degradation being complete.

5.3.5 Properties

Trench Wastes

The characteristics of the waste and their expected evolution have been used to estimate the hydraulic conductivity of the waste 'as disposed' and for future times. The central value for the as-disposed hydraulic conductivity is 1 10^{-7} m s^{-1} [89] [64]. The hydraulic conductivity of the waste is expected to decrease as it degrades. Degradation of cellulosic waste is expected to be a key short- and medium-term processes. The central value of the hydraulic conductivity at 2130 is taken as 1 10^{-8} m s^{-1} [89]. This is based on the values elicited for the 2011 ESC [23], but with a modified timeframe for cellulose degradation based on the updated understanding of the near field [6].

Vault Wastes

The drainage material used as void fill for the vaults will be inert, low-fines, free draining granular material, controlled via a technical specification, to ensure a minimum hydraulic conductivity of 1 10^{-4} m s^{-1}. Natural variability in drainage material will occur and expert elicitation identified a representative central value of 3 10^{-3} m s^{-1} for use in most calculations [21].

Flows will be predominately vertical and preferentially through vertical gaps between container stacks. Horizontal flows will be lower but will also be preferentially through gaps (including features such as fork-pockets in the bases of containers).

Based on average disposed materials properties for the wastes, a central value for the as-disposed hydraulic conductivity of vault stacks is 1 10^{-6} m s^{-1} [89].

Reference [89] calculates combined central effective horizontal and vertical hydraulic conductivities of the vault waste mass and drainage material as 1.0 10^{-3} m s^{-1} and 1.7 10^{-4} m s^{-1} respectively, for the first 600 years. The horizontal hydraulic conductivity is higher than the central value of hydraulic conductivity for the drainage material due to the presence of open (unfilled) fork-pockets in the bases of the containers. Reference [89] then presents combined horizontal and vertical hydraulic conductivities for more degraded wastes (after 600 years) as 7.7 10^{-5} m s^{-1} and 1.7 10^{-4} m s^{-1}, respectively.

5.4 Trench and Vault Bases

5.4.1 Nature of the Trench and Vault Bases

Trenches

The trenches were excavated into Quaternary deposits. The first trench was an existing railway cutting through the northern part of the LLWR site associated with the Royal Ordnance Factory (ROF) [3]. Subsequently, five wider and deeper trenches were purposely excavated parallel to, and on either side of, Trench 1 so that their bases should lie within natural low-permeability clay at a depth of 5 m to 8 m below ground level. A final trench, Trench 7, of irregular shape was excavated to fully use the site area to its north-eastern boundary. All trenches have a north to south fall, to facilitate the collection of leachate at the southern end of each trench (Figure 5.7).

From Trench 3 onwards, bentonite was rotovated into the bases of the trenches where the natural clay was absent [35]. Although the trench bases have low permeability, some leachate drains through the bases into the underlying ground [7] [9].

Vaults

Vault 8, Vault 9 and the future vaults have different base designs (Figure 5.9). The base of Vault 8 comprises a concrete running slab, overlying a drainage layer and then a natural clay layer. The perimeter of the drainage layer butts against natural sediments; it is not sealed. Where the clay layer was thin or absent, the natural deposits were dug out and replaced with engineered BES that was compacted into position. Any leachate that permeates through the concrete running slab is captured in the drainage layer and directed into the leachate management system.

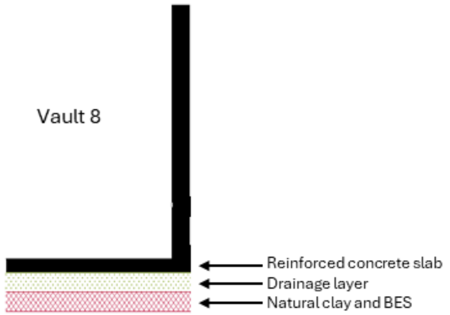
The Vault 8 base was designed to ensure good leachate management and control during the operation of the facility but was not designed to operate in the long term after repository closure. Changes in performance of the vault base are therefore expected after closure, although it will continue to have a significant effect on post-closure drainage patterns.

The Vault 9 base includes two geomembranes and two BES layers. Like the Vault 8 base it was designed to ensure good leachate management and control during the operation of the facility. The Vault 9 base is expected to degrade more slowly than the Vault 8 base, as it includes a double composite liner, and have a significant effect on post-closure drainage patterns for much longer.

The future vault bases are designed to capture leachate effectively during the operational phase and to the end of the period of active institutional control, although leachate generation is expected to drop to negligible levels during the period of active institutional control. In the long-term, leachate can access the under-vault drainage blankets by overtopping the 1 m high vault walls (Figure 5.9 and Subsection 5.5.5.2). Long-term degradation of the vault bases, assumed to be designed with a single composite liner, will aid passive drainage by providing a direct route to the drainage blankets.

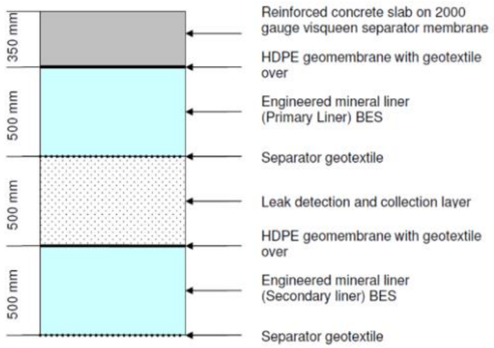
The Vault 8 and Vault 9 concrete slabs have cracks resulting from static and dynamic loads. However, this does not affect their function as a flat surface for moving and stacking containers. Although small amounts of leachate may flow into these cracks, the underlying layers are the main barriers preventing leachate draining into the underlying ground. Similar cracks are expected to develop in the bases of the future vaults.

Vault 8



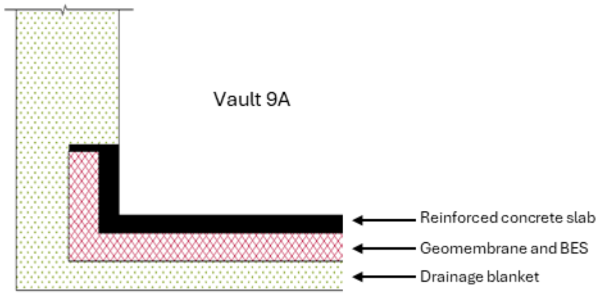
Design to provide improved capture of leachate compared with the trenches. Originally designed for tumble-tipped waste rather than stacked containers.

Vault 9



Designed to maximise operational containment and capture of leachate for waste storage, as a Permit for disposal was not in place at the time of construction.

Future vaults



Includes passive drainage arrangements consistent with the optimised approach to isolating the waste and containing contaminants [10].

Figure 5.9: Vault base designs

The concrete slabs are formed from conventional structural concrete (cement, sand and aggregate) with steel reinforcing bars to improve their tensile strength (Subsection 3.4). In each vault the concrete slab has expansion joints to prevent cracking as the material expands and contracts in response to temperature changes. The expansion joints are sealed.

The BES in the vault bases is a similar mix to the final cap BES, and the HDPE geomembranes are similar to the cap geomembrane. The processes which degrade the BES and geomembranes in the vault bases are the same as the processes which degrade these materials in the cap (Subsection 3.4).

5.4.2 Factors Affecting the Trench and Vault Bases

Trenches

The hydraulic properties of the trench bases are not expected to change significantly over time. There could be some washout and cation exchange of the bentonite that was rotovated into the bases where the natural clays were absent. However, this would tend to be offset by loading and compaction of the rotovated material and clogging of the whole area of the trench bases by fines derived from the degrading waste. Expert judgement is weighted towards a small net long-term decrease in the permeability of the trench bases.

Vaults

The precise details of the design of the vault bases differ between Vaults 8, 9 and the future vaults (Figure 5.9). Nevertheless, for the purposes of the EPA, it is appropriate to assume that all vault bases operate in a simple manner and progressively degrade and lose functionality through similar processes:

- leakage through construction joints;
- leaching and alteration of the cement binder in the concrete;
- cracking of the concrete base slab through loading and expansive rebar corrosion.

These processes will potentially slightly increase the permeability of the vault bases, but to some extent, will be countered by clogging of any defects. The inherent low permeability of the concrete that results from the aggregate grading and density of the constituent components is likely be evident as a permeability contrast long into the future.

Geomembranes and BES in the bases of Vault 9 and the future vaults will be degraded by the processes described for the cap in Subsection 5.2.2. The rates of degradation will be different to the cap as the strain and chemical environments are different, and the rates of degradation of the basal geomembranes are more uncertain than the cap geomembrane. Nevertheless, both the geomembranes and BES are expected to retain their low permeability long into the future.

5.4.3 Evolution of the Trench and Vault Bases

Trenches

The bases of the trenches are expected to evolve very little over time and to continue much as they do today. These features are therefore considered in the EPA as having little or no long-term influence on closure system performance. Infiltration will continue to drain through the trench bases unless infiltration exceeds their drainage capacity, when water levels will rise above the level of the clays in the trench walls and water will drain laterally. If this does not provide enough extra drainage capacity, then water levels will continue to rise until water overtops the cut-off wall and discharges to the ground surface. The uncertainty in system performance is captured over time by slightly higher or lower estimates of permeability to reflect variations in the possible performance envelope.

Vaults

The concrete base slabs, the underlying low permeability layer(s), and connections to the under-vault drainage blankets at the 1 m level are the main components controlling leakage through the bases and water levels in the vaults. In all the vaults, as the cap begins to degrade, leachate may collect and pool on the running surface, with slow flow downwards to the underlying low permeability layer through cracks that may have developed in the running service or through degraded expansion joints.

Over long timescales, expansive corrosion of steel rebar in the slabs is expected to generate further cracks increasing their hydraulic conductivity. The high calcium content of the vault leachate is likely to result in cation exchange of BES and a slight increase in permeability, particularly in the vicinity of cracks in the overlying base slab. However, where the BES is protected by a geomembrane, this process will not start until the geomembrane degrades, except immediately below defects (small holes) in the geomembrane.

Although the permeabilities of the base slab and underlying BES are expected to increase over time, we expect limited change in the overall permeability of these components because the concrete under load will retain its high density and the increase in permeability by partial cation exchange of the BES will be small. The relatively low permeability characteristics of the base slabs and underlying BES are therefore likely to persist.

Degradation of the vault bases is consistent with the optimised approach of providing passive drainage after the end of the PoA, and one reason why the future vault bases have been optimised to be simpler (single rather than double composite) than the Vault 9 base design.

There will be differences between the vaults reflecting differences in the designs. For example, downwards flow through the base of Vault 8 might be higher than for Vault 9 and the future vaults because it does not have a geomembrane, and water that flows through the Vault 8 concrete base slab may escape laterally out of its drainage layer.

These differences are reflected in the parameter (hydraulic conductivity) PDFs for assessment modelling. Separate PDFs have been developed for each layer within the

Vault 8 base, the Vault 9 base and the future vault bases. Uncertainty in system performance is reflected in the ranges of the hydraulic conductivity PDFs.

5.4.4 REEC Storyboard for the Vault Bases

The best estimate conceptual model of evolution of the vault bases with time is described by the storyboard shown in Figure 5.10. In the storyboard, timeframes have been assigned to the processes and events described in the preceding subsection. In the next subsection, the storyboard for the REEC and storyboards for the AEECs [21] inform parameterisation of the components' properties.

Figure 5.10: Storyboard for evolution of the vault bases in the REEC

Component	Reference Engineering Evolution Case			
	During completion / as built	**100 years (to end PoA)**	**500 years**	**1,000 years**
Vault bases (V8, V9, Future) (5)	Vault bases in good working order showing no significant defects or settlement beyond the cracks in place after completion of disposals. Hydraulic performance controlled by geomembranes, BES and natural clays (Vault 8). Minor damage to base slabs due to cap loading and settlement of underlying geology although no obvious reduction in performance.	Negligible deterioration and no obvious reduction in performance.	Deterioration of expansion joints within a few hundred years, minor corrosion of reinforcement in concrete slabs, and negligible change to cement paste, leading to slight reduction in performance. Nearer to 1,000 years: continuing corrosion of reinforcement bars leading to expansion of reinforcement and cracking of concrete although cement paste remains intact. Net result is a widespread moderate increase in the permeability of the base. A significant reduction in the structural performance of the vault base leads to increased cracking where differential stresses are high, which manifests as locally higher permeabilities in these areas. However hydraulic	Continuing structural failure of concrete. Cement paste still largely intact. At 1,000 years, antioxidant depletion leading to oxidation and failure of geomembranes in some areas. By 2,000 years, this is widespread. However, BES still effective despite cation exchange of BES being advanced. No degradation of natural clays. Assumption at 5,000 years: Complete structural failure of concrete and dissolution / washout of cement paste leads to residual sand and gravel matrix only. Relatively high permeabilities exist across the whole of the concrete

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
			performance still dominated by geomembranes, BES and natural clay (Vault 8). Potential around this time for geomembranes to start to undergo antioxidant depletion.	elements of the vault base. However, the BES and natural clays still provide a function.

5.4.5 Properties

5.4.5.1 Vault 9 and Future Vault Bases

Although the detailed designs of the vault bases differ (Figure 5.9) e.g. in terms of the number of composite layers and the thicknesses of different elements, the performance, evolution and properties of the individual concrete, BES and geomembrane components of the bases are anticipated to be very similar, allowing a simplified and consistent representation in the EPA.

Steel-reinforced Concrete Slab (Operating Surface)

A datapack was developed to support selection of parameter values for steel reinforced concrete components and review workshops. The datapack included information on the processes which cause degradation of structural concrete and literature information on the properties of 'as built' and degraded structural concrete. This included literature data from SKB [58] [90] and Nagra [55] used in their repository specifications, safety and performance assessments. The datapack is presented in Appendix D of reference [21].

.The main mechanisms of degradation of reinforced concrete relevant to the LLWR are leaching and chemical alteration of the cement paste, expansive corrosion of metal rebar resulting in cracking of the concrete, and degradation of materials sealing expansion joints. In addition, operational loads are expected to crack the vault concrete bases. Cracks are observed in the existing vault bases, but these do not affect the operational performance of the bases.

The envelope of performance for the Vault 9 and future vault concrete slabs is provided in Table 5.7.

