LLW Repository Ltd

The 2011 Environmental Safety Case

Environmental Safety Case – Main Report

LLWR/ESC/R(11)10016

May 2011

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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 radioactive waste. The LLWR is owned by the Nuclear Decommissioning Authority (NDA) and operated on behalf of the NDA by a Site Licence Company (SLC) – LLW Repository Ltd.

We, LLW Repository Ltd, are committed to operating the LLWR as a safe and efficient facility that provides a continuing option for the disposal of low-level radioactive waste in the UK. This will be achieved consistent with good practice for the near-surface disposal of radioactive waste, in accordance with environmental and health and safety regulation and guidance, and in compliance with the terms of our Nuclear Site Licence and Permit to dispose of radioactive waste.

This report is the main report presenting the 2011 Environmental Safety Case for the LLWR – the 2011 ESC. The report has been prepared by the Environmental Safety Case Project and is issued under the authority of the Managing Director of LLW Repository Ltd.

ESC objectives

Under the terms of our Permit granted by the Environment Agency, we are required to submit an ESC for the LLWR no later than 1st May 2011 and at intervals thereafter as requested by the Agency. The ESC:

- presents the arguments and evidence concerning the environmental safety of disposals of solid radioactive waste at the LLWR, at present and in the future, consistent with the Agency's Guidance on Requirements for Authorisation;

- provides a basis for the environmentally safe management of the site by the SLC, and regulation of the site by the Agency, including setting of conditions on its future management and acceptance of waste.

The ESC is addressed primarily to the Agency and is intended to inform and enable their regulation of the LLWR. It also provides a plan for the future management of the LLWR and a baseline against which proposed changes in the plan for the development of the facility can be tested. As such, it will be of interest to our other stakeholders, both local and national.

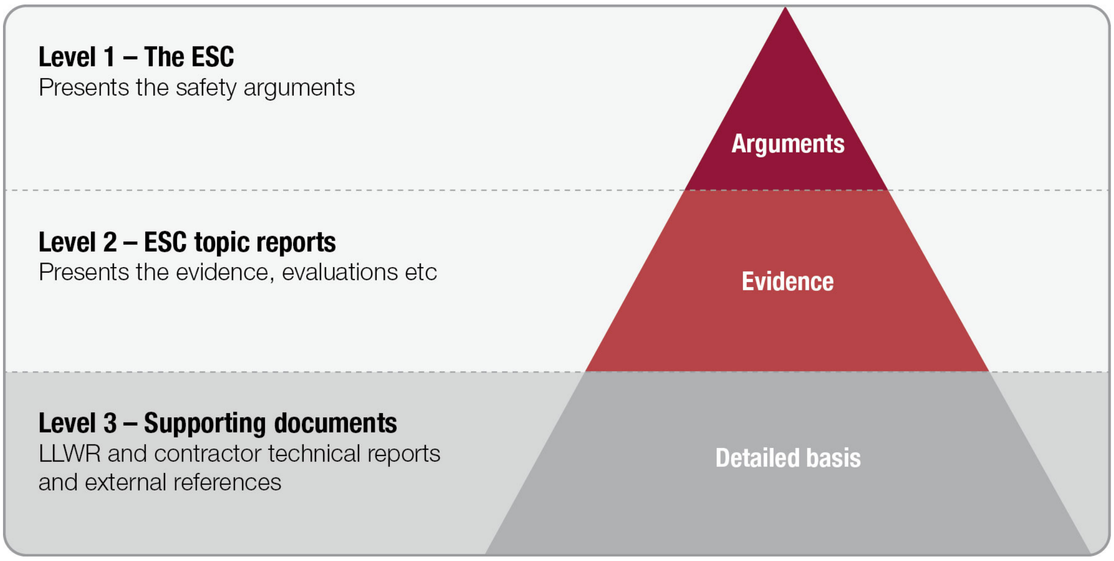
ESC document plan

The 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 this 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, and assessments.

This is the Level 1 report. The ESC Level 1 and 2 reports are listed in the table at the end of this Preface, which also shows for the Level 2 reports the set of arguments for which each report mainly provides evidence. The ESC is supported by a large number of technical and scientific reports and references that we refer to as ‘Level 3’ documents.



The ESC documentation concept

Scope and audiences

The 2011 ESC is based on an optimised ‘Site Development Plan’ developed under our Environmental Safety Strategy. The Plan sets out our proposals and assumptions on operations, remedial activities, vault design, capacity and future waste disposal practice, closure design and management up to the end of management and regulatory control. It provides a basis for our quantitative assessments. The Plan is flexible, however, and will be amended as necessary in the light of UK radioactive waste management needs, operating experience, results of monitoring, future iterations of the ESC, regulatory and planning guidance and decisions, and stakeholder views.

The safety arguments set out in the Level 1 report comprise arguments concerning the development and safety of the Site Development Plan. The Level 1 report focuses on the arguments in principle, referring to the more detailed and quantitative evidence that is presented in the Level 2 reports. The main features and findings of the supporting reports are presented, demonstrating that the Site Development Plan is optimised, and that the assessed safety is consistent with the regulatory guidance over the lifetime of the facility, including after closure. The Level 1 report is intended to be complete enough to inform managers from the Environment Agency, Government ministries and local government representatives and officials on the environmental safety of disposal of radioactive waste at the facility. It is also intended to be an entry point to the safety case for the Agency’s technical staff and assessors.

The Level 2 reports present the evidence that underpins our safety arguments, including descriptions of our management framework, system understanding, optimisation, assessments and proposed conditions for acceptance of waste. The Level 2 reports are primarily addressed to the Agency’s Nuclear Regulator for the site and technical staff, and may be of interest to experts in specific technical fields. To fully satisfy themselves, however, for example, to find supporting information and details of the model formulations and data used, technical specialists and reviewers in specific topic areas may need to refer to Level 3 documents.

We have also produced a Non-technical Summary of the ESC, to help a wider group of stakeholders understand its nature, conclusions and implications.