Table 5.7: Hydraulic conductivity of the Vault 9 and future vault concrete slabs

Time	Distribution	Hydraulic Conductivity (m s^{-1})		Condition	Basis for Values
‘As built’ and during operations	Log triangular	Min	$1\ 10^{-11}$	Includes operational cracks. No degradation prior to strip capping.	Literature data presented in reference [21], reference [49] and observed run-off from concrete in rainfall events.
		Mode	$1\ 10^{-10}$		
		Max	$1\ 10^{-9}$		
Immediately following strip capping	Log triangular	Min	$1\ 10^{-9}$	Step change due to cracking caused by capping. Then some gradual degradation by the end of the PoA.	Values reflect the hydraulic conductivity of the base becoming controlled by the underlying geomembranes and BES.
		Mode	$1\ 10^{-8}$		
		Max	$1\ 10^{-7}$		
End of the PoA	Log triangular	Min	$1\ 10^{-9}$	Possibly some crack growth or widening by the end of the PoA.	Includes the potential for crack growth and widening and degradation of material sealing expansion joints.
		Mode	$1\ 10^{-8}$		

Time	Distribution	Hydraulic Conductivity (m s^{-1})		Condition	Basis for Values
		Max	1 10^{-6}	No chemical degradation over the first 1,000 years of the post-PoA period.	
End of the PoA + 1,000 years	Log triangular	Min	1 10^{-8}	Step change as more fractures penetrate the full thickness of the slab at end of the PoA + 1,000 years. Then gradual degradation to the parameter values for 5,000 y.	Corrosion of rebar causes widening of existing through cracks and forms new through cracks. Timing underpinned by models of rebar corrosion and cracking (Table 5.8).
		Mode	1 10^{-7}		
		Max	1 10^{-6}		
5,000 years	Log triangular	Min	1 10^{-7}	Largely degraded, properties at or nearing long-term stable values.	Base slab has significant chemical degradation and rebar corrosion increases introducing further cracking.
		Mode	1 10^{-6}		
		Max	1 10^{-5}		

The Vault 9 and future vault bases are large areas of poured concrete. Their hydraulic conductivities are expected to be higher than smaller, cast structural concrete components due to the presence of expansion joints and small defects. Like the Vault 8 and Vault 9 bases, the future vault bases are expected to crack during operations [5], immediately increasing the hydraulic conductivity of the concrete compared with when the concrete had cured but had not been subject to static and dynamic operational loads. These factors are reflected in the hydraulic conductivities for the concrete slabs 'as built' and during operations (Table 5.7). The hydraulic conductivities of the concrete slabs are higher than the 'as built' values elicited for the 2011 ESC [85], which are representative of smaller, cast structural concrete components.

Further cracking is expected during the closure process, due to the loads from the profile fill and cap on the base. This would result in a step increase in hydraulic conductivities. The extent of cracking and crack properties are very uncertain, and therefore so is the hydraulic conductivity of the cracked concrete. The hydraulic conductivity values were chosen to reflect the hydraulic conductivity of the bases becoming controlled by the underlying geomembranes and BES, rather than the concrete.

We do not expect there to be significant further degradation of the bases by the end of the PoA. However, it is possible there could be some gradual crack growth or widening as the system equilibrates with the load from the cap and profile fill. This is reflected in the increased maximum hydraulic conductivity at the end of the PoA compared with immediately following strip capping.

Around the end of the PoA, or at most timescales of a few hundred years, degradation of the material sealing expansion joints would also contribute to increasing hydraulic conductivity of the vault bases. This is assumed to be captured by the parameter range for the end of the PoA which includes cracks through the bases.

The low infiltration through the cap means there should be little chemical degradation of the bases after 1,000 years. However, there would be sufficient water in the concrete pores to support expansive corrosion of rebar, leading to cracking of the concrete. The porewater pH will typically be high, around pH 12.5, so the rebar corrosion rate will be low. It could take of the order 5,000 years for cracks between adjacent rebar to join up and penetrate through the full thickness of the concrete slab (Table 5.8).

Operational cracking of the bases, followed by leaching and chemical alteration of the crack surfaces prior to capping may locally reduce the pH around rebar intersected by the cracks. Assuming the pH around the rebar falls to around pH 10.5 to 11, calculations (Table 5.8) show this would lead to locally higher rates of rebar corrosion, crack widening and further crack development, on timescales of hundreds to around a thousand years.

Table 5.8: **Calculated time for concrete crack development in structural concrete (properties from reference [91]). 12 mm diameter rebar.**

Crack type	Time of crack (y)			Method
	pH 7	pH 11	pH 12.5	
First crack*	0.2	35	210	[92]
50 mm crack**	5	800	4,800	Scaling of experimental results [91]
50 mm crack**	4-5	670-780	4,000-4,700	Scaling of model results [91]

* A very small crack that does not connect to cracks associated with adjacent rebars or penetrate the concrete cover.

** Long enough to penetrate the typical thickness of concrete cover and therefore reaching the surface of the component.

Leaching and chemical alteration of the cement paste are not expected to be significant until the cap geomembrane degrades, because infiltration is expected to be low while the cap geomembrane is intact. The cap geomembrane may still be intact when the repository starts to be disrupted by coastal erosion, so much of the reinforced concrete may be in good condition when disruption starts.

Timescales significantly longer than those for the start of disruption of the repository would be needed for leaching and chemical alteration, combined with vault-wide expansive rebar corrosion and cracking, to lead to the concrete degrading to residual sand, aggregate and secondary minerals.

BES (in the vault bases)

A datapack was developed to support selection of parameter values for BES and review workshops [93]. Key information from the datapack, parameter values from the review workshops, and justification for the values are summarised below.

The specification for the Vault 9 base BES incudes a maximum of 5% air voids [5], implying almost the entire pore space would be filled with water when placed. Sodium bentonite is used to make the BES in the vault bases. The specification for the Vault 9 BES requires between 5 wt% and 10 wt% sodium bentonite [5]. The BES would have been mixed using freshwater. The properties of fully hydrated Vault 9 BES are estimated in Table 5.9, using laboratory data from reference [94]. The best estimate hydraulic conductivity exceeds (i.e. is lower than) the requirement for the Vault 9 base BES. The estimated hydraulic conductivity is consistent with the results of lab scale hydraulic conductivity tests of BES mixes reported in reference [95].

Table 5.9: Estimated hydrated hydraulic conductivity (m s^{-1}) of Vault 9 base BES in equilibrium with different water compositions, using laboratory data from reference [94]

Mix	Min	Best estimate	Max
7.5:92.5 Modified compaction	Freshwater		
	$1\ 10^{-12}$	$1\ 10^{-11}$	$1\ 10^{-10}$
	Low salinity water		
	$6\ 10^{-11}$	$2\ 10^{-10}$	$8\ 10^{-10}$

The hydraulic properties of the BES will evolve as the porewater chemistry evolves to be in equilibrium with the geochemical environment. Cation exchange of sodium in montmorillonite with calcium and potassium in water increases the hydraulic conductivity of BES, as does increase in the salinity of the BES porewater. For example, again using laboratory data from reference [94], hydration with low salinity water increases the hydraulic conductivity by one order or magnitude or more, compared with hydration with freshwater. The magnitude of the increase is sensitive to the chemistry of the water in addition to its salinity.

Reference [95] compared the hydraulic conductivities of sodium and calcium bentonites and concluded that complete cation exchange of sodium for calcium would increase the hydraulic conductivity of 7.4 wt% bentonite BES from around $5\ 10^{-11}$ m s^{-1} by about two orders of magnitude, to around $2\ 10^{-9}$ m s^{-1}. Consequently, it is expected the hydraulic conductivity of BES in the vault bases will increase as higher salinity, high calcium and potassium content waters, conditioned by the waste and vault cementitious components, infiltrate the BES.

The hydraulic conductivity of BES can also increase with time due to washout of the bentonite. This is a slow process because the low hydraulic conductivity of the BES limits flow through the material.

The envelope of performance for BES in the bases of Vault 9 and the future vaults is provided in Table 5.10.

The hydraulic conductivities described in Table 5.9 can be achieved in small scale applications, but the hydraulic conductivity is likely to be higher at the vault scale due to variability associated with the number of placement operations and the time for placement. Therefore, to achieve the design specification hydraulic conductivity of less than $1\ 10^{-10}$ m s^{-1} at the vault scale, the mix hydraulic conductivity would have to be lower at the laboratory scale.

The best estimate (modal) ‘as built’ hydraulic conductivity is set at the specification. The range then reflects that with optimal placement the ‘as built’ hydraulic conductivity could be more similar to the laboratory scale, but it is also possible that problems during placement or contact with waters with elevated calcium or potassium content or salinity could lead to higher hydraulic conductivity. The CQA approach is a key factor controlling the maximum possible hydraulic conductivity.

There would not be any significant infiltration through the cap while the geomembrane in the cap is functioning. Therefore, there would be little water available to contact and degrade the BES in the vault bases. Similarly, the geomembranes above the basal BES layers would protect the BES from leaching or interaction with porewaters from the overlying concrete base slabs, waste and other cementitious components.

After 1,000 years, infiltration through the cap would likely still be low, and the geomembranes protecting the basal BES layers would likely still be intact. Therefore, it is possible there would not be any degradation of the BES. This is reflected in the minimum hydraulic conductivity, which is equal to the ‘as built’ value. However, given the low bentonite content of the BES, participants at review workshops considered that some degradation is to be expected, e.g. due to diffusion of calcium and potassium from the concrete into the BES through defects (small holes) in the geomembranes, resulting in localised ion exchange. This is reflected in increases to the model and maximum hydraulic conductivities, by one and two orders of magnitude respectively, compared with earlier times. The magnitude of these changes is consistent with the literature data and results of experiments reported in reference [95], described above.

Before 5,000 years the geomembrane in the cap is expected to have failed, resulting in increased infiltration into the vaults, and flow downwards through the vault bases. Similarly, the geomembranes protecting the BES layers are likely to have failed. There is likely to be further decrease in the BES performance through washout and cation exchange. The bentonite could also be chemically degraded through reaction with solutes from the vault concrete bases. However, chemical degradation is expected to be limited to a narrow zone at the interface with the concrete bases, e.g. by comparison with reference [96].

The elicited hydraulic conductivities at 5,000 years are unchanged from the 2011 ESC. The maximum hydraulic conductivity assumes total loss of the bentonite, so only sand remains, while the minimum hydraulic conductivity is the modal value for ‘as built’ BES. The modal hydraulic conductivity at 5,000 years reflects:

- degradation of the BES following failure of the geomembranes in the cap and bases;
- the presence of localised areas that are relatively more degraded because they were below defects in the geomembranes and saw more flow at earlier times;
- the effects of clogging by secondary mineral precipitates.

Table 5.10: Hydraulic conductivity of BES in the base of Vault 9 and the Future Vaults

Time	Distribution	Hydraulic Conductivity (m s^{-1})		Condition	Basis for Values
'As built' and hydrated	Log triangular	Min	$1\ 10^{-11}$	Based on the design specification and unchanged from the 2011 ESC [23].	Estimated from BES specification [5], laboratory data [94] and tests reported in reference [95]. Performance controlled by CQA.
		Mode	$1\ 10^{-10}$		
		Max	$1\ 10^{-9}$		
End of the PoA	Log triangular	Min	$1\ 10^{-11}$	Protected by the geomembrane, no processes identified that could lead to significant degradation.	As above.
		Mode	$1\ 10^{-10}$		
		Max	$1\ 10^{-9}$		
End of the PoA + 1,000 years	Log triangular	Min	$1\ 10^{-11}$		Modal value increased from previous time

Time	Distribution	Hydraulic Conductivity (m s^{-1})		Condition	Basis for Values
		Mode	1 10^{-9}	Some degradation in performance expected due to the low bentonite content.	snap by one order or magnitude reflecting complete ion exchange of Na for Ca [95].
		Max	1 10^{-7}		
5,000 years	Log triangular	Min	1 10^{-10}	Further degradation following failure of the geomembranes.	Chemical degradation as presented in [96] and elicited values unchanged since 2011 ESC [23].
		Mode	1 10^{-8}		
		Max	1 10^{-6}		

Basal geomembranes

Long-term system performance will not be sensitive to assumptions about the geomembranes in the Vault 9 and future vault bases. This is because long-term hydraulic performance will be dominated by the drainage components. Therefore, basal geomembranes were subject to an appropriate level of analysis (updated literature review and standard review) that was robust and sufficient to provide confidence in outcomes and is proportional to their system roles (i.e. less complex and less important than the geomembrane in the final cap).

The existing Vault 9 base geomembranes comprise 2 mm-thick HDPE. In addition, the future vault bases are also anticipated to include 2 mm-thick HDPE geomembranes. Literature sources referred to in assessment of the final cap performance consider basal geomembranes, as well as geomembranes in capping systems, and the conclusions made are generalised. Therefore, the overall arguments on defects, antioxidant depletion and subsequent degradation made for the cap geomembrane also apply to the basal geomembranes for the LLWR. Data on the timescales for antioxidant depletion are provided in Table 5.3.

The basal geomembranes are located below the concrete base slabs and founded on BES. As they will be placed on a flat surface, they will be in a lower strain environment compared with the cap geomembrane, except at the perimeter of the vault, where the geomembranes turn sharply to rise 1 m up the vault walls. The heterogeneity of the subgrade under the vault bases could lead to limited settlements under final cap loads. However, the BES and underlying layers will provide strain distribution functions. There is confidence strains on the geomembrane will be tolerable e.g. reference [42].

The main consideration in terms of differences of evolution concerns chemical conditions. There is evidence from the literature that contact of geomembranes with higher pH waters can enhance the rate of antioxidant depletion e.g. reference [97]. However, this is very case-specific and the specification for existing Vault 9 geomembranes for the LLWR [98] requires the geomembranes to be resilient to typical landfill leachate chemistries which implies a range of pH values. (This can be made more explicit in future specifications.) The uncertain potential for evolution to be influenced by leachate chemistries leads to enhanced uncertainty in performance for the basal geomembranes, represented by an increased potential for earlier degradation.

The envelope of performance for geomembranes in the Vault 9 and future vault bases is provided in Table 5.11.