<table>
<tr><td colspan="2">Level 1</td></tr>
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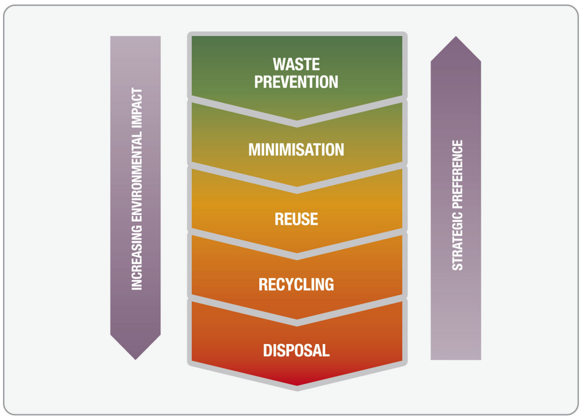
Executive Summary

The Low Level Waste Repository (LLWR) has been the UK's principal facility for the disposal of solid low-level radioactive waste (LLW) since it opened in 1959. We are regulated by the Environment Agency under the Environmental Permitting (England and Wales) Regulations 2010.

Our role, defined within the NDA UK Strategy for LLW and consistent with Government Policy, is to promote and ensure the best use of the LLWR. This means developing plans for the safe and optimised use of the LLWR for disposal of LLW and implementing those plans, subject to necessary planning approvals and regulatory permissions. The development of the ESC has been framed by this role.

Our objective is to develop the LLWR to:



- maximise the capacity of the facility to accept LLW requiring vault disposal consistent with the characteristics of the site;
- while supporting the implementation of the waste hierarchy in the management of LLW in the UK, which will reduce the volume of waste that needs to be disposed;
- while optimising the environmental performance of the disposal facility both during operations and in the long term.

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

This report and supporting volumes comprise our 2011 Environmental Safety Case – the 2011 ESC. It has been prepared and submitted to the Environment Agency in fulfilment of a specific requirement (Requirement 6 of Schedule 9) of our current Permit. The ESC will support our application for a new Permit to continue to dispose of LLW at the site, which we intend to submit to the Environment Agency in due course. It will also support our application for the necessary planning permissions to continue to develop and close the site.

The ESC has been developed according to our Environmental Safety Strategy, which lays out our approach to achieving the continuing environmental safety of the LLWR. It presents the approach by which we have developed an optimised Site Development Plan (SDP) for the LLWR to help meet our objective, and our demonstration of the environmental safety of the Plan.

At a high level, our case is that:

- We have worked within a sound management framework and firm safety culture, while engaging in dialogue with stakeholders.

- We have characterised and established a sufficient understanding of the LLWR site and facility, and their evolution, relevant to its environmental safety.

- On which basis, we have carried out a comprehensive evaluation of options to arrive at an optimised SDP for the LLWR.

- We have assessed the environmental safety of the SDP, showing that impacts are appropriately low and consistent with regulatory guidance. Using our assessments, we have determined the radiological capacity of the facility and conditions under which waste may be safely accepted and disposed.

Consistent with the environment agencies' guidance, our Environmental Safety Case is presented in terms of a set of arguments in support of each of the above claims. For each argument, we identify the regulatory Requirement or guidance that the argument addresses and, also, the supporting ESC report ('Level 2' report) in which the evidence in support of that argument is presented. We confirm that each of the regulatory Requirements has been addressed. A more detailed analysis of the requirements and supporting guidance and where they are addressed in our documentation is given in the '*Addressing the GRA*' report.

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

The 2011 ESC addresses the deficiencies identified by the Environment Agency in the safety cases presented by the previous operator of the LLWR in 2002. The ESC describes how this has been done.

The development and documentation of our ESC has been subject to independent peer review by groups of individual experts with relevant experience from both the UK and abroad.

The SDP provides a basis for our quantitative assessments and demonstration of environmental safety. The Plan is flexible, however, and will be amended as necessary in the light of UK radioactive waste management needs, operating experience, results of monitoring, future iterations of the ESC, regulatory and planning guidance and decisions, and stakeholder views. Under the Plan, the LLWR could continue to operate as the primary destination for disposal of LLW in the UK until about 2080 using a Reference Disposal Area formerly known as the 'consented area', or to up to 2130 using an Extended Disposal Area.

Once the ESC is submitted to the Environment Agency, we will begin its implementation, as required by our Permit. New Waste Acceptance Criteria, new waste emplacement strategies and a new approach to capacity management developed in the ESC will be introduced.

The ESC will be maintained under a formal change control process. This will ensure that a suitable tool continues to be available to support future regulatory and management decisions concerning the facility, and that the SDP continues to provide optimised environmental performance.

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Contents

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1 Introduction

1.1 Background and Objectives of the ESC

The Low Level Waste Repository (LLWR) is the UK's principal facility for the disposal of solid low-level radioactive waste. The LLWR is owned by the Nuclear Decommissioning Authority (NDA) and operated on behalf of the NDA by a Site Licence Company (SLC) – LLW Repository Limited.

We, LLW Repository Limited, are committed to operating the LLWR as an efficient and safe facility, providing a continuing option for the disposal of low-level radioactive waste in the UK. This will be achieved consistent with good practice for the near-surface disposal of radioactive waste, in accordance with applicable environmental and health and safety regulations and guidance, and in compliance with the terms of our Nuclear Site Licence and environmental Permit.

Disposal of radioactive waste and radioactive discharges from the site are regulated by the Environment Agency under the Environmental Permitting (England and Wales) Regulations 2010.

Our current Permit [18], which is a variation on an Authorisation issued under previous legislation on 1st May 2006, is based on the Agency's review and consideration of safety cases prepared by the previous site operator [19,20]. The Agency considered that these safety cases, and especially the Post-closure Safety Case, were deficient in a number of respects (see Section 6), and had failed to make '*an adequate or robust argument for continued disposals of LLW*' [21]. The Agency, therefore, determined in its Decision Document [22] that continued disposal of Low Level Waste (LLW) would be authorised only up to the capacity of the then operating vault (Vault 8), and that any further consignments to the facility would be for the purpose of storage only.

The Agency set a firm goal for the site operator to come forward with reasoned proposals for the management and use of the site and a satisfactory safety case. The Agency included in the Authorisation (now Permit) a schedule, Schedule 9, of improvements and information requirements that operator must complete towards that goal. In particular, Requirement 6 of Schedule 9 requires:

> '*The Operator shall update the Environmental Safety Case(s) for the site covering the period up to withdrawal of control and thereafter*',

with a completion date of the 1st May 2011 (and at such intervals thereafter as the Agency specifies in writing).