Table 5.11: Hydraulic conductivity of the geomembranes in vault bases

Time	Distribution	Hydraulic Conductivity (m s^{-1})		Condition	Basis for Values
End of the PoA	Cumulative	0%	1 10^{-14}	Reflects uncertainties associated with placement of the geomembrane, welds etc, basal movements during disposals and capping, and interactions with alkaline waters associated with concrete and leachate.	Literature review and predicted strains reported in reference [42].
		20%	1 10^{-14}		
		80%	1 10^{-12}		
		100%	1 10^{-9}		
End of the PoA + 500 years	Cumulative	0%	1 10^{-14}	Uncertainty in performance additionally takes account for potential for accelerated antioxidant depletion, compared to the final cap, as in higher pH environment, noting limited infiltration and thus limited leachate contacting geomembrane.	As above, including consideration of specific literature on antioxidant depletion [97] and final cap condition [64] [66].
		5%	1 10^{-14}		
		80%	1 10^{-12}		
		100%	1 10^{-6}		
PoA + 1,000 years	Cumulative	0%	1 10^{-14}		
		60%	1 10^{-12}		
		70%	1 10^{-6}		
		100%	1 10^{-6}		

Time	Distribution	Hydraulic Conductivity (m s^{-1})		Condition	Basis for Values
PoA + 2,000 years	Cumulative	0%	1 10^{-14}		
		40%	1 10^{-12}		
		50%	1 10^{-6}		
		100%	1 10^{-6}		
5,000 years	Single value	1 10^{-6}		Fully degraded.	Nominal value equal to the maximum value for the BES at this time, i.e. hydraulic conductivity is controlled by the BES.

The maximum initial hydraulic conductivity for the geomembrane is specified as $1\ 10^{-14}$ m s^{-1}. The use of a maximum means the geomembrane could be manufactured to have a lower permeability. However, further reductions in permeability will have negligible impact on any model outcomes and so it is not necessary to represent them in the distribution.

The values at the end of the PoA reflect the potential for a range of processes to have affected the geomembranes, for example differential loading of the slabs and potential differential movements of the subgrade during waste emplacements and final capping, and inaccuracies in emplacement or welding. The strain environment was discussed during review workshops. The workshops noted that the literature since the 2011 ESC indicates an enhanced likelihood of strain tolerance for these geomembranes. Overall, considering the uncertainties, the likelihood of as-built performance ($1\ 10^{-14}$ m s^{-1}) at the end of the PoA was agreed to be 20% (for each of the basal geomembranes).

The arguments on longevity of 2 mm HDPE geomembranes in LLWR conditions for the final cap (Subsections 5.2 and 5.2.4) also apply here. There is the potential for the geomembrane performance to persist over timescales of over 2,000 years. However, the experts involved in the review considered the potential effects of alkaline conditions need to be reflected in the distributions, and these are captured in the relative probabilities of degradation over earlier timeframes. Therefore, there is an enhanced probability of early degradation compared to the final cap.

As for the final cap, it is considered that some cracking will occur during the antioxidant depletion process and during the following period of oxidation induction. Subsequently as oxidation of the geomembrane progresses, the geomembranes will crack initially locally, and then shortly afterwards will, in effect, degrade completely. This is because stress cracks will propagate throughout the geomembranes, together with the stresses on the geomembranes then being sufficient for the brittle material to be degraded across the system.

The final degraded hydraulic conductivity is set to be equivalent to the BES conductivity at relevant timeframes as this is consistent with the modelling approach that is likely to be implemented.

To give an appropriate representation of the probability of the geomembrane having degraded, the probability that the hydraulic conductivity is less than $1\ 10^{-12}$ m s^{-1} at the end of the PoA was considered through iterations of expert review. A probability of 80% was agreed. The final point in the distribution recognises the uncertainty associated with the potential for chemical degradation of the geomembrane.

It is near certain that the geomembrane will have degraded after 5,000 years. In between the end of the PoA and 5,000 years, the experts considered that it is increasingly more likely that degradation will have occurred with increasing time. The judgments on probability for these intervening times reflected both the potential for geomembrane performance to persist for a prolonged period, as for the cap geomembrane, and the increased uncertainty in performance at earlier times, relating to the potential impacts of local chemical conditions.

5.4.5.2 Vault 8 Base

The Vault 8 base comprises a steel-reinforced concrete slab (operating surface) and an underlying drainage layer (Figure 5.9). It is founded on natural clays, which provide a low permeability barrier to releases to groundwater. Where the clays were thin or absent the natural sediments were excavated and replaced with BES.

The drainage layer includes perforated concrete pipe drains, which form part of the leachate management system. We have not made final decisions on the fate of these drains when the leachate management system is decommissioned, for example whether they will be left open or plugged. It is also possible that we might take advantage of these drains to provide an additional post-closure drainage connection to Vault 9 or Vault 9a. Regardless of the fate of these drains, they will not significantly affect the long-term performance of the base, so they are not discussed further.

Steel-reinforced concrete slab (operating surface)

Although the concrete slab is a little thinner than the Vault 9 and future vault base slabs, it has better reinforcement [5]. The Vault 8 base slab should have similar performance to the Vault 9 and future vault base slabs. Therefore, participants at review workshops agreed that parameterisation of the performance of the Vault 8 concrete base slab should be like the Vault 9 and future vault base slabs.

The best estimate (modal) hydraulic conductivity during the operational phase is the same as Vault 9 and future vaults, reflecting literature values [21] and the observed runoff from the concrete during rainfall events, indicating the hydraulic conductivity of the concrete is low. The only difference to the values agreed for Vault 9 and the future vaults is the maximum hydraulic conductivity immediately following strip capping. This is an order of magnitude higher than Vault 9 and the future vaults reflecting the potential for soft points in the ground below the base and greater uncertainty in the base construction and quality. The presence of any soft points, and greater uncertainty in base construction, would not significantly affect the long-term degradation processes (rebar corrosion and cracking, leaching and chemical degradation), which control the long-term hydraulic conductivities. Therefore, the long-term hydraulic conductivities are the same as Vault 9 and the future vaults.

Drainage layer

The specification for the drainage layer [72] indicates it should have very similar hydraulic properties to the drainage blankets below the future vaults (Subsection 5.8.5). Therefore, the drainage layer is taken to have the same hydraulic properties as the drainage blankets. There is not expected to be significant clogging of the basal drainage layer because:

- flow through the basal drainage layer is expected to be low, due to the low infiltration through the cap;
- suspended sediment will be filtered out as water drains through cracks in the concrete base slab;

- chemical conditions in the basal drainage layer are expected to be like those in the vault, outside the containers, so there will not be any chemical changes to drive precipitation (Subsection 5.8.3.1).

Natural clay and BES

The Vault 8 BES comprises a mix of limestone aggregate and 5 wt% sodium bentonite [99]. Where BES was placed, the natural sediments were removed to a depth of 300 mm and replaced with the BES mix. The BES mix was compacted using a vibrating roller [99]. This should have achieved a high density.

The key difference to Vault 9 and the future vaults is that BES is only present across part of the Vault 8 base. The properties of the BES layer below Vault 8 need to be calculated using the weighted contributions of the BES and the natural clay. The spatial extent of the natural clay and BES are uncertain. A uniform distribution between 35% and 65% is expected to capture the areal extent of natural clay, with the remainder of the area comprising BES.

Although the Vault 8 BES contains a little less bentonite than the Vault 9 BES, calculations using laboratory data, analogous to those presented in Table 5.9 for Vault 9 BES, give very similar hydraulic conductivities to Vault 9 BES. For simplicity, the hydraulic conductivities of the Vault 8 BES are taken to be the same as the Vault 9 and future vault BES, even though it is of slightly different composition and may be a little more vulnerable to degradation as it is not overlain by a geomembrane. However, the closure cap provides the Vault 8 BES with the same protection from infiltration as the Vault 9 and future vault BES.

The hydraulic conductivity of the natural clay underlying Vault 8 is given in Table 5.12. Section 6.0 of reference [99] states that the natural clay has a mean hydraulic conductivity of $7.7\ 10^{-9}$ m s^{-1}, with Subsection 5.4 of reference [100] noting the hydraulic conductivity varies by two orders of magnitude. The hydrogeological test method is not given. There is assumed to be no degradation of the natural clay.

The measured hydraulic conductivity of the natural clay relates what was termed the G5 clay layer in the geological model of the time. The G5 clay layer is one component of the B2 unit, which also includes deeper clays. Our groundwater flow models [7] show that at the site scale the vertical hydraulic conductivity of the B2 unit is lower than reported by reference [99]. The difference may reflect the presence of multiple clays within the B2 unit, spatial variations in the hydraulic conductivities, or limitations of the hydraulic conductivity measurements. For example, the hydraulic conductivities of the clays may be lower than the lower limit of the test method. These factors need to be considered when applying the parameter values in models.

Table 5.12: Hydraulic conductivity of the natural (G5) clay underlying Vault 8

Time	Distribution	Hydraulic Conductivity (m s^{-1})	
All	Log triangular	Min	1 10^{-9}
		Mode	1 10^{-8}
		Max	1 10^{-7}

5.4.5.3 Shielded Module Base

The steel reinforced concrete bases of the shielded modules are thicker than the vault concrete bases. At the review workshops it was assumed the shielded modules would be small enough that they would not require expansion joints in the base. This is a plausible assumption because expansion joints in the Vault 8 base are at distances of the order 40 m to 50+ m [21].

The degradation processes described in Subsection 5.4.5.1 for the Vault 9 and future vault concrete bases are relevant to the bases of the shielded modules. However, the bases of the shielded modules are expected to degrade more slowly than the vault base slabs due to their greater thickness, absence of operational cracks and expansion joints, and protection from infiltration provided by the module roof and by drainage features which are designed to divert any water that enters the modules into the wider vaults.

The envelope of performance for the shielded module concrete bases is provided in Table 5.13.

Table 5.13: Hydraulic conductivity of the shielded module concrete bases

Time	Distribution	Hydraulic Conductivity (m s^{-1})		Notes
'As built' and during operations	Log normal	5th %ile	1 10^{-13}	Distribution truncated at 1 10^{-14} and 1 10^{-10} m s^{-1}.
		50th %ile	1 10^{-12}	
		95th %ile	1 10^{-11}	
5,000 years	Log triangular	Min	1 10^{-8}	Step change at 5,000 years as cracks penetrate the full thickness of the slab.
		Mode	1 10^{-7}	
		Max	1 10^{-6}	

The ‘as built’ hydraulic conductivity is based on the values elicited in the 2011 ESC for ‘as built’ structural concrete components [23].

Given the expected absence of cracks in the module base, and the slow chemical degradation, we expect that high pH would be maintained around the rebar for several thousand years. If the pH around the rebar is maintained at around pH 12.5 to 13, slow expansive corrosion of the rebar is calculated to result in cracks developing from the rebar to the surface of the base slab after 4,000 to 5,000 years (Table 5.8). Assuming rebar is present throughout the full thickness of the slab, cracks associated with individual bars could join at this time and penetrate the full thickness of the slab, increasing the hydraulic conductivity.

If chemical degradation of the surface of the concrete reduces the pH around the rebar closest to the surface, the corrosion rate would increase, resulting in cracking, and faster penetration of chemical alteration into the concrete. However, as there is insufficient infiltration for significant chemical degradation to begin until the geomembrane in the cap has failed (expected to be around 2,000 years), it would still take several thousand years for cracking to penetrate the full thickness of the base. Therefore, the hydraulic conductivities at 5,000 years assume limited chemical degradation of concrete but cracking through the full thickness of the slab.

The hydraulic conductivities at 5,000 years are the same as the Vault 9 and Future Vault bases, when they are in a similar condition, which occurs at the end of the PoA + 1,000 years (Table 5.7).

5.4.5.4 Shielded Module Roof

The shielded module roofs have much in common with the bases, including the same thickness, so it is logical to consider the bases and roofs together.

Although construction of the roofs is different to the bases, involving casting a reinforced concrete stab over steel reinforced concrete tiles [5], they are relatively small features that can be built to high quality. Therefore, the ‘as-built’ properties are assumed to be the same as the shielded module bases.

The roofs are designed to be trafficked over during closure operations and carry profile fill and cap loads without cracking. They are expected to be protected from significant leaching and chemical degradation by the final cap for around 2,000 years. As the geomembrane in the cap fails and some water starts to infiltrate through the cap (a few tens of millimetres per year, Figure 5.6), there will be some leaching and chemical degradation of the roofs. This is further discussed in reference [21].

Chemical degradation of the top few centimetres of the roofs might lead to lower pH conditions around the rebar closest the top surface, leading to faster rebar corrosion and cracking. This cracking could allow more water to enter the roof slabs, resulting in further alteration, and accelerated rebar corrosion and cracking deeper in the slabs. However, the cold join between the cast roof slab and the underlying tiles could stop crack propagation, and by the time the alteration front penetrates significantly into the roofs, cracks may have already developed through the full thickness of the roof due to:

- cracking associated with slower corrosion of the deeper rebar; and
- cracking as the roofs, and supporting walls and base, weaken and can no longer carry the weight of the profile fill and cap, for example due to bending stresses, stress increases, and delamination of the joint between the cast roof slab and underlying tiles.

The evolution and properties of the shielded module roofs is more complicated and uncertain than the evolution and properties of the shielded module bases. However, given that differences in performance are most likely to arise on timescales beyond those for start of disruption by coastal erosion the properties of the shielded module roofs are assumed to be same as the shielded module bases (Table 5.13).

5.5 Trench and Vault Side Walls

5.5.1 Nature of the Trench and Vault Side Walls

Trenches

The trenches are excavated into natural clays[13], but the clays do not extend all the way to the ground surface, i.e. to the top of the trenches. Water can more readily drain through areas of the walls formed by sands and silts, including areas where the clays are absent and if the water level rises above the elevation of the top of the clays.

Vaults

Vault 8, Vault 9 and the future vaults have different wall arrangements. These are illustrated in Figure 5.11. The detailed arrangements and construction of the walls are outlined in reference [5].

Vault 8 has walls up to the current ground surface (around 21 m AOD). The north and west walls were constructed from cast panels of reinforced concrete, while the east wall, adjacent to the trenches, is a secant pile wall. Vault 9 has a similar construction to Vault 8 but with additional inner walls. The basal BES layer extends 1 m high[14] into the cavity between the inner and outer walls, to minimise the risk of lateral seepage during vault operation. Future vaults will follow a similar construction, but the height of the concrete walls will be limited to 1 m above the base, so after the end of the PoA water can passively overtop the walls and access the sub-vault drainage blankets.