This report is the main document setting out our 2011 Environmental Safety Case (ESC) in fulfilment of the above requirement of our Permit.

The main objective of the ESC is meet the Agency's requirement to submit an updated safety case, and in so doing set out arguments and evidence sufficient to demonstrate that the LLWR can continue to be operated as a disposal facility for LLW.

In achieving this objective, the ESC will also provide a sound basis for future management of the site by the SLC and regulation of the site by the Agency.

1.2 Scope and Documentation of the ESC

The regulatory requirements that must be met to be allowed to dispose of LLW in a near-surface facility are set out in the Environment Agency's '*Near-surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation*' (the GRA) [23]. The scope and content of our ESC must, therefore, be consistent with the GRA, and satisfy the qualitative and quantitative requirements therein.

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

Requirement R3: Environmental safety case (from [23])

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

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

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

Our primary objective, defined within the NDA Strategy for LLW (see Subsection 2.1), is to promote and ensure best use of the LLWR. This means developing plans for the safe and optimised use of the LLWR for disposal of LLW and implementing those plans, subject to the necessary planning approvals and regulatory permissions. Our ESC is presented within the framing and context provided by this objective.

We have worked towards this objective according to an Environmental Safety Strategy (ESS), which lays out our approach to achieving the continuing environmental safety of the LLWR. The ESS is the process and means by which we achieve our primary objective in a demonstrably environmentally safe way. Our ESS leads to an optimised Site Development Plan (SDP), our plan for developing the site consistent with our Strategy. The SDP forms the basis of our assessments of repository performance, an important part of our demonstration of environmental safety.

We have decided that we will develop and present the arguments and evidence that comprise our ESC and will then show that the arguments and evidence we have advanced satisfy the requirements of the GRA.

The overall document plan for the ESC and the intended audiences for the reports have been set out in the Preface. This 'Main Report', the 'Level 1' report, of the ESC, sets out our arguments that it is environmentally safe for the LLWR to continue to operate as a facility for the disposal of LLW.

This report is a high-level articulation of our safety arguments. The report refers down to the 'Level 2' reports, which give more complete presentations of our arguments and also present the supporting evidence that underpins our arguments. A listing of the Level 2 reports is given in the table in the Preface. The categorisation of the Level 2 reports is explained in Subsection 4.1.

1.3 Structure

In this report:

- Section 1, this section, has set out the high-level background to the submission of our 2011 ESC, our overall objectives and the objective and scope of this report.

- Section 2 summarises the context for this ESC and provides a high-level introduction to the site. This includes the national strategic context, the history and current conditions, and the environmental context of the LLWR. The future evolution of the site environment is also described.

- Section 3 sets out the objectives, scope and nature of our ESC and describes our ESS, by which we develop an optimised SDP that forms the basis for our assessments and demonstration of environmental safety.

- Section 4 describes our safety case arguments under four headings. These are: management and dialogue; system characterisation and understanding; optimisation and SDP; and assessment.

- Section 5 presents, at a high level, a future programme of work related to further reducing uncertainties related to the environmental safety of the LLWR.

- Section 6 outlines progress that has been made in developing the ESC since the previous environmental safety cases for the LLWR were presented.

- Section 7 confirms that each of the relevant Requirements of the GRA are addressed by one or more of the safety case arguments presented in Section 4 and thus provides a map by which the Environment Agency may begin to examine our approach to complying with each of the Requirements.

- Section 8 provides a set of concluding statements that we consider encapsulates the key features of our 2011 ESC.

An acronym list for the report and a general glossary for the ESC are provided in Appendices 1 and 2 respectively.

2 The Low Level Waste Repository

This section summarises the context, or starting conditions, from which we began to develop our 2011 ESC. This includes the:

– national policy and strategic waste management context;
– history and current conditions of the site;
– environmental context of the site.

The future evolution of the site is also briefly described.

2.1 National Context and Role of the LLWR

The NDA has published a '*UK Strategy for the Management of Solid Low Level Radioactive Waste from the Nuclear Industry*' [24]. The Strategy has been prepared by the NDA for the UK Government and devolved administrations in response to the '*Policy for the Long Term Management of Solid Low Level Radioactive Waste in the United Kingdom*', published in 2007 [25]. The NDA has also developed a strategic partnership with the LLWR SLC, to deliver and implement the strategy.

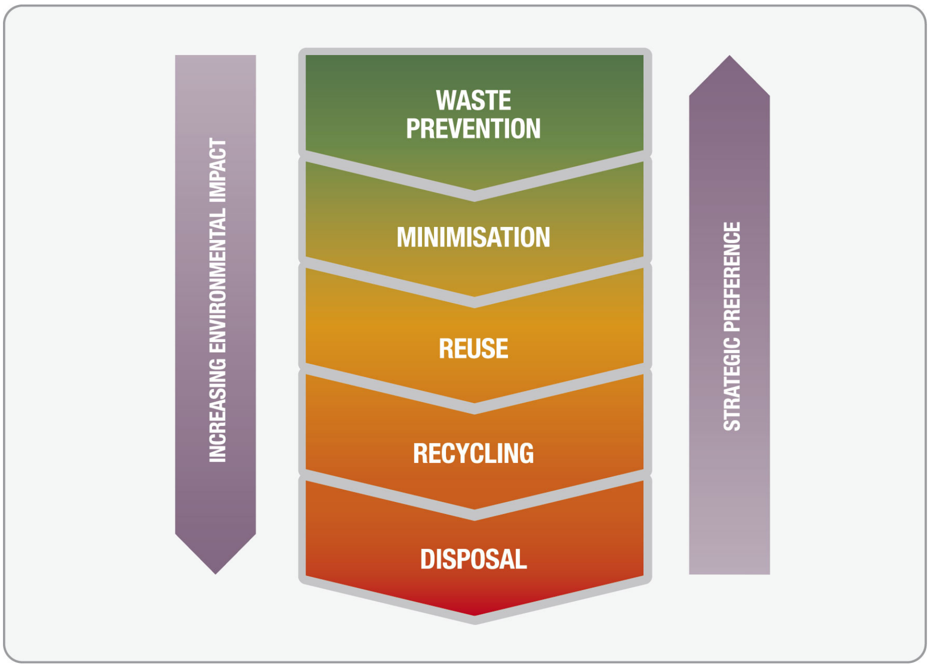

Figure 2.1 Waste hierarchy

Under the UK Strategy, systematic implementation of the waste hierarchy (see Figure 2.1) at waste producer sites will reduce the volume of LLW that needs to be managed. Where wastes already exist or cannot be prevented from arising, the strategy seeks to increase opportunities for reuse and recycling of waste materials. Consistent with the Policy, waste consignors are also expected to make appropriate use of alternative waste management routes to effect volume reduction. Treatment of wastes by incineration or compaction reduces the volume of waste to be disposed. Treatment of metals can lead to recycling and a reduced volume of secondary wastes that need to be disposed. The UK Strategy also aims to increase the amount of radioactive waste that is handled as Very Low Level Waste (VLLW) or exempt waste that can be disposed to fit-for-purpose facilities that reflect the lower hazard associated with VLLW.