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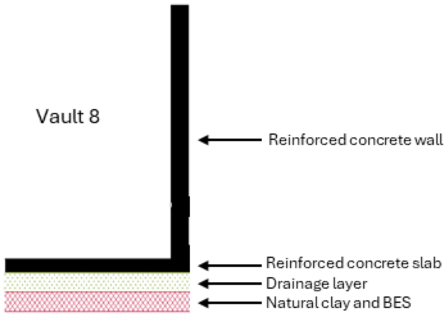
[13] Bentonite was rotovated into the bases of Trenches 3 to 7 where the natural clays were thin or absent, but it is not known to have been rotovated into the side walls.

[14] The BES was originally designed to extend up the full height of the cavity to ground level. However, during construction it was only placed to the 1 m level to be more consistent with the optimised approach that was developed for the 2011 ESC.

Overflow drainage holes are planned to link Vault 8 and Vault 9 with Vault 9a. The drainage holes will start around 1 m above the Vault 8 and Vault 9 concrete slabs. Existing leachate collection drains below the Vault 8 concrete base slab may be redirected to provide an additional connection to Vault 9a, and connections will be installed between Vault 8 and Vault 9. These connections are intended to minimise the risk of Vault 8 and Vault 9 overtopping, by allowing infiltration to Vault 8 and Vault 9 to access the drainage blanket below Vault 9a. Similarly, infiltration to Vault 9 will be able access the drainage blanket below Vault 10 by overtopping the south wall. We are confident that connections can be made that will provide the required functionality, but we have not made final decisions on the detailed designs at this stage.

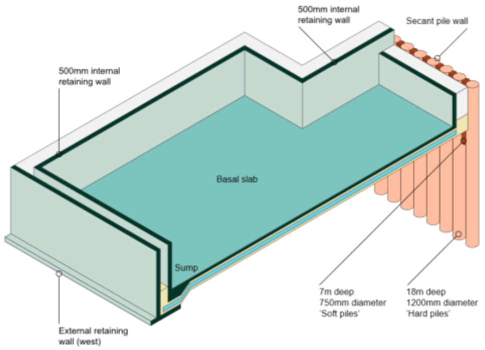
The future vaults have 1.1 m high south walls (Figure 3.4). If a drainage blanket does not have sufficient capacity, a small further rise in the vault water level will allow water to flow over the south wall. It will then be able to access additional drainage capacity in the adjacent vault(s).

Vault 8



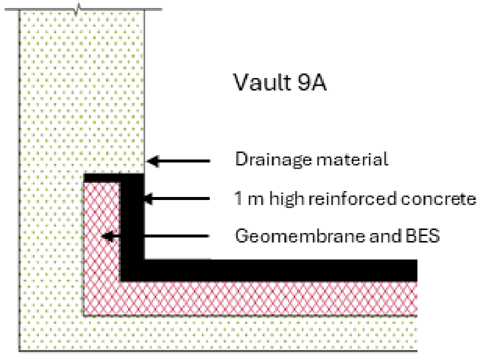
Designed to provide improved capture of leachate compared with the trenches. Originally designed for tumble-tipped waste rather than stacked containers.

Vault 9



Full height walls designed to maximise operational containment and capture of leachate for waste storage, as a Permit for disposal was not in place at the time of construction. Optimisation for the 2011 ESC [78] led to BES being terminated at 1 m above the operating surface consistent with plans for passive drainage.

Future vaults



1 m high west walls provide access to drainage blankets.

If the drainage blanket does not have sufficient transmissivity, 1.1 m high south walls allow waters to overtop to adjacent vaults to access drainage capacity there.

Figure 5.11: Vault wall designs

5.5.2 Factors Affecting the Trench and Vault Side Walls

Trenches

Few factors have been identified that could affect operation of the trench side walls. The areas of the walls comprising sand and silts, i.e. where the clays are absent, may become clogged at the interface between the waste and the walls. This minor clogging is unlikely to affect the performance of the walls which are likely to function in perpetuity.

Vaults

Degradation of walls constructed from panels of reinforced concrete is likely to occur in response to the same factors identified for the vault concrete bases. This includes failure of construction joints and cracking of the reinforced concrete. BES present to the 1 m level in the cavity between the Vault 9 inner and outer walls will be degraded by the processes described for BES in the vault bases (see Subsection 5.4.2), including cation exchange.

The eastern secant pile walls will also be affected by cracking of the reinforced concrete. During construction of Vault 8, water flowed from the trenches through the secant pile wall into the vault. Flow from the trenches into Vault 8 was prevented by the finishing layer of concrete, however the secant pile wall provides a route for water to access the drainage layer below the Vault 8 base slab [101].

While the cap is performing well and water levels in the trenches are low, we do not expect there to be any significant flow from the trenches into the vaults. However, as the cap and secant pile wall degrade, flow from the trenches into the vaults may re-establish.

5.5.3 Evolution of the Trench and Vault Side Walls

Trenches

We do not expect there to be any significant evolution of the trench walls until they are disrupted by coastal erosion.

Uncertainty in system performance over time is captured by slightly higher or lower estimates of hydraulic conductivity to reflect the possible performance envelope.

Vaults

The vault walls are likely to show a slight increase in hydraulic conductivity over decades to centuries where cracking of the concrete and cation exchange of the BES have occurred. Over a longer period, the high density of the concrete constituents and existence of a BES layer (in Vault 9 and the future vaults) are likely to ensure the walls have an impact on the local hydrogeology for the foreseeable future. Although the walls will retain some of their characteristics, this is unlikely to have any significant effect on closure system behaviour as water is intended to overspill the future vault walls at a level of 1 m above the top of the base.

Uncertainty in system performance is captured over time by slightly higher or lower estimates of hydraulic conductivity to reflect the possible envelope of performance.

5.5.4 REEC Storyboard for the Vault Walls

The best estimate conceptual model of evolution of the vault walls with time is described by the storyboard shown in Figure 5.12. In the storyboard, timeframes have been assigned to the processes and events described in the preceding subsection. In the next subsection, the storyboard for the REEC and storyboards for the AEECs [21] inform parameterisation of the component's properties.

Figure 5.12: Storyboard for evolution of the vault walls in the REEC

Component	Reference Engineering Evolution Case			
	During completion / as built	**100 years (to end PoA)**	**500 years**	**1,000 years**
Vault side walls (6)	Vault side walls in good working order with no significant defects. Minor structural damage due to vault operations and, or cap construction, no deterioration of materials.	Minor deterioration of materials.	Degradation of expansion joints within a few hundred years of PoA but walls withstand lateral loading. Vault base remains structurally intact, supporting the walls, such that there is negligible change in performance of walls. Nearer 1,000 years: Continuing corrosion of reinforcement bars leads to localised loss of structural capacity. Failure of some stacked containers and creation of isolated point loads leads to additional lateral loads on walls, resulting in some localised wall failure. However overall walls continue to perform.	Continuing structural failure of concrete. Cement paste still largely intact. Overall performance of walls continues to be good. Assumption at 5,000 years: Complete structural failure of all stacked containers, concrete base, and corrosion of reinforcement within walls leads to complete wall failure around the vaults and total loss of performance.

5.5.5 Properties

5.5.5.1 Trench Walls

The trenches are cut into the B2 lithofacies unit. The hydrogeological properties of the B2 unit are described in reference [7]. We assume the properties of the B2 unit do not evolve with time in our assessment models [40].

5.5.5.2 Vault 9 and Future Vault Walls

The Vault 9 and future vault walls include reinforced concrete walls, and a secant pile wall that runs between the vaults and Trench 3. The inner and outer reinforced concrete walls in Vault 9, and reinforced concrete walls in the future vaults (Figure 5.11) are assumed to have the same performance, evolution and properties.

BES and geomembranes present to the 1 m level in the Vault 9 and future vault walls are assumed to have the same performance, evolution and properties as BES and geomembranes in the vault bases (Subsection 5.4.5.1), as these are extensions of the same elements.

The envelope of performance for the Vault 9 and future vault walls is provided in Table 5.14 (reinforced concrete) and Table 5.15 (secant pile wall). The Vault 9 west wall contains drainage slots to Vault 9a and therefore the properties below only apply to the Vault 9 west wall below the elevation of the drainage slots. The hydraulic conductivity of the Vault 9 west wall above the base of the drainage slots should be taken to be the same as the hydraulic conductivity of the drainage material between container stacks in the wider vault.

Table 5.14: Hydraulic conductivity of the Vault 9 and future vault reinforced concrete walls (excluding the Vault 9 west wall above the elevation of the base of the drainage slots)

Time	Distribution	Hydraulic conductivity (m s^{-1})		Notes
'As built' and during operations	Log normal	5th %ile	1 10^{-13}	Distribution truncated at 1 10^{-14} and 1 10^{-10} m s^{-1}.
		50th %ile	1 10^{-12}	
		95th %ile	1 10^{-11}	
End of the PoA	Log triangular	Min	1 10^{-11}	Gradual change from 'as built' and during operations as expansion joints fail
		Mode	1 10^{-10}	
		Max	1 10^{-9}	
5,000 years	Log triangular	Min	1 10^{-8}	Step change as cracks penetrate the full thickness of the walls.
		Mode	1 10^{-6}	
		Max	1 10^{-4}	

Table 5.15: Hydraulic conductivity of the Vault 9 and future vaults secant pile walls

Time	Distribution	Hydraulic conductivity ($m\ s^{-1}$)		Notes
‘As built’ and during operations	Log triangular	Min	1 10^{-9}	Wall known to be leaky.
		Mode	1 10^{-8}	
		Max	1 10^{-7}	
End of the PoA	Log triangular	Min	1 10^{-9}	No significant change.
		Mode	1 10^{-8}	
		Max	1 10^{-7}	
End of the PoA + 1,000 years	Log triangular	Min	1 10^{-8}	Step change as cracks penetrate the full thickness of the hard piles.
		Mode	1 10^{-6}	
		Max	1 10^{-5}	
5,000 years	Log triangular	Min	1 10^{-7}	Loss of cement paste.
		Mode	1 10^{-6}	
		Max	1 10^{-5}	

The reinforced concrete walls can be cast to high quality. Therefore, the ‘as-built’ hydraulic conductivity is based on the values elicited in the 2011 ESC for ‘as built’ structural concrete components [23].

As-built drawings for Vault 9 were used to identify the locations and dimensions of the expansion joints in the east and west inner walls, and outer west wall, and then calculate an estimate of the effects of joint failure on the overall hydraulic conductivity of the wall [21]. Joint failure is estimated to increase the hydraulic conductivity of the wall by around two orders of magnitude, from 1 10^{-12} m s^{-1} to 1 10^{-10} m s^{-1} (Table 5.14).

Chemical degradation of the walls is expected to be slow due to the low rates of infiltration through the cap. ‘As built’ and following closure there are not expected to be significant cracks in the walls. Given the expected absence of cracks, and the slow chemical degradation, high pH should be maintained around the rebar for several thousand years. Slow expansive corrosion of the rebar under high pH conditions would result in cracks developing from the rebar to the surfaces of the walls after 4,000 and 5,000 years.

Chemical degradation of the outer few centimetres of the walls might lead to lower pH conditions around the rebar closest the surfaces, leading to faster rebar corrosion and cracking. This cracking could allow more water to enter the walls, resulting in further alteration, and accelerated rebar corrosion and cracking deeper in the walls. However, by the time the alteration front penetrates significantly into the walls, cracks may have already developed through the full thickness of the walls due to:

- cracking associated with slower corrosion of the deeper rebar; and
- cracking as the walls weaken and can no longer carry lateral earth loads.

The best performance for the Vault 9 and future vault walls at 5,000 years is the same as the vault bases when they are in a similar condition, which is at the end of the PoA plus 1,000 years. The hydraulic conductivities for expected (modal) and worst performance were set with reference to the estimated properties of the shielded module walls at 5,000 years (Subsection 5.5.5.4). The hydraulic conductivities are expected to be higher than the concrete forming the shielded module walls at this time because the walls are thinner, and more poorly laterally restrained, e.g. where gaps between the container stacks and the walls are too small to fill with granular material during closure.

The secant pile wall is essentially only a structural component and is not expected to have the low permeability of high-quality structural concrete. There is known to be some leakage through the wall, and this provides an indication of the ‘as-built’ hydraulic conductivity, which is expected to be higher than the hydraulic conductivity of the vault bases during operations.

The trenches and ground immediately below the repository cap are expected to become dryer once the closure engineering is installed, so piles are less likely to be in contact with saturated trench waste and ground, and there is not expected to be flow through the wall into the vault. Given this, and the thickness of the wall, there is not expected to be any significant degradation by the end of the PoA.

The quality of the concrete is expected to be lower than the other concrete components, so the rebar is expected to be less well protected. Therefore, the rebar is expected to corrode more quickly, leading to cracking earlier than in many of the other concrete components. The effects of lower quality concrete on rebar corrosion are conceptualised as being similar to the impacts of operational and closure cracks in the vault bases, so expansive rebar corrosion is assumed to result in cracks through the wall after 1,000 years. This would result in a step increase in the hydraulic conductivity of the wall. Although there would be little chemical degradation of the piles at this time, the hydraulic conductivity would be similar to a fully degraded wall.

As the cut-off wall degrades and as some water starts to infiltrate through the cap, water saturations in and immediately below the repository will start to increase. There will start to be some chemical degradation of the secant pile wall, for example due to leaching of hydroxide by flows through the wall, and diffusion of hydroxides away from the wall. The wall is assumed to be substantially chemically degraded after 5,000 years, although this does not lead to significant increases in the hydraulic conductivity compared with 1,000 years.

5.5.5.3 Vault 8 Walls

The Vault 8 walls include reinforced concrete walls, and a secant pile wall that runs between the vault and Trench 3.

The properties of the reinforced concrete walls are assumed to be same as the Vault 9 and future vault reinforced concrete walls (Subsection 5.5.5.2) for the same reasons. Although there are more expansion joints in the Vault 8 walls than the Vault 9 walls, the joints are a little narrower. The effect of additional failed joints on the estimated hydraulic conductivity of the walls is small compared with uncertainty in the hydraulic conductivity of the failed joints, and uncertainty in the potential impacts of joint widening due to expansive corrosion of the metal dowels [5] and cracking of the concrete adjacent to the joint.

The Vault 8 south wall will contain drainage slots to Vault 9a and therefore the properties below only apply to the Vault 9 south wall below the elevation of the drainage slots. The hydraulic conductivity of the Vault 8 south wall above the base of the drainage slots is taken to be the same as the hydraulic conductivity of the drainage material between container stacks in the wider vault.

The detailed design of the secant pile wall is different to Vault 9 and the future vaults, but it is assumed to have the same performance, evolution and properties (Table 5.15).

5.5.5.4 Shielded Module Walls

The shielded module walls would contain drainage holes to direct any water infiltrating through the module roof into the wider vault. The effective hydraulic conductivity of the walls should therefore be taken to be the same as the hydraulic conductivity of the drainage material between container stacks in the wider vault. If the walls include expansion joints, these could fail by the end of the PoA, or a little later, providing an additional route to direct any infiltration into the wider vault.

The reinforced concrete walls are expected to be more durable than the vault walls because they are thicker. The hydraulic conductivities of the concrete forming the walls (Table 5.16), i.e. excluding the drainage holes and any expansion joints, are the same as the shielded module base (Table 5.13), except for the maximum hydraulic conductivity at 5,000 years. This is one order of magnitude higher than the base, reflecting the potential for effects such as spalling of concrete.

Table 5.16: **Hydraulic conductivity of the concrete forming the shielded module walls, i.e. excluding the drainage holes and any expansion joints**

Time	Distribution	Hydraulic conductivity ($m\ s^{-1}$)		Notes
'As built' and during operations	Log normal	5th %ile	$1\ 10^{-13}$	Distribution truncated at $1\ 10^{-14}$ and $1\ 10^{-10}$ $m\ s^{-1}$.
		50th %ile	$1\ 10^{-12}$	
		95th %ile	$1\ 10^{-11}$	
5,000 years	Log triangular	Min	$1\ 10^{-8}$	Step change as cracks penetrate the full thickness of the walls.
		Mode	$1\ 10^{-7}$	
		Max	$1\ 10^{-5}$	

5.6 Cut-off Wall

5.6.1 Nature of the Cut-off Wall

The purpose of the cut-off wall is to resist shallow lateral flows of water into and out of the repository. In doing so, the cut-off wall helps to direct infiltration through the final cap to deeper groundwater pathways.

A cement-bentonite cut-off wall currently extends along the east and north sides of the trenches. The wall was constructed by excavating a trench and filling it with cement-bentonite slurry. The cement causes the slurry to set solid. The resulting material has low compressive strength but is less brittle and vulnerable to cracking than typical concrete. Its key characteristic is its low permeability.

The cut-off wall will be tied into the low permeability layers in the cap. Therefore, the cut-off wall will be progressively extended, concurrent with strip capping, until it encircles the repository. Future extension of the cut-off wall will use the same construction method and a similar low permeability formulation to the existing wall sections and will be of a similar thickness. The precise details of the various parts of the cut-off wall, which vary in depth around the repository, are described in reference [5] and supporting documents.

5.6.2 Factors Affecting the Cut-off Wall

Performance of the cut-off wall may be reduced by:

- desiccation resulting in irreversible cracking - this is most likely to affect the upper parts of the wall;
- cation exchange and washout of the bentonite;
- leaching and chemical alteration of the cement.

These processes will result in an increase in permeability and are likely to occur on timeframes of decades to centuries.

5.6.3 Evolution of the Cut-off Wall

The cut-off wall is expected to operate as constructed and to direct water flows around the facility for decades to centuries before slowly increasing in permeability as cation exchange and washout of the bentonite and leaching of the cement progress. Water shed to the perimeter of the cap should help to keep the wall hydrated, except possibly the very top of the wall where it connects to the cap resistive layers.

These changes are unlikely to materially affect the role of the cut-off wall. The wall will continue to operate in the manner intended for many centuries and will provide a permeability contrast and remain a hydrogeological feature in the area for millennia.

The uncertainty in system performance and performance envelope is captured by adopting slightly higher and lower hydraulic conductivities into the future up to the start of disruption by coastal erosion.

5.6.4 REEC Storyboard for the Cut-Off Wall

The best estimate conceptual model of evolution of the cut-off wall with time is described by the storyboard shown in Figure 5.13. In the storyboard, timeframes have been assigned to the processes and events described in the preceding subsection. In the next subsection, the storyboard for the REEC and storyboards for the AEECs [21] inform parameterisation of the component's properties.

Figure 5.13: Storyboard for evolution of the cut-off wall in the REEC

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
Cut-off wall (7)	Cut-off wall in good working order with no significant construction defects.	No significant degradation, performance as built.	Some washout of bentonite and cement or deterioration in the vicinity of construction joints or areas of wall thinning. Permeability slightly increased from as-built condition. Nearer 500 years: Some further washout of bentonite and cement, localised increase in permeability through cation exchange and, or in areas of local deterioration in the vicinity of construction joints and areas of wall thinning. Combined effect reduces effective performance of cut-off wall from as-built condition.	Significant deterioration of cut-off wall through cation exchange, washout of bentonite and cement, and localised areas of deterioration. However, flows through the wall (and thus washout and rates of exchange) are insufficient to significantly challenge overall performance – a permeability contrast will remain, if reduced. Assumption at 5,000 years: Complete deterioration and washout of bentonite cement, cut-off wall no longer functions as an effective barrier to flow of water.

5.6.5 Properties

The existing cut-off wall was successfully implemented and achieved an appropriate hydraulic conductivity on post-implementation sampling and testing [102], Its good condition has been further confirmed by inspections and monitoring since then. There is therefore excellent confidence in the constructability of the remainder of the cut-off wall. The post-installation testing of the wall provides a strong basis for the start-point of the hydraulic conductivity parameterisation of both existing and future sections of the wall.

The main requirement for the cut-off wall to function is that it retains a permeability contrast with the surrounding geology. There is confidence that this will be maintained for a prolonged period, for reasons including the following.

- The (lateral) hydraulic conductivity of the surrounding geology [7] is typically several orders of magnitude higher than the anticipated properties of the cut-off wall.
- The cut-off wall is 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, will be confined by the ground on either side and is unlikely to move or evolve significantly.

Evolution will mainly be via cation exchange of the bentonite component of the mix, and the leaching of the cement and washout of bentonite and other materials with time. This will mostly occur once the cap begins to degrade and there is potential for higher flows. However, such effects will be limited and the expert reviews undertaken for the EPA, including reviewing recent additions to the cut-off wall literature [21], confirmed previous judgements that there is high confidence in the provision of a long-term permeability contrast [23] [79]. Therefore, the hydraulic conductivities elicited for the 2011 ESC [23] were still considered to be appropriate (Table 5.17).

Table 5.17: Hydraulic conductivity of the cut-off wall

Time	Distribution	Hydraulic conductivity (m s^{-1})		Condition	Basis for values
‘As built’ and during operations	Log triangular	Min	1 10^{-10}	Accounts for uncertainty in sloughing of trench material into wall, imperfect joints between panels and imperfect alignment of panels at depth.	Elicitation of values in 2011 [23].
		Mode	1 10^{-9}		
		Max	1 10^{-8}		
End of the PoA	Log triangular	Min	1 10^{-10}	There will be little degradation from the as-built condition	Elicitation of values in 2011 [23].
		Mode	1 10^{-9}		
		Max	1 10^{-8}		
End of the PoA + 1,000 years	Log triangular	Min	1 10^{-9}	Significant degradation has occurred which is continuing.	Interpolation between values for end of PoA and 5,000 years accounts for uncertainty in condition.
		Mode	1 10^{-8}		
		Max	1 10^{-6}		
5,000 years	Log triangular	Min	1 10^{-8}	Leaching out of cement and washing out of bentonite,	Values derived using a model, replacing

Time	Distribution	Hydraulic conductivity (m s^{-1})		Condition	Basis for values
		Mode	$1\ 10^{-7}$	leaving a very weak structure which could readily collapse. Creation of a vertical path could occur.	fractions of wall with much higher hydraulic conductivity.
		Max	$1\ 10^{-5}$		

5.7 Leachate Management System

The leachate management system, while essential for continued site operations, will be decommissioned before the end of the period of active institutional control. Some residual or buried elements of the system are likely to remain, such as the drains in the Vault 8 base (Subsection 5.4.5.2). We have not made final decisions on the fate of these elements, for example whether they will be left open or plugged. It is also possible that we might take advantage of some elements, for example the Vault 8 drains might be used to provide an additional post-closure drainage connection to Vault 9 or Vault 9a.

Residual elements of the leachate management system are not expected to significantly influence the performance of the closure system. The residual elements will lie entirely below the cap and within the cut-off wall, so they will not provide potential fast flow or bypass pathways which could significantly change system performance. The existing leachate management system has therefore not been considered beyond the end of the period of active institutional control.

5.8 Under-vault Drainage and Underlying Geology

5.8.1 Nature of Under-vault Drainage and Underlying Geology

Future vaults are planned to have a drainage layer comprising strong, coarse, chemically inert aggregate that will be constructed beneath their bases. This is intended to maximise access to the natural drainage through the underlying geology and to direct post-closure drainage to deeper groundwater pathways [10]. Vaults 8 and 9 do not have a basal under-vault drainage layer that connects to the underlying geology. As described in Subsection 5.5, drainage routes will be provided through the Vault 8 and Vault 9 south walls allowing water in these vaults to access the drainage blankets in the future vaults.

The passive drainage system comprises four elements (Figure 5.14):

1) drainage pathways between the stacks of containers (and Vault 8 and Vault 9 south walls) to the top of the 1 m high future vault walls;
2) drainage material that connects the future vaults to the underling drainage blankets;
3) the drainage blankets below the future vaults;
4) the natural geology underlying the drainage blankets.

Here we consider all four elements of the system, noting the first three elements will be constructed from the same material (or very similar materials).

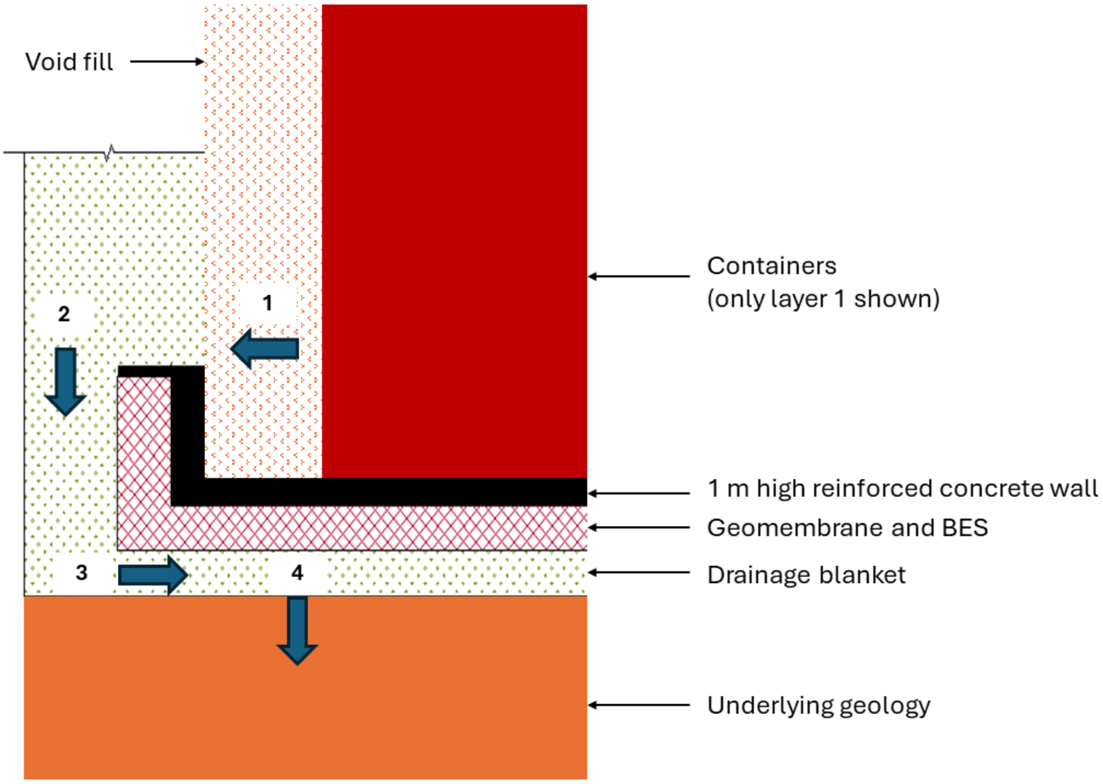


Figure 5.14: Post-PoA passive drainage in future vaults

The underlying geology comprises a complex sequence of glacial and periglacial deposits. In the simplest terms these can be described as follows.

- The B2 unit comprising clay-dominated deposits and sand-dominated deposits. The repository, including drainage blankets, is constructed in this unit. Water from the drainage blankets will drain downwards through the B2 unit into the underlying B3 unit.
- The B3 unit comprising sands and gravels. The unit is laterally continuous. Groundwater flows laterally in this unit discharging at the coast.

Details are given in the '*Hydrogeology'* report [7].

5.8.2 Factors Affecting the Under-vault Drainage and Underlying Geology

The passive drainage system will be constructed from strong, chemically inert, coarse aggregate, so the area of the drainage blankets and the properties of the B2 unit control the total 'as built' drainage capacity. Clogging is the only process that can reduce performance of the passive drainage system. Clogging can occur through deposition of fine-grained material (physical clogging), precipitation of solutes (chemical clogging), and formation of biofilms living on dissolved organics (biological clogging). Physical, chemical and biological clogging processes may occur together. All three processes require flow of water through the passive drainage system to occur.

Although the individual gaps between the container stacks are relatively small, their combined area is substantial, and they provide multiple routes for water to flow laterally to the 1 m high future vault walls. Therefore, localised clogging is not expected to impact flow of water to the 1 m high future vault walls, as water will find routes around any areas of local clogging.