A key NDA priority is to make the best use of existing LLW management assets. Continued availability of the LLWR, where the majority of UK solid LLW is currently disposed, is thus central to the UK Strategy. The Strategy seeks to extend the life of the LLWR by only disposing of wastes that require disposal in engineered vaults and whose volume has been minimised.

A Strategic Environmental Assessment (SEA), conducted to support the development of the UK Strategy, concluded that optimised use of the LLWR is preferred over other options for the provision of LLW disposal capacity [26]. Optimised use of the LLWR was assumed to involve rigorous application of the Waste hierarchy across NDA sites and disposing only those wastes that require the level of safety and security offered by engineered vault disposal.

The conclusions of the SEA (and hence the UK Strategy that it informs) are nevertheless contingent on the assumption that all alternative strategic options would be capable of meeting regulatory requirements and, specifically, that '*LLW Repository Ltd will be able to make an acceptable Environmental Safety Case for the LLWR*' [26]. Early replacement of the LLWR is not anticipated in the UK Strategy [24], provided an ESC for the continued use of the facility can be made and subject to all necessary regulatory and planning permissions [26].

The strategic role of the LLWR is, therefore, to maximise its potential to accept for disposal LLW, requiring vault disposal and treated to minimise its volume, in a safe and optimal way, while supporting the implementation of the waste hierarchy in the UK. The development of the ESC has been framed by this role.

2.2 History and Description of LLWR as it Exists Today

The site of the LLWR was first developed in 1940 as a Royal Ordnance Factory (ROF) for the production of TNT. Ownership later passed to United Kingdom Atomic Energy Authority, which in 1957 was granted planning consent for the disposal of waste in the northern 40 ha of the site. The first Certificate of Authorisation for disposal of LLW was granted in 1958 under the terms of the Atomic Energy Act 1954, and disposal operations commenced in 1959. Ownership and responsibility for the site was transferred to British Nuclear Fuels Ltd (BNFL) when the company was formed in 1971, and the site became a part of the NDA's estate when that body was established in 2005. The site is operated on behalf of the NDA by a Site Licence Company (SLC) – LLW Repository Limited.

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

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

During disposals, the waste was covered by soil at the end of each day and, periodically, a hardcore layer was placed to facilitate tipping operations. Trench 7 was closed in 1995.

From 1987 onwards, disposal operations were upgraded. Remedial work was also carried out on the trenches; this included installation of a low-permeability cut-off wall (COW) (to limit lateral movements of groundwater and radionuclides) to the north and east of the trenches, interim capping of the filled trenches and upgrading of the leachate drainage system, to allow for discharge directly to sea (rather than surface water) through the Marine Pipeline via the Marine Holding Tanks (MHT).

An engineered, concrete disposal vault was constructed, Vault 8, which allowed the orderly emplacement of containerised waste within an engineered concrete structure according to modern disposal standards. The emphasis of the Vault 8 design was largely on operational aspects of waste emplacement and storage. The vault has surface water drains to collect rainwater from the surface of the base slab, while an under-slab drainage blanket and perimeter drains collect groundwater from beneath and around the vault. Vault 8 commenced operation in 1988, the first seven years of its operation overlapping with the operation of Trench 7, to use up the available capacity in the trench. Vault 8 is now almost full to its originally planned capacity.

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

The 2002 Safety Cases [19, 20] were originally expected to establish a basis for the continued authorisation of disposal operations at the LLWR. The Safety Cases were supported by a Site Development Plan that set out expectations for the development of future vaults and final closure of the facility within what was formerly understood to be the ‘consented area’ for disposals (dating back to the 1957 planning consent). These plans were not put into effect, for two reasons. First, Cumbria County Council, the planning authority, established that the concept of a ‘consented area’ had no meaning in the context of current and future use of the LLWR site, and that future developments would require planning permission. Second, as introduced in Subsection 1.1, the Environment Agency, in its review of the 2002 Safety Cases and the subsequent Decision Document, considered that the Safety Cases had failed to make ‘*an adequate or robust argument for continued disposals of LLW*’ [21] (see Section 6). When the Agency issued a revised Authorisation for the site in 2006, it was for disposal only up to the originally planned capacity in Vault 8.

In the light of decisions taken by the regulators and planning authorities, a detailed analysis and associated rationale was developed for a preferred ‘Modular Vault’ design [27], to be adopted in the construction of Vault 9 and to serve as a baseline for any future vaults. Planning permission for Vault 9 was granted in January 2008, on the basis that it would be used for storage only. Achieving planning permission for the vault to be converted to use for disposal will be conditional on satisfying Agency requirements for authorisation for disposal. The 2011 ESC is a thus key document in our plans to achieve both regulatory and planning permission and for continued disposals of LLW at the facility.

Construction of Vault 9 started in 2008 and construction was completed in December 2010. The Modular Vault design formed the basis for the construction, although more recent work for the 2011 ESC has led to design modifications related to long-term passive leachate management [10].

Most wastes are received within steel half-height ISO (International Organization for Standardization) containers or third-height ISO containers, which are filled with cement grout and are now being stacked within Vault 9. The remaining disposal capacity in Vault 8 is being reserved for heavy or uncontainerised wastes that cannot be stored in Vault 9. Sometimes, containers are accepted that are too heavy to be fully grouted and then emplaced. Currently, the grouting of such containers is completed after emplacement in Vault 8, from where they will not need to be moved. Larger items also continue to be placed or grouted directly into Vault 8 within specific areas of the vault.

The central bay of Vault 8 is also being used to store ISO containers stacked up to an additional height of two half-height ISO containers, above the disposed containers stacked up to a height of four half-height ISO containers. These higher-stacked containers were placed in Vault 8 before Vault 9 became available. The intention is to leave these containers in place permanently if permission can be obtained to continue disposal at the LLWR and planning permission for higher stacking is obtained.

Figure 2.2 shows the LLWR site looking south.

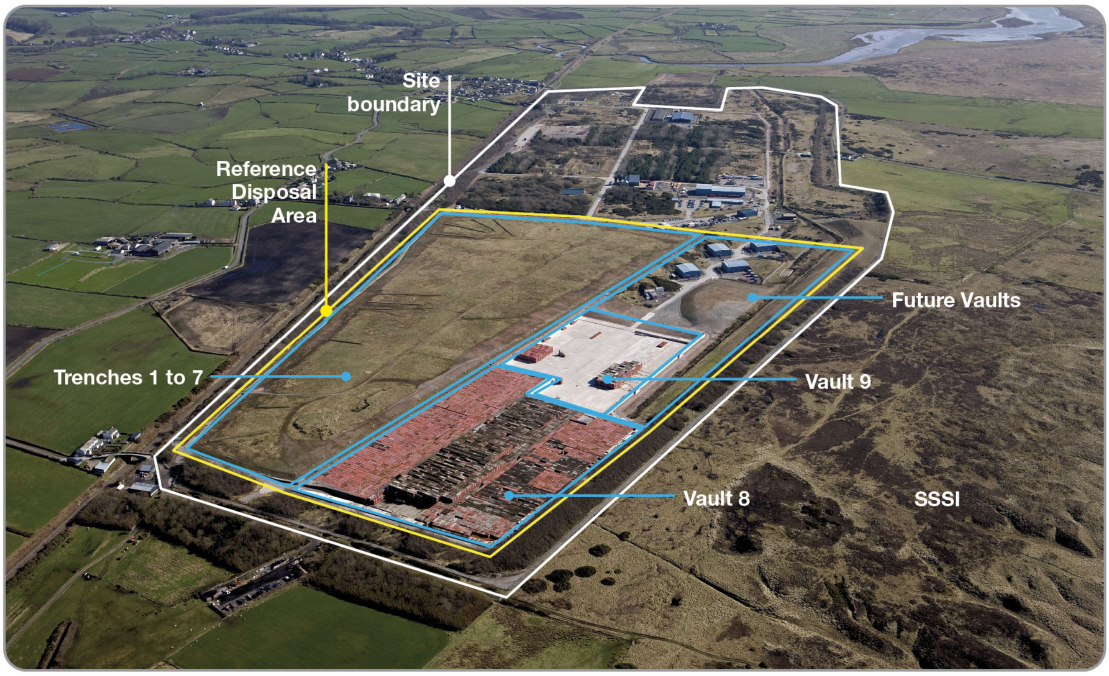

Figure 2.2 The LLWR site in March 2011

The LLWR is owned by the Nuclear Decommissioning Authority (NDA), which is a non-departmental public body created under the Energy Act 2004. The NDA is a strategic authority that owns the 19 civil nuclear sites, and associated nuclear liabilities and assets, previously under the control of UKAEA and BNFL. The NDA's future plans account for the need to fund LLW disposal from its programme.

Further information on the site is given in the *'Site History and Description'* Level 2 report [3].

2.3 Environmental Context of the LLWR

The LLWR is located on the West Cumbrian coastal plain, close to the village of Drigg and approximately five kilometres south-east of Sellafield – see Figure 2.3. Apart from nearby Sellafield, the area is predominantly rural. The site is mainly surrounded by grazing land, but some cereal crops are grown in fields to the east. The area along the coast adjacent to the site is designated as a Site of Special Scientific Interest (SSSI), known as the Drigg Coast SSSI. The area is also a Special Area of Conservation (SAC) under the European Habitats Directive. Along the north-eastern boundary is the Carlisle to Barrow-in-Furness railway line, a siding from which enters the site for the delivery of waste containers and other items and materials. The main north-south road through West Cumbria, the A595, runs about two kilometres to the east of the site. The Ravenglass Estuary lies to the south. The Cumbrian mountains rise further to the east. The LLWR lies outside the Lake District National Park, which is bounded by the A595 and the Ravenglass Estuary.

Figure 2.3 The LLWR site and its immediate environs

The LLWR site is about two kilometres long and half a kilometre wide and lies on a northwest-southeast axis. A boundary fence, designed to prevent unauthorised access, encloses the site. The northern half of the site is used for waste disposal. The south western boundary of the northern area of the site borders the SSSI. The height of the site varies from 20 m AOD to the north-east and west of the site to less than 5 m AOD 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 AOD. The Drigg Stream flows through the site roughly parallel with the western site boundary. Towards the centre of the site, the Drigg Stream is joined by the East-West Stream, which originates off the site to the north east, draining farmland and also taking water from the Railway Drain. The Drigg Stream leaves the site to the south and discharges into the River Irt, which is tidal at that point. The Irt forms the northern arm of the Ravenglass Estuary, comprising also the rivers Mite and Esk, which discharges to the sea opposite the village of Ravenglass.

Further information on the environmental context of the LLWR can be found in the '*Site History and Description*' report [3].

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

In the area of the LLWR site, groundwater generally flows from the Lake District hills towards the coast. Groundwater observations have allowed the identification of an Upper and Regional Groundwater. The Upper Groundwater is present within the upper Quaternary deposits and overlies the Regional Groundwater. The Upper Groundwater is most evident in the north-west and central parts of the site, where it has a groundwater flow pattern that is distinct from that of the Regional Groundwater. The Regional Groundwater is observed in the Quaternary drift deposits and in the underlying Ormskirk Sandstone. The groundwater flow direction in the Regional Groundwater at the LLWR is generally to the south-west (towards the coast), where it discharges to the inter-tidal zone and off-shore. Towards the south-east boundary of the site, the direction of groundwater flow in the Upper Groundwater merges with that in the Regional Groundwater and the two cannot be differentiated. A component of the Regional Groundwater passing under the south-eastern part of the site (but not the disposal area) discharges to the River Irt and the Ravenglass Estuary.