The element of the passive drainage system at greatest risk of clogging is the material which connects the vaults to the underlying drainage blankets, because it has the smallest area for flow. The risk of physical clogging is partly mitigated by the vault wall design arrangements whereby leachate overflowing into the drainage media will be drawn from the surface of the water column impounded by the vault walls. This operation is analogous to the way siltation lagoons operate and draw clean water from the surface. Large particulates and coarse particles are therefore expected to have dropped out of suspension before the leachate over-spills the vault walls into the drainage system.

As the under-vault drainage blanket will be formed of aggregate with a permeability far greater than the underlying geology, its performance is always likely to exceed the underlying geology. Therefore, its performance is insensitive to the actual permeability as long as it remains greater than the underlying geology. Given the very high initial ('as built') permeability of the drainage system, and large contact area with the underlying geology, there is expected to be sufficient redundancy in the system to cover all possible clogging situations.

The cut-off wall resists lateral inflow of water from outside the repository into the drainage blankets, which would use some of their capacity. Degradation of the cut-off wall could result in higher lateral inflow. However, as discussed in Subsection 5.6.3, the cut-off wall is always expected to have lower lateral permeability than the natural sediments (B2 unit). Combined with the small area for lateral inflow compared with the area for vertical drainage (i.e. the plan area of the drainage blankets), lateral inflow is only expected to use a very small proportion of the drainage capacity.

The only situation that could significantly reduce the capacity of the drainage blankets is if regional groundwater heads rise into the drainage blankets. In this situation, the drainage capacity would be greatly reduced (and in response the drainage blankets would become water saturated) because:

- water would flow laterally through the drainage blanket instead of draining vertically downwards, which would greatly reduce the area for flow;
- the lateral hydraulic gradient driving flow would be of the order a few percent, so substantially reduced compared with the unit gradient (i.e. one hundred percent) for vertical drainage.

We have developed a groundwater flow model of the site and surrounding environs [48]. We have used this to explore evolution of groundwater flows in response to evolution of the engineering performance (described by this EPA), climate change, sea-level rise and coastal erosion. We have modelled future groundwater flows for reference, low and high emissions and sea-level rise scenarios. Regional groundwater heads only rise to the level where they impact the performance of the drainage blankets immediately prior to start of disruption of the repository by coastal erosion in the High Emissions Scenario. As the vault base and drainage blanket elevations step down from Vault 9a to Vault 14 [5], the Vault 14 drainage blanket is impacted first and the Vault 9a drainage blanket is impacted last.

5.8.3 Evolution of the Under-vault Drainage and Underlying Geology

Clogging requires flow of water through the drainage system to occur. There will be no significant flows through the system until the cap geomembrane degrades, and infiltration starts to increase. There will be negligible clogging and therefore degradation of the performance of the drainage blankets until after the cap geomembrane fails. This cap geomembrane is not expected to fail for a long period (Section 5.2).

Given the expected low volumes of flow through the passive drainage system, that the permeability of the drainage blankets is always likely to be significantly greater than the underlying geology, and the redundancy in flow paths provided by the large volume of drainage material and large areas for flow, the drainage system is expected to operate as designed for millennia, until coastal erosion disrupts the facility. There may be areas of local clogging, but widespread clogging is not expected. Water will find routes around any areas of local clogging. Further evidence there will not be widespread clogging is provided below.

In the unexpected event that clogging reduces the drainage capacity sufficiently for water in a vault to rise above the 1 m level, water can overtop the southern vault wall to access the drainage capacity in an adjacent vault. This provides additional redundancy in the form of additional potential drainage routes.

5.8.3.1 Clogging Assessment

We have undertaken an extensive search for literature on the processes which cause clogging in potentially analogues facilities such as conventional landfills [36]. The literature review has recently been updated to capture publications during the last few years [21]. The literature focuses on sites where clogging has been observed, and related supporting research. We identified potential sources of clogging material and the nature of the clogging observed (physical, chemical, biological, and combinations thereof), and considered whether there is the potential for similar sources and mechanisms to occur at the LLWR.

None of the sites and associated studies considered systems that are directly analogous to the LLWR. Nevertheless, the review provided confidence that, while localised clogging may occur, it is unlikely that any of the laterally extensive features associated with water flows and drainage within the system will be significantly negatively affected by clogging. Clogging may lead to a general evolution of material properties on different scales. However, the supply of clogging materials will not be sufficient to compromise the overall performance of the passive drainage system, especially given the redundancy in drainage provided by the optimised designs.

One of the most relevant studies involved container scale clogging experiments using leachates representative of those generated by methanogenic stage landfills [103]. Realistic lifetime loading rates of methanogenic leachate were applied, and clogging was not generally apparent in any of the drainage media studied. This finding contrasts with the results of other studies which reported significant clogging of landfill drainage media and systems. Reference [103] concluded that clogging was associated with acidogenic leachates but not methanogenic leachates. Conditions in the LLWR trenches are currently methanogenic and methanogenic conditions are expected to develop in the vaults once they are capped [6]. Although the LLWR leachate chemistries are significantly different to a conventional landfill, e.g. much lower organic loading, this provides some evidence against extensive clogging.

Given the limited applicability of literature to the LLWR, we have developed additional lines of reasoning reflective of LLWR conditions.

We undertook scoping calculations and developed PHREEQC models [36] [85] to help understand the potential extent of chemical clogging. We also identified a sophisticated model called BioClog [104] that calculates the impacts of biological clogging on the hydraulic conductivity of leachate collection systems in municipal solid waste facilities.

We used the outputs of our chemical clogging calculations, and our wider understanding of engineering performance and conditions in the near field, to undertake calculations of biological clogging of the drainage blankets using BioClog [61] [85], The understanding gained, configuration of the BioClog model, and model results were reviewed in detail by a multi-disciplinary enhanced review workshop [105].

The results of our scoping calculations, and models developed using PHREEQC and BioClog, indicate that extensive clogging of the passive drainage system is not expected. The results are further described below.

Our early work also considered clogging at interfaces in the drainage system. Clogging at interfaces might occur in response to changes in flow or biogeochemical conditions. Deposition of a relatively small amount of material at an interface might impact the performance of the whole drainage system, so clogging at interfaces is a particularly important topic. We concluded that while there could be some clogging of interfaces, complete clogging is not expected.

More recent near-field work [6] has further refined our understanding of biogeochemical conditions in the repository. The outputs of this work show that the potential for general clogging and clogging at interfaces is even lower than considered in earlier EPA work [85] [105]. The updated implications for clogging, and in particular chemical clogging, are captured in the following description of how we expect the passive drainage system to evolve.

The summary is split into physical, chemical and biological clogging mechanisms for simplicity. However, there is often no clear separation between the different mechanisms and clogs are formed due to processes spanning two or three of these categories acting together. For example, microbes may produce amorphous by-products which change the local chemistry to increase mineral precipitation but also traps fine particles; this process is observed for some landfills (see references [36] and [21]). However, the facility design, the nature of wastes and materials, and related chemical conditions at the LLWR are not analogous to sites where these processes are observed, and more broadly arguments on the low probability of extensive clogging at the LLWR by either physical, chemical and biological mechanisms are also relevant to these combined processes.

Physical clogging

The engineering design provides multiple pathways and the largest practicable area for water to enter the sub-vault drainage blankets. The drainage blankets are laterally extensive to maximise access to the drainage provided by the underlying geology. As built, the drainage rate (mm y^{-1}) provided by the underling geology is the limiting part of the system, as it is not practicable to further increase the area of the drainage blankets.

Fine material can be generated by processes including flaking of paint from the containers, corrosion of the containers, and degradation of the waste. Corrosion rates inside and outside the containers are expected to be low [6], so only limited corrosion of the containers is expected before the repository starts to be disrupted by coastal erosion (Table 5.6). The intact containers will help to retain particulates from the waste and grout, so overall, the amount of fine material generated is expected to be low, and much lower than the amount which would be generated in a conventional landfill. The amount of fine material generated is expected to be insufficient for widespread clogging of the drainage material between container stacks.

Fine material may be washed downwards and settle under gravity. It may build up on the vault concrete base, in the bottom of the gaps between the container stacks, to some extent offsetting the increase in hydraulic conductivity of the concrete base as it degrades. If this results in water levels in vaults rising, once the water level reaches 1 m, water will flow over the vault walls to access the drainage blankets. Water will flow over fine material deposited at the bottom of the gaps between container stacks to access the drainage blankets. Therefore, the vaults will behave rather like a settlement tank, with limited entrainment of fines. Also, water flow rates in the gaps between container stacks are expected to be too low to suspend significant amounts of material and carry it into the drainage blankets.

Chemical clogging

Chemical clogging occurs through precipitation of solutes. The main precipitates reported in literature information on clogging are calcium carbonate and compounds of iron, sulphur and manganese [106]. Chemical clogging of the drainage system is expected to be a minor process due to the performance of the cap. Infiltration into the repository is expected to be small, so the volumes of water flowing into the drainage system and the associated solute fluxes will also be small. If precipitation does occur the amounts of material precipitated will be small relative to the volume of drainage material, so water will easily find new routes around any clogging. Therefore, drainage performance will not be significantly impacted. Consideration of the chemical conditions provides additional arguments that the amounts of material precipitated would be small.

Most of the water entering the drainage blankets will be leachate from the vaults. A small amount of trench leachate could potentially drain from Trench 3 into the vaults and drainage blankets. Vault leachate is considered first, then trench leachate.

Vault leachate is expected to be mildly to moderately alkaline, with low dissolved calcium (around 0.8 mmol l^{-1})[15] and low carbonate [6]. Under the very reducing conditions in the vaults, the leachate will be fully saturated with iron (II) and manganese (II) from the container metal, but the concentrations will be limited by the alkaline pH conditions. Precipitation is usually driven by a change in pH and, or redox conditions. Reaction of the vault leachate with the vault bases and drainage materials is not expected to result in any large changes in the pH, and conditions in the vault bases and drainage materials are expected to be reducing. Therefore, in general solutes are not expected to precipitate, including at interfaces in the drainage system.

Earlier calculations [85], which are now considered to be very cautious, showed that even with an ineffective cap and all infiltration contacting the grout, there could not be sufficient precipitation during the assessment timeframe to clog all the drainage material.

Trench leachate is mildly acidic, is approximately saturated with calcite and is in equilibrium with elevated pCO_2 due to microbial degradation of organic waste in the trenches [6]. Mixing of trench leachate with higher pH vault leachate would increase the pH of the trench leachate and could result in some precipitation of carbonate minerals and chemical clogging. During construction of Vault 8, leachate from Trench 3 was able to pass through the secant pile wall into Vault 8 until the finishing layer of concrete was applied. This shows that as the secant pile wall degrades there is potential for some leachate from Trench 3 to enter all the vaults and the drainage blankets. Leachate may also pass through the subsurface parts of the wall, which do not have a finishing layer of concrete, into the drainage blankets. However, while the cap is performing well and the trenches are largely unsaturated this would not happen, or the amount of trench leachate entering the vaults and drainage blankets would be very small, so the amount of clogging would be very small.

There are likely to be pH and redox changes as leachate mixes with groundwater below the repository. This may result in precipitation in the B2 unit, but there are several reasons why this would not be significant:

- the volumes precipitated would be small due to the small solute fluxes;
- the cut-off wall would reduce lateral flow of groundwater into the B2 unit at the elevation of the repository to a low level, so there is limited supply of groundwater to mix with leachate;

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[15] For the first few hundred years post-capping infiltration will contain up to 9 mmol l^{-1} calcium due to leaching accessory gypsum from the BES layer in the cap. However, the amount of infiltration will be very small. Once the cap geomembrane fails and infiltration increases there will be no gypsum remaining in the BES. The main source of calcium will be the grout, with water that contacts the grout containing around 0.8 mmol l^{-1} calcium.

- if any clogging does occur, water can flow laterally in the B2 unit, increasing the area for drainage compared with the area of the drainage blankets;
- clogging is likely to have limited impact on the vertical permeability of the B2 unit, which is already low, because clogging is unlikely to reduce the permeability of the clays.

Biological clogging

Biological clogging will be limited by the low infiltration through the cap, and because the organic content of future vault waste is projected to be low. This conclusion is supported by the results of our clogging literature review [36] [21] and calculations using BioClog, which indicate that while the cap geomembrane is intact there will be no significant clogging. Clogging will only begin once the cap geomembrane fails. There may be some clogging of the gaps between the waste stacks, but this is expected to be limited on the timescales to start of disruption of the repository by coastal erosion. There would be no significant clogging of the drainage blankets. As noted previously, if localised areas of clogging occur, it is anticipated that there are sufficient pathways to the drainage blankets, and sufficient total volume of drainage material, for water to find a new pathway around the local clogging.

5.8.4 REEC Storyboard for the Under-vault Drainage and Underlying Geology

The best estimate conceptual model of evolution of the under-vault drainage and underlying geology with time is described by the storyboard shown in Figure 5.15. In the storyboard, timeframes have been assigned to the processes and events described in the preceding subsection. In the next subsection, the storyboard for the REEC and storyboards for the AEECs [21] inform parameterisation of the component's properties.

Figure 5.15: Storyboard for evolution of the under-vault drainage and underlying geology in the REEC

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
Under-vault drainage and underlying geology (9)	As built: Blankets and breaks installed as vaults are constructed (Figure 3.4). To time of completion of closure engineering: Blanket connected to vaults over 1 m upstand walls as the cap is constructed.	With low flows and limited waste degradation, low solute and organic loads, only extremely localised clogging will occur and in general drainage blanket and connections will continue to perform well.	As for 100 years.	>2,000 years: Waters begin to flow to the drainage blanket as they overtop the 1 m vault walls. Some clogging but no significant change to permeability contrasts underneath the vaults. As the cap fails eventually the B2 unit and then drainage blanket layers will reach capacity and saturate. Some continued clogging but a sufficient permeability contrast will be maintained. Assumption at 5,000 years: Drainage blanket will continue to be saturated. Some continued clogging but a permeability contrast will be maintained across most of the blanket. Expected to be disrupted by coastal erosion before this time.

5.8.5 Properties

The drainage material will be inert, low-fines, free draining granular material, controlled via a technical specification, to ensure a minimum hydraulic conductivity of $1\ 10^{-4}$ m s^{-1}. Natural variability in drainage material will occur and expert elicitation identified a representative central value of $3\ 10^{-3}$ m s^{-1} for use in most calculations [21].