Further information the geology and hydrogeology in the vicinity of the site is given in the '*Hydrogeology*' Level 2 report [7].

At its north-western corner, the LLWR site is only about 400 m from the high water mark, so that the site is vulnerable to sea-level rise and coastal erosion. Thus, consideration of sea-level rise and coastal processes and assessment of their effects are significant aspects of the ESC. Based on qualitative and quantitative evidence, including modelling studies, we have concluded that the site will be eroded on a timescale of a few hundred to a few thousand years, with consequent disruption of the repository [8].

While this situation is unusual for a radioactive waste repository, we observe that in the long term all near-surface disposal facilities are vulnerable to disruption by natural erosion processes, human actions or combinations of natural and human events. This is taken into account by setting limits on the types and activity of waste that may be disposed to a near-surface facility. The key question is whether the potential impacts when erosion occurs are consistent with regulatory guidance levels, that is, sufficiently low. The Environment Agency has given a formal view that, providing the requirements of the GRA are met (including that the risk guidance level is met and the risks presented by the site are optimised), the potential for disruption of the site by coastal erosion at some point in the future is an acceptable risk [28].

A summary of the evidence and our arguments on coastal erosion and vulnerability of the facility to such erosion, and the impacts that will result, are given in Subsections 4.3 and 4.5.

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3 The 2011 ESC

This section sets out in more detail the objectives, scope and nature of our Environmental Safety Case (ESC), and describes our Environmental Safety Strategy (ESS), by which we develop an optimised Site Development Plan (SDP). The management and engineering measures in our SDP are an important part of the implementation of our ESS and form the basis for our assessments and demonstration of environmental safety.

3.1 Environmental Safety Case (ESC)

The main objective of the 2011 ESC is to provide a clear demonstration of the environmental safety of past and planned future disposals of waste at the LLWR. It is designed to satisfy the requirements of the Environment Agency as set out in their guidance (the GRA [23]) and as elaborated through liaison with Environment Agency staff (see Section 2 in the '*Management and Dialogue*' report [2]).

The GRA sets a fundamental protection objective:

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

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

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

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

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

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

The ESC presents the knowledge and understanding on which our assessments of environmental safety are based. It also provides the basis for our decision-making concerning the options that are available to further improve the facility. The ESC is an important tool for deciding on future facility management and waste acceptance.

The GRA (paragraph 6.2.2 in [23]) defines an environmental safety case as:

> '*a set of claims concerning the environmental safety of disposals of solid radioactive waste, substantiated by a structured collection of arguments and evidence.*'

The scope of the ESC is wide ranging, encompassing information on:

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

As stated already, in Subsection 1.2, we have taken the above GRA definition of an ESC as a guide for the presentation of our safety arguments and evidence. The structuring of our safety arguments is described in Subsection 4.1 and the arguments presented in the rest of Section 4. How our ESC meets the requirements of the GRA is set out in Section 7.

The GRA requires that an environmental safety strategy is described (paragraph 7.2.2 in the GRA [23]). Our Environmental Safety Strategy (ESS) is the subject of the rest of this section.

The development of an ESC is an iterative process ongoing throughout the life of a facility. It involves progressive development and focused improvement of data, understanding, design options and assessments. The development must integrate information from a wide range of technical studies, as well as non-technical inputs and decisions. The development of the 2011 ESC has been iterative, building on the 2002 Safety Cases [19,20] and the submission made in 2008 [29,30,31,32,33] against Requirement 2 of Schedule 9 of our Permit. How the ESC has developed and been improved since 2002 is described in Section 6.

The further development of the ESC will be managed under formal change control, as a 'living' safety case, as changes occur and decisions are made. The ESC will develop incrementally in this way. There will also be further 'full' iterations of the ESC over the life of the LLWR, at such times as required by the Environment Agency and possibly by future management decisions on the role of the LLWR. The future programme to implement and develop the ESC is described in Section 5.

3.2 Environmental Safety Strategy

3.2.1 Definition

The GRA glossary defines environmental safety strategy as:

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

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

In paragraph 7.2.2 of the GRA, it is stated that an ESS:

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

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

In this subsection (Subsection 3.2), we describe our approach to achieving environmental safety, the part of our ESS concerned with the process that leads to environmental safety. An important way of achieving environmental safety, particularly radiological safety, is optimisation. Our approach to optimisation is summarised in Subsection 3.3. Optimisation leads, along with other inputs, to our SDP. Our SDP describes how we will implement our overall ESS, which will achieve environmental safety along with our environmental management systems and processes. It forms the basis of our safety assessments for the ESC. The arguments and evidence supporting our ESS and ESC are given in Section 4. A summary of the control measures and their functions (see below in Subsections 3.2.2 and 3.3) included our ESS is presented in Table 3.1 at the end of this section (Section 3).

3.2.2 Approach to Ensuring Environmental Safety

Framing and constraints

There are a number of factors that frame and constrain our ESS. The strategic role of the LLWR has been discussed in Subsection 2.1. Our objective is to develop the LLWR to:

- maximise the capacity of the facility to accept LLW requiring vault disposal consistent with the characteristics of the site;

- while supporting the implementation of the waste hierarchy in the management of LLW in the UK, which will reduce the volume of waste that needs to be disposed;
- while optimising the environmental performance of the disposal facility both during operations and in the long term.

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

The LLWR has been operating for over 50 years and hence the history of the site and its current state of development, as well as its environmental context, as described in Subsections 2.2 and 2.3, respectively, constrain the ESS.

Our ESS has been developed and implemented taking account of the above factors.

Approach and principles

Our ESS needs to identify the management and engineering control measures that are needed to ensure environmental safety.

In identifying the control measures, we have followed a number of 'principles', listed below. Some of these principles are derived from the five main Principles set out in the GRA (see Section 4 in reference [23]), from which the requirements in the GRA are derived.

- Sound management and safety culture;
- Engagement with regulators and other stakeholders;
- Firm understanding of the framing and constraints, environmental context, potential hazards posed by the wastes, and the ways in which the hazards might lead to impacts;
- Use of optimisation, thus ensuring proportionality;
- According people and the environment in the future the same level of environmental protection as now;
- Preference for passive over active controls during the Period of Authorisation (PoA) and reliance only on passive engineering controls after the period of management control;
- Use of simple approaches, as far as practicable;
- Consistency with regulatory limits and guidance levels;
- Assurance of protection through monitoring and any required intervention during active institutional control.

Derivation of controls

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

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

In practice, we can:

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

We have identified the control measures that we need to implement through a process of optimisation, described in the next subsection.

3.3 Optimisation

Optimisation is defined in the Glossary of the GRA [23] as '*the principle of ensuring that radiation exposures are as low as reasonably achievable (ALARA) in the given circumstances*'. In paragraph 6.3.58, optimisation is said to be '*about finding the best way forward where many different considerations need to be balanced*'. It is stated that '*Relevant considerations include, for example, economic and societal factors, and the requirement to manage any non-radiological hazards.*' It is stated that '*Although reducing radiological risk is important, it should not be given a weight out of proportion to other considerations*', and that '*the best way forward is not necessarily the one that offers the lowest radiological risk*'.

Optimisation is the process we have used to determine a preferred set of control measures that are consistent with the goal of achieving radiation doses and risks that are ALARA. We have taken into account a range of factors, including the need to ensure adequate protection from the non-radiological hazards presented by the wastes. It is through this process that we have developed our SDP. The control measures also become part of our ESS. Our SDP can be viewed as our plan for implementing our ESS and the way we will ensure environmental protection as the site is developed.

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

The potential controls that we considered in our optimisation process included:

- Controls over waste inventory:
  - What, if anything, should be done about the existing disposals?
  - What controls are appropriate over the acceptance of wastes for disposal in the future?
  - What conditioning is appropriate for wastes consigned for disposal?
- Controls over design and operation:

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

The optimisation process involved developing, comparing and selecting a set of control measures that will provide optimised environmental protection.

Especially with respect to the long-term environmental management of the LLWR, significant uncertainties arise and judgements are required that cannot readily be captured through quantitative analysis. Hence a detailed, quantitative multi-criteria decision analysis that is sometimes favoured for selecting options has not been applied. Rather, a range of approaches have been followed in the evaluation of options. The aim has been to make visible the key underpinning evidence and logic that has led us to put forward the proposed set of controls for future management of the LLWR.

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

- groundwater;
- gas release;
- coastal erosion;
- human intrusion.

For example, the final repository cap will function to limit infiltration into the wastes in order to: ensure low releases of contaminated leachate from the facility; reduce the impacts of radioactive gas release by providing a barrier to the release of radon; ensure that erosive effects are limited as far as practicable; and to prevent or discourage human intrusion into the wastes.

The detailed description of the options that have been considered, their evaluation, and selection of a set of compatible and complementary options that form the SDP is presented in the '*Optimisation and Development Plan*' report [10]. Therein, the relevant option assessment studies and their outcomes are grouped together as follows:

- management controls and interventions relating to the past disposals at the LLWR;

- management and engineering controls over future waste disposals, including acceptance criteria, treatment and packaging, and methods for waste emplacement and capacity management;

- passive engineering controls over the environmental performance of the LLWR during the PoA and beyond, taking account of the functional role of engineering features, as well as their design and timing of implementation;

- active management controls over environmental performance, including for discharges during the PoA as well as post-closure management control over the LLWR site.

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

3.4 Site Development Plan

This section presents key features of the optimised SDP developed within our ESC. The SDP is our current view of how the LLWR should be developed and provides the basis for quantitative modelling and assessments of environmental safety within the 2011 ESC.

Our ESC considers a reference case of the Plan in which an area covering the northern 40 hectares of the site, the Reference Disposal Area (RDA), is developed for the disposal of LLW, and a variant case in which a further adjacent 11 hectares, the Extended Disposal Area (EDA,) is developed for further disposals of LLW. Both these cases are assessed in the ESC. The RDA is the area formerly known as the 'consented area' (a term that no longer has legal meaning), that is, the land defined by a line continuing along the southerly end of the trenches and the site boundaries to the north of that line. The EDA is adjacent and to the south of the RDA. Development of the RDA repository will require a further five vaults to be constructed, up to Vault 14, and the EDA repository six more vaults, to Vault 20.

Development of the RDA, according to our SDP, would allow the site to continue to operate as the primary destination for disposal of LLW in the UK until about 2080, based on current assumptions about future LLW arisings and application of waste segregation, diversion and treatment (see Subsection 2.1). Development of the EDA would provide volumetric capacity for disposal of all LLW in the 2007 United Kingdom Radioactive Waste Inventory (UKRWI) [34] and for continued operation up to 2130, again depending on assumptions about future arisings and their management.

It is the intention of the LLWR that the SDP as set out in this report, and in more detail in the 'Optimisation and Development Plan' report [10], will form the basis for future development of the facility. All plans for the future use of the LLWR facility, however, are subject to the agreement of the owner, the NDA, and depend on the granting of the necessary planning consents and regulatory permits and permissions. In addition, the future use of the LLWR depends on the requirements for management of radioactive waste in the UK.

In summary, our SDP is as follows:

- No intrusive remediation of the trenches is planned, however, active leachate management, the closure engineering that will be constructed, and renewal of the interim trench cap (if necessary) will optimise the long-term environmental performance of both the trenches and vaults.

- Waste will only be accepted for disposal and emplaced in the vaults consistent with the requirements of the ESC. Waste will only be accepted for disposal when it has been shown that it is appropriate to dispose of it in an engineered vault, for example, the disposal of VLLW will be avoided as far as is practicable. The capacity of the repository will be managed to ensure that it is used optimally.

- Engineered vaults will be constructed, eventually filling the northern part of the site up to a line continuous with the southerly end of the trenches in the RDA, and with additional vaults to the immediate south of this if the facility is further extended.

- A final cap will be progressively constructed over the vaults and trenches. Eventually, the whole area of trenches and vaults will be covered by a single, gently-domed low permeability engineered cap, designed for stability and resistance to erosion and presenting acceptable visual impact. Suitable long-term vegetation cover will be established on the cap area and periphery. If necessary, the interim cap over the trenches will be renewed before final capping.

- A passive gas venting system will be incorporated into the final cap to provide confidence that differential pressures will not threaten the performance of the cap as a barrier to infiltration. Final decisions on the vent design and whether or not the vent will be closed before the end of active institutional control will be made later.

- The vaults will step down in the southerly direction following the natural slope of the site and containerised waste will be stacked in the vaults, utilising as much as possible of the profile volume below the engineered cap.