The outcomes of the literature review, chemical clogging calculations, detailed BioClog calculations, and logical arguments, all indicate that little clogging of the drainage system is expected, with no significant effect on the hydraulic conductivity. The low cap infiltration rates, low organic content of the vault waste and biogeochemical conditions in the vaults are not conducive to significant clogging. These characteristics of the repository are very different to the characteristics of conventional landfills and other systems where extensive clogging is observed. Therefore, the clogging enhanced review workshop, and EPA concluded that the hydraulic conductivity of the passive drainage system will evolve very little up to the time of facility disruption. In assessment models, the 'as built' hydraulic conductivity of the passive drainage system can be applied for all future times, i.e. $3\ 10^{-3}$ m s^{-1}.

6 Repository Evolution and Performance

6.1 Introduction

In Section 5 we discussed the evolution, performance and properties of each key engineering component and presented the REEC storyboard for each component. In this section we present the REEC storyboard for the whole system (repository). We have also developed AEEC storyboards for the repository (Table 4.1), which are presented in reference [21].

As noted in Subsection 4.1, evolution and performance of the individual key components is affected by the repository conditions and interactions between the key components. The conceptual models for the evolution and performance of the individual components and the whole repository were iterated until they were aligned (consistent). Therefore, the storyboard for the whole system presented in this section was iterated with the conceptual models and storyboards for the individual key components presented previously (Section 5) until they were aligned. The final aligned storyboards are presented in this report.

6.2 REEC Storyboard

The REEC storyboard is presented in Figure 6-1. This combines the storyboards for the key components shown in Figure 5.3, Figure 5.8, Figure 5.10, Figure 5.12, Figure 5.13 and Figure 5.15.The storyboard is consistent with that presented in reference [21] but has been edited to improve clarity.

In the REEC the cap geomembrane is assumed to still contain antioxidants and remain intact when the repository starts to be disrupted by coastal erosion. There is good evidence from laboratory testing and analogue facilities (i.e. field data) that the cap geomembrane could remain intact for these timescales in the physically and chemically benign cap environment. Infiltration into the repository is low throughout the EPA timeframe, and the wastes are likely to be mostly unsaturated.

There will be little leaching of the trench and vault waste, and little degradation of grout and cementitious components in the vaults and BES in the vault bases through leaching and chemical alteration. However, sufficient water is expected to generally be present for metal corrosion to proceed and for microbes to be active where conditions allow, i.e. in the trenches and outside the containers in the vaults. Geochemical conditions in the vaults will not evolve significantly, but there will be some evolution of conditions in the trenches as degradation of organic waste gradually reaches completion, with only increasingly recalcitrant (i.e. difficult to degrade) organic wastes remaining.

Corrosion rates will be low, so there will be limited corrosion and weakening of containers in the vaults. There may be some further settlement of surcharged containers, but limited settlement of future stronger containers. Even if there was much greater settlement than expected, calculations show the resulting strains would not damage the cap. The cap is resilient to the maximum plausible settlements, taking no credit for the containers.

With very low infiltration, fluxes of fine particles that could cause physical clogging, fluxes of solutes that could precipitate and cause chemical clogging, and fluxes of dissolved organics that could support microbial activity resulting in biological clogging, will be low. There will be little clogging of the passive drainage.

Cracking in response to physical loads and expansive rebar corrosion will be the main degradation mechanisms for the vault concrete components. Loading of the vault concrete operating surfaces during waste emplacement and then by the profile fill and the cap will cause some cracking, but this is not significant for post-closure performance. In Vault 9 and the future vaults, the main elements controlling drainage through the vault bases will be the geomembranes and BES, not the concrete operating surface. If infiltration through the cap exceeds drainage through the vault bases, then water levels in the vaults will rise until water is able to overtop the 1 m high future vault walls and flow into the drainage blankets below the future vault bases. However, with very low infiltration through the cap, water levels in the vaults may not rise to the 1 m level, and all infiltration might drain through the vault bases.

Corrosion of rebar in reinforced concrete and metal dowels in the expansion joints of concrete components, and degradation of seals in expansion joints, may have larger effects on the hydraulic conductivities of the vault concrete components than cracking from physical loads. However, again the consequences for water levels in the vaults and drainage from the vaults will not be significant. The vault walls will be laterally restrained, so as they crack and weaken, they are unlikely to move sufficiently to impact the vaults or the adjacent trench (Trench 3).

Figure 6.1: Combined Reference Engineering Evolution Case (REEC)

Component	Reference Engineering Evolution Case			
	During completion / as built	**100 years (to end PoA)**	**500 years**	**1,000 years**
Final cap (1)	As built performance.	Some settlement of vaults and trenches, but differential settlement limited. Further development of minor defects in the geomembrane and BES allow small increases in infiltration. Cap surface water drains clogged.		To c.1,000 years: Further clogging of drainage layers, localised wind erosion and a slight thinning of parts of the cap. Geomembrane still functioning, BES layer showing some (limited) increase in permeability, principally through cation exchange and washout below defects in the geomembrane.
Interim trench cap (2)	Northern area covered by first strip of the final cap, southern area replaced. Existing soils retained and existing geomembrane extensively punctured prior to final capping or replacement. Replacement includes, GCL and overlying GDL, with new	Replacement GCL and GDL layers removed from southern area, final cap complete. Retained soils form part of the profile material for the final cap.	Negligible evolution of the retained soils that form part of the profile material for the final cap.	Negligible evolution of the retained soils that form part of the profile material for the final cap.

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
	cover soils. GCL and GDL removed prior to final capping. Interim cap will be surcharged prior to final capping, expressing short-term settlements from the waste underneath, possibly with some changes to density, porosity and geometry.			
Trench wastes (3)	The wastes will continue to degrade, especially cellulosics. They will generate some bulk gas during this process. Loading during interim cap upgrades and then surcharging and final cap emplacement is expected to release some water from the waste.	Continued degradation of wastes.	Around this time, it is expected that cellulosic degradation rates will be falling, not least as the faster degrading cellulosics will have degraded leaving slower degrading cellulosic materials such as wood. In central projections 50% or more of the total degradation of cellulosics will have occurred in most trenches [6].	Continued waste degradation. >1,000 years: Waste degradation substantially complete. Assumption at 5,000 years: Degradation complete.

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
Vault waste container stacks (4a) Existing and Committed LLW	Containers deformed by surcharging, with the majority of HHISOs undergoing deformation of load-bearing elements leading to available voidage being expressed, and some (limited) damage to the multi-barrier concept. Upper containers in stacks suffer lid damage and wastes are compressed by profile fill which fills available voidage in top of stack containers. Some degradation of the containers, e.g. due to corrosion during the operational phase. Some limited damage to upper containers from closure operations, e.g. placement of vault void fill.	A small number of containers may have undergone substantial further loss of integrity by this time, but probably this will apply to very few.	Between around 300 to 500 years the majority of disposed cellulosic and other easily degradable organics will have degraded. Most of the containers may have further deformed, as the surcharged containers will not resist voidage expression on waste degradation. There will be some associated container stack movements (but the impacts of this on the cap will be substantially limited by the presence of adjacent stacks, void fill and profiling fill), and the vertical drainage channels will remain intact. It is expected that for many of these containers the grouted waste matrix will still provide some support, and not all voids within the containers	There will still be limited mixing of container contents and parts of some wastes (especially thick metals and grouts) will still be intact. Waste degradation will continue with corrosion also influencing evolution, although the impacts of corrosion will continue to be a longer-term process. >1,000 years: Container and waste degradation will continue leading to eventual complete degradation. Assumption at 5,000 years: Degradation substantially complete. Most likely the repository will be disrupted by

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
			and wastes will be expressed as stack settlement. Corrosion will not contribute significantly to stack evolution on this timeframe.	coastal erosion prior to degradation being complete.
Vault waste container stacks (4b) Future LLW and ILW that can be managed as LLW	Minor degradation of containers in Vaults following placement but functionally operating as designed. Container protection units prevent damage to top of stack containers and provide an additional protective barrier to infiltration into stacks.	A small number of containers may have structurally deformed by this time. The majority of disposed cellulosic and other easily degradable organics will have degraded by this time. Container protection units continue to be largely intact and will divert infiltration down the sides of waste stacks.	Beyond around 500 years it is cautiously assumed a small minority of the containers may have failed structurally with some container stack deformation (but the impacts of this on the cap will be limited by the presence of adjacent stacks and profiling fill). It is expected that most of the container protection units will still be intact and preventing ingress of water into waste stacks. It is expected that for the small subset of containers that have failed, the grouted waste matrix will still provide some	Some additional containers have failed but the majority remain intact. Container protection units degrade more slowly than the containers with the majority remaining intact. >1,000 years: Container and waste degradation will continue, with the rate of waste degradation reducing, leading to eventual complete degradation. There will still be limited mixing of container contents and parts of some wastes (especially thick

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
			support and so not all voids within the containers and wastes will be expressed as settlement. Voidage will in any case be lower than for the existing and committed LLW.	metals and grouts) will still be intact. Corrosion rates will be slow and so most containers and CPUs will retain integrity for most of this time period. Some residual settlement but not enough to challenge performance. Assumption at 5,000 years: Degradation substantially complete including container protection units. Most likely the repository will be disrupted by coastal erosion prior to degradation being complete.
Vault waste container stacks (4c) Future ILW disposed in	Shielded modules operating as designed and protecting containers by successfully carrying all capping loads and diverting all infiltration away from the waste. Only minor	Some deformation and cracking of concrete in shielded modules, Structure still effective in protecting the containers from infiltration, loads, and crushing.	A small fraction of shielded module roofs assumed to have structurally failed and only partially preventing loads being passed to waste. A minority of loaded containers	Shielded modules units likely to persist significantly beyond 1,000 years and protect against settlements.

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
external concrete structures	degradation of containers in shielded modules.	Negligible settlement seen above shielded modules.	below roof failures are assumed to have failed structurally and excess voidage in wastes expressed. The resulting strains on the cap are within tolerance. However, across the shielded modules, the combined effect of residual shielded module structures, containers and the grouted waste matrix will provide support, such that only very limited voids within the containers and wastes will be expressed as settlement. Overall shielded modules intact.	Assumption at 5,000 years: Shielded module, container and waste degradation will continue leading to eventual substantial degradation by around 5,000 years. No notable performance difference remaining between different categories of vault disposals. Most likely the repository will be disrupted by coastal erosion prior to degradation being complete.
Vault bases (V8, V9, Future) (5)	Vault bases in good working order showing no significant defects or settlement beyond the cracks in place after completion of disposals. Hydraulic performance	Negligible deterioration and no obvious reduction in performance.	Deterioration of expansion joints within a few hundred years, minor corrosion of reinforcement in concrete slabs, and negligible change to cement paste, leading to	Continuing structural failure of concrete. Cement paste still largely intact.

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
	controlled by geomembranes, BES and natural clays (Vault 8). Minor damage to base slabs due to cap loading and settlement of underlying geology although no obvious reduction in performance.		slight reduction in performance. Nearer to 1,000 years: continuing corrosion of reinforcement bars leading to expansion of reinforcement and cracking of concrete although cement paste remains intact. Net result is a widespread moderate increase in the permeability of the base. A significant reduction in the structural performance of the vault base leads to increased cracking where differential stresses are high, which manifests as locally higher permeabilities in these areas. However hydraulic performance still dominated by geomembranes, BES and natural clay (Vault 8). Potential around this time	At 1,000 years, antioxidant depletion leading to oxidation and failure of geomembranes in some areas. By 2,000 years, this is widespread. However, BES still effective despite cation exchange of BES being advanced. No degradation of natural clays. Assumption at 5,000 years: Complete structural failure of concrete and dissolution / washout of cement paste leads to residual sand and gravel matrix only. Relatively high permeabilities exist across the whole of the concrete elements of the vault base. However, the BES and natural clays still provide a function.

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
			for geomembranes to start to undergo antioxidant depletion.	
Vault side walls (6)	Vault side walls in good working order with no significant defects. Minor structural damage due to vault operations and, or cap construction, no deterioration of materials.	Minor deterioration of materials.	Degradation of expansion joints within a few hundred years of PoA but walls withstand lateral loading. Vault base remains structurally intact, supporting the walls, such that there is negligible change in performance of walls. Nearer 1,000 years: Continuing corrosion of reinforcement bars leads to localised loss of structural capacity. Failure of some stacked containers and creation of isolated point loads leads to additional lateral loads on walls, resulting in some localised wall failure.	Continuing structural failure of concrete. Cement paste still largely intact. Overall performance of walls continues to be good. Assumption at 5,000 years: Complete structural failure of all stacked containers, concrete base, and corrosion of reinforcement within walls leads to complete wall failure around the vaults and total loss of performance.

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
			However overall walls continue to perform.	
Cut-off wall (7)	Cut-off wall in good working order with no significant construction defects.	No significant degradation, performance as built.	Some washout of bentonite and cement or deterioration in the vicinity of construction joints or areas of wall thinning. Permeability slightly increased from as-built condition. Nearer 500 years: Some further washout of bentonite and cement, localised increase in permeability through cation exchange and, or in areas of local deterioration in the vicinity of construction joints and areas of wall thinning. Combined effect reduces effective performance of cut-off wall from as-built condition.	Significant deterioration of cut-off wall through cation exchange, washout of bentonite and cement, and localised areas of deterioration. However, flows through the wall (and thus washout and rates of exchange) are insufficient to significantly challenge overall performance – a permeability contrast will remain, if reduced. Assumption at 5,000 years: Complete deterioration and washout of bentonite cement, cut-off wall no longer functions as an effective barrier to flow of water.

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
Leachate management system (8)	As built - leachate management system in good working order. Assume no leakage out of system. To completion of closure engineering - leachate management system maintained until the end of the PoA such that it generally functions adequately. Some minor reduction in performance may be expected, e.g. due to siltation or leakage through deteriorated construction joints.	End of PoA and beyond: N/A as leachate management system decommissioned following cessation of institutional control.		
Under-vault drainage and underlying geology (9)	As built: Blankets and breaks installed as vaults are constructed (Figure 3.4). To time of completion of closure engineering: Blanket connected to vaults over 1 m	With low flows and limited waste degradation, low solute and organic loads, only extremely localised clogging will occur and in general drainage blanket and	As for 100 years.	>2,000 years: Waters begin to flow to the drainage blanket as they overtop the 1 m vault walls. Some clogging but no significant change to

Component	Reference Engineering Evolution Case			
	During completion / as built	100 years (to end PoA)	500 years	1,000 years
	upstand walls as the cap is constructed.	connections will continue to perform well.		permeability contrasts underneath the vaults. As the cap fails eventually the B2 unit and then drainage blanket layers will reach capacity and saturate. Some continued clogging but a sufficient permeability contrast will be maintained. Assumption at 5,000 years: Drainage blanket will continue to be saturated. Some continued clogging but a permeability contrast will be maintained across most of the blanket. Expected to be disrupted by coastal erosion before this time.

6.3 Inputs to Assessments

The conceptual models, component properties and calculated infiltration rates presented above and in Section 5, and additional AEECs presented in reference [21], were fed into our underpinning near-field work and groundwater flow modelling, and our assessments of the potential impacts from:

- aqueous releases of radionuclides and non-radiological contaminants to groundwater;
- releases of radionuclides in gas;
- releases of radionuclides during disruption of the repository by coastal erosion;
- inadvertent human intrusion into the repository.

As noted in Subsection 4.5.1, the EPA engineering evolution cases need not necessarily correspond on a one-to-one basis with ESC assessment calculation cases. However, they inform the ESC assessment calculations, which also consider a wider range of factors.

Feedback from our underpinning work and assessments to the EPA was then as described in Subsection 4.7. The next section summarises the outcomes of the EPA and changes since the 2011 ESC, and then Section 8 looks ahead to potential future development of the EPA.

7 Summary

7.1 Summary of Development of the EPA and EPA Outcomes

Summary of development of the EPA

Development of a formal EPA for the 2026 ESC started in 2015. The EPA builds on the assessment of engineering performance undertaken for the 2011 ESC, which principally comprised elicitation of the evolution, performance and properties of key engineering components, and modelling water levels and flows within the repository.

The EPA has been developed using a systematic, five-step approach, to provide a comprehensive analysis of the evolution of the key engineering components and the whole repository. The EPA has been developed by a multidisciplinary team, including experts in repository and landfill engineering and construction. Important insights were provided by our optimisation work [10], which considers the performance of many options in detail, and describes the arguments for our preferred options. The team also drew extensively on literature information and data, their experience and, where appropriate, models to develop understanding of component evolution and to parameterise performance.

The EPA considers the evolution and performance of individual engineering components, and the evolution and performance of the whole system, including interactions between components. Conceptual models for individual components are aligned with the conceptual models for the whole system. A range of engineering evolution cases are considered, including a reference engineering evolution case, and cases with better and worse performance. 'What-if' cases have been explored to assess low probability situations, and to show that certain situations are not plausible.

Confidence the EPA describes the credible envelope of potential evolution and performance of the repository is provide by:

- a systematic and comprehensive approach;
- iterative development;
- the range of modes of evolution considered;
- use of a multidisciplinary team;
- the amount of literature review and analysis conducted;
- the large number of multidisciplinary workshops;
- audit back against the full EPA undertaken for the 2002 PCSC.

The envelope is expected to capture remaining uncertainties in the rates of processes and effects of interactions.

The EPA is fully integrated with the engineering design and optimisation, RMS and wider ESC, including determination of biogeochemical conditions in the near field which are coupled to the engineering performance.

The EPA provides a robust basis for ESC assessment calculations. It provides conceptual models of how the engineering will evolve and perform, and this informs choices of calculation cases in the ESC assessments. The EPA provides parameter values for use in the assessments.

EPA outcomes

The engineering is expected to perform as designed during the PoA. At the end of the PoA, controls will be withdrawn and the engineering will function passively. The condition and performance of the engineering at the end of the PoA are important as this will affect long-term evolution and performance.

The engineering will slowly degrade over time and its performance will decrease. The condition and performance of the engineering become increasingly uncertain with increasing time after the end of the PoA. Therefore, although the EPA considers the whole lifetime of the repository, the focus is on the post-PoA period.

Post-PoA, the key engineering components are:

- the final cap;
- passive drainage features;
- the cut-off wall.

The engineering components aim to:

- reduce infiltration into the repository as much, and for as long, as can reasonably be achieved;
- passively drain infiltration out of the bases of future vaults to:
  - keep the waste dry;
  - minimise water contact with the waste;
  - prevent water levels in the repository rising to the point where leachate discharges to surface soils and shallow groundwater at the perimeter of the cap.

The final cap is the most important engineering component. It reduces rates of infiltration into the repository to very low levels. This reduces leaching from the waste, degradation of the containers, waste and other engineered components, and minimises the potential for clogging of passive drainage.

In the vaults, the permeability contrast between the containers and the granular void fill between the container stacks will direct infiltration down the gaps between the container stacks and away from the waste. Passive drainage features provide routes for infiltration to drain downwards and out of the bases of the future vaults. The cut-off wall works with the drainage features by resisting lateral flows out of the repository but also resisting lateral inflows which might interact with the waste and would use some of the drainage capacity.

Cap

The potential for settlement to damage the cap has been a key focus of our design and optimisation work. We are confident that the maximum plausible strains resulting from settlement of the waste would not damage the cap. Therefore, the EPA has focused on understanding the long-term performance of the cap layers.

The final cap is a multi-layer, multi-barrier design. The key layers for preventing infiltration are the low permeability layers and the overlying drainage layers. The low permeability layers comprise a geomembrane and underlying Bentonite-enhanced Sand (BES) layer. Together the low permeability and overlying drainage layers resist infiltration and direct (shed) water sideways to the perimeter of the cap.

We plan to use a 2 mm thick HDPE geomembrane. Manufacturers include antioxidants in their geomembrane formulations to resist oxidation and embrittlement, maintaining the strain tolerance of the geomembrane. Consistent with literature conceptual model for geomembrane failure, once antioxidants have been depleted, we expect the geomembrane will become brittle, stress fractures will develop and the geomembrane will fail. Literature data shows the time to loss of antioxidants, quickly followed by oxidation induction, and then failure of the geomembrane is strongly dependent on temperature, with degradation occurring faster with increasing temperature. A large body of research and field evidence developed over the last decade and more shows that in the low temperature, low strain, chemically inert environment of the LLWR cap, the geomembrane should remain intact for hundreds of years to a few thousand years.

HDPE is impermeable, so water will only be able to pass through defects (small holes) in the geomembrane. These may arise from manufacturing defects (pin holes) and damage during installation (small holes, tears, and defects in the welds between strips of geomembrane). Construction management and quality assurance are key to the 'as built' condition and performance of all the cap layers, but particularly the cap geomembrane. We have considered construction risks and how they could be mitigated, capturing good practice guidance and learning from experience, to understand the quality of installation that can be achieved. We expect to achieve a good quality installation, but it is not plausible the geomembrane will be free from manufacturing or installation defects.

We have undertaken an extensive elicitation exercise to quantify PDFs for the types and prevalence of defects that may be present in the geomembrane, and the hydraulic conductivities of the BES and drainage layers, 'as built' and at later times. Modal input parameter values assume good CQA, and the types and numbers of defects that are consistent with this.

We have also elicited PDFs for the time to loss of antioxidants from the geomembrane and the time to complete failure of the geomembrane. The best estimate lifetime of the geomembrane is 1,800 years, which is similar to the longest projected timescale for start of disruption of the repository by coastal erosion. Therefore, the geomembrane is more likely to be intact and functioning well than failed when the repository starts to be disrupted by coastal erosion.

These datasets have been used to undertake probabilistic calculations of the distributions of potential cap infiltration rates as built and at later times. The resulting distributions are bimodal, with a range of lower rates of infiltration while the geomembrane is intact, and a range of higher rates of infiltration when the geomembrane has failed. Over time, the most likely infiltration rates shift from the lower distribution to the higher distribution as the probability of geomembrane failure increases.

Over the full assessment timeframe, the range of potential infiltration rates varies from very low to 100% of HER. The latter is unrealistic as there are strong arguments the cap will not be substantially eroded before it is disrupted by coastal erosion, so a substantial portion of HER would drain to streams via interflow, and at certain times of the year potentially also by overland flow. The calculated mean infiltration rates with the geomembrane intact are very low.

Passive drains

Passive drainage features will be constructed from inert, strong, coarse aggregate, so clogging is the only process that could impact their performance. We have undertaken an extensive search for literature on clogging in potentially analogous facilities such as conventional landfill sites. The literature focuses on sites where clogging has been observed, and related supporting research. None of the sites and associated studies considered systems that are directly analogous to the LLWR. Nevertheless, the review provided confidence that, while localised clogging may occur, it is unlikely that any of the laterally extensive features associated with water flows and drainage within the system will be significantly negatively affected by clogging.

Given the limited applicability of literature to the LLWR, we have developed additional lines of reasoning reflective of LLWR conditions. We have used logical arguments, simple calculations, and complex models using the BioClog code to understand the potential for physical, chemical and biological clogging, and the coupled impacts of these processes. Our analyses all indicate the potential for clogging is low, due to the engineering design which provides large areas and multiple pathways for drainage, the chemical conditions which are not conducive to precipitation and chemical clogging, and the nature of the wastes, which have limited organic content and therefore limited potential to support biological clogging. Low rates of infiltration are also beneficial as they limit the potential fluxes of suspended solids, solutes and dissolved organics into the drainage features. Overall, we conclude that the hydraulic conductivity of the passive drainage system will evolve very little up to the time of facility disruption.

Cut-off wall

The cut-off wall is made from a cement-bentonite mix, which gives a low permeability material. The wall is expected to slowly degrade through loss of cement minerals, cation exchange and washout of the bentonite. The hydraulic conductivity of the wall is expected to increase as it degrades. The low hydraulic conductivity of the wall means degradation should be slow, with loss of cement and cation exchange being largely diffusive processes. Any washout of bentonite is most likely to occur from the outer surface of the wall. The hydraulic conductivity of the cut-off wall is expected to remain lower than the lateral hydraulic conductivity of the adjacent ground through the assessment timeframe.

Other components

We have also conceptualised degradation of the vault bases and walls and developed PDFs for the hydraulic conductivities of these components as built and at later times. The vault bases and walls have less impact on the post-PoA engineering performance than the final cap, passive drains, and cut-off wall. The vault bases and walls are primarily important during the PoA for operations and capturing leachate, however their continued presence will affect water levels and flows within the repository post-PoA.

The bases and walls are constructed from several sub-components made from different materials. Hydraulic conductivity PDFs have been developed for each sub-component, so assessment modellers have the choice of representing each sub-component explicitly or calculating upscaled conductivities for the whole component.

Conclusions

The EPA provides substantial confidence the engineering should perform well throughout the assessment timeframe. This is reflected in the reference engineering evolution case, which describes our best estimate of evolution and performance. Alternative engineering evolution cases, and cap infiltration and component hydraulic conductivity PDFs, provide the information needed to explore the implications of uncertainty in engineering performance in our pathway assessments. The engineering evolution cases need not necessarily correspond on a one-to-one basis with pathway assessment calculation cases. However, they inform the pathway assessment calculations, which also consider a wider range of factors.

7.2 Summary of Changes Compared with the 2011 ESC

The 2011 ESC considered how engineered components would evolve. Component properties were elicited during workshops involving experts in a range of relevant disciplines [23]. However, a formal EPA was not developed as part of the 2011 ESC.

Starting in 2015, we have iteratively developed an EPA for the 2026 ESC. The EPA, our optimisation and engineering design work, near-field work and ESC assessments are closely integrated. The EPA provides a more robust assessment of engineering evolution and performance, and stronger underpinning evidence and arguments, than the 2011 ESC elicitation.

The greatest change to our understanding of engineering evolution and performance compared with the 2011 ESC is our understanding of cap performance. There is robust evidence, and international consensus, that the cap geomembrane will be considerably more durable than considered in the 2011 ESC. This means the cap will provide its best performance for longer.

Instead of eliciting infiltration rates through the cap, we have elicited the types and numbers of defects in the cap geomembrane, and the hydraulic properties of the cap BES, so infiltration rates can be calculated. Defects in the cap geomembrane and the properties of the BES can be elicited more robustly than infiltration rates, so we expect that this change in approach will lead to more robust estimates of cap infiltration.

We have also undertaken a large amount of work on settlement, as a solid base is needed to construct a high-performance cap, and settlement is one of the key processes affecting long-term cap performance. We have further optimised the repository design to provide a solid base for cap construction and provide confidence strains from settlement will not damage the low permeability cap layers.

A high-performance cap reduces waste and container degradation rates: directly by limiting the amount of water available to support anaerobic corrosion and microbial degradation, and indirectly by limiting leaching of cement and grout, keeping the pH in the vault waste high. High pH minimises corrosion rates and microbial activity. In turn, this reduces container and waste settlement, although our analyses show the cap is robust to all plausible settlements.

8 Future Developments

The EPA will continue to be updated as necessary and proportionate, to reflect developments in the design, monitoring of the performance of the system and wider developments in scientific understanding. Monitoring of the closure engineering performance [9] and results from engineering trials will be key inputs to ongoing development of the EPA.

We have recognised that long-term gas pressures in the repository could be higher than considered previously. In response, we have commenced work to further consider optimisation of our approach to managing bulk and trace gases generated in the repository, and the design of gas management features. Arguments on safety in the 2026 ESC are not contingent on the outcomes of this work. Therefore, this work is scheduled as a continuing ESC activity, consistent with the principle of ongoing optimisation of the design of the future strip(s) of the final cap that will include the vent (or vents). The EPA may need to be updated to reflect the outputs from this work, for example to consider the long-term performance of gas vents if they are left open post-PoA.

Future optimisation and detailed design work will involve delivering strengthened containers for LLW, with CPUs. If disposal of ILW is taken forward, we would further develop relevant aspects of the design. This might include further optimisation and detailed design work for a new SWTC compatible mild steel container and shielded modules, depending on the characteristics of the ILW that would be optimal to dispose at the LLWR. Our current designs are sufficiently developed that we do not expect future detailed design work to result in major changes to the broad evolution and performance described in this EPA. Detailed changes will need to be captured in updates to the EPA, but this might not be documented for some time, until all the detailed design work is complete. The EPA will input to the detailed design work, and ongoing development of the RMS, which provides the specifications for the detailed design work.

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