- Vaults will be constructed as needed, filled, closed and capped progressively, at the same time capping over the adjacent strip of trench area. In the 2011 ESC, the volume between the current temporary cap over the trenches and the final cap profile is assumed to be filled with inert materials[1].

- During operations, leachate from the trenches and rainwater run-off from the open vaults will continue to be managed by collection, monitoring and controlled discharge to sea via the Marine Pipeline, subject to the requirements of our Permit. The effect of the progressive capping will be to reduce infiltration to the trenches and hence progressively reduce trench leachate. It will also minimise the area of open vaults and hence degradation of the waste containers and potentially contaminated rainwater run-off.

- In order to promote unsaturated (that is, partially saturated) conditions in the vaults for as long as possible following closure, future vaults will be designed without containing side walls and incorporating engineered passive drainage

[1] An opportunity has been identified that some of this volume might be filled with VLLW. Whether this will be practical depends on a number of factors, including the timing of arising of suitable volumes of VLLW. This option has not been assessed in the 2011 ESC. Its adoption would be the subject of separate assessment, and regulatory and planning determinations.

arrangements so that, following final closure, residual infiltration though the cap may drain freely.

- An underground, low permeability COW will be constructed to tie into the final cap perimeter and the existing COW at the northeast corner of the site. The wall will extend to 2 m below the bases of the vaults, except round the eastern and southern perimeter of the vaults in the EDA, where the depth will be 4 m. The wall will be of sufficient depth to limit inflow of surface water and shallow groundwater at the level of the vaults and trenches, and outflow of contaminated leachate close to the ground surface near the facility.

- Active leachate collection and management will continue during operations and up to 100 years after final disposals.

- The site will remain under active institutional control, and it is assumed regulatory control, for a period of at least 100 years after final disposals[2]. During this time, a site boundary will be maintained to prevent access by the public.

- Monitoring to meet regulatory requirements and to provide re-assurance that the facility is performing safely and as expected will continue during active institutional control. Remedial actions, such as addressing any problems with the interim trench cap, will be taken if required.

- During the institutional control period, arrangements will be put in place to maintain knowledge of the hazardous nature of the facility following final closure. Through local consultation, a sustainable use of the site will be established consistent with the long-term environmental safety of the repository. The aim will be to provide a sustainable amenity to the local community and, also, thereby, help maintain knowledge and lower the likelihood of developments or uses that might lead to adverse impacts[3].

Figure 2.2 shows the repository today. A schematic plan of the EDA repository is shown in Figure 3.1. Representations of the further development of the repository are shown in Figure 3.2 to Figure 3.4. Figure 3.2 shows the final cap completed over Vault 8 and the adjacent area of the trenches, with a further area of the interim cap over the trenches being used to store excavated material. Figure 3.3 shows the final cap completed over the RDA repository (assuming no further vaults are constructed after Vault 14) and Figure 3.4 shows the cap completed over the EDA repository.

[2] Our current assessments show that a 100-year period of site control is sufficient to ensure compliance with the risk and dose guidance levels for the groundwater, coastal erosion and human intrusion pathways. There may be a need to prevent agricultural use of the cap for another 200 years in order to ensure compliance with the risk guidance level in respect of releases of carbon-14 labelled gas from the repository.

[3] We do not rely on knowledge retention or amenity use in our demonstration that regulatory risk guidance level will be met beyond 300 years.

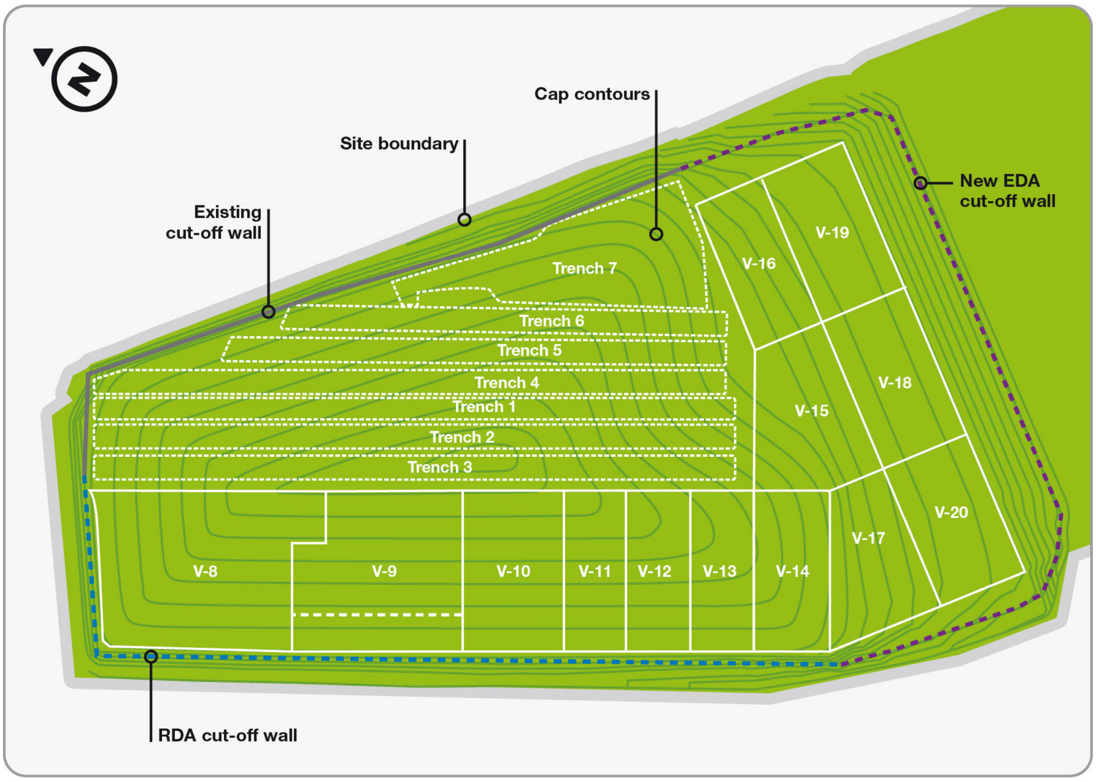

Figure 3.1 Schematic plan of the EDA repository

Figure 3.2 Vault 8 final capped

Figure 3.3 Final cap completed over RDA Repository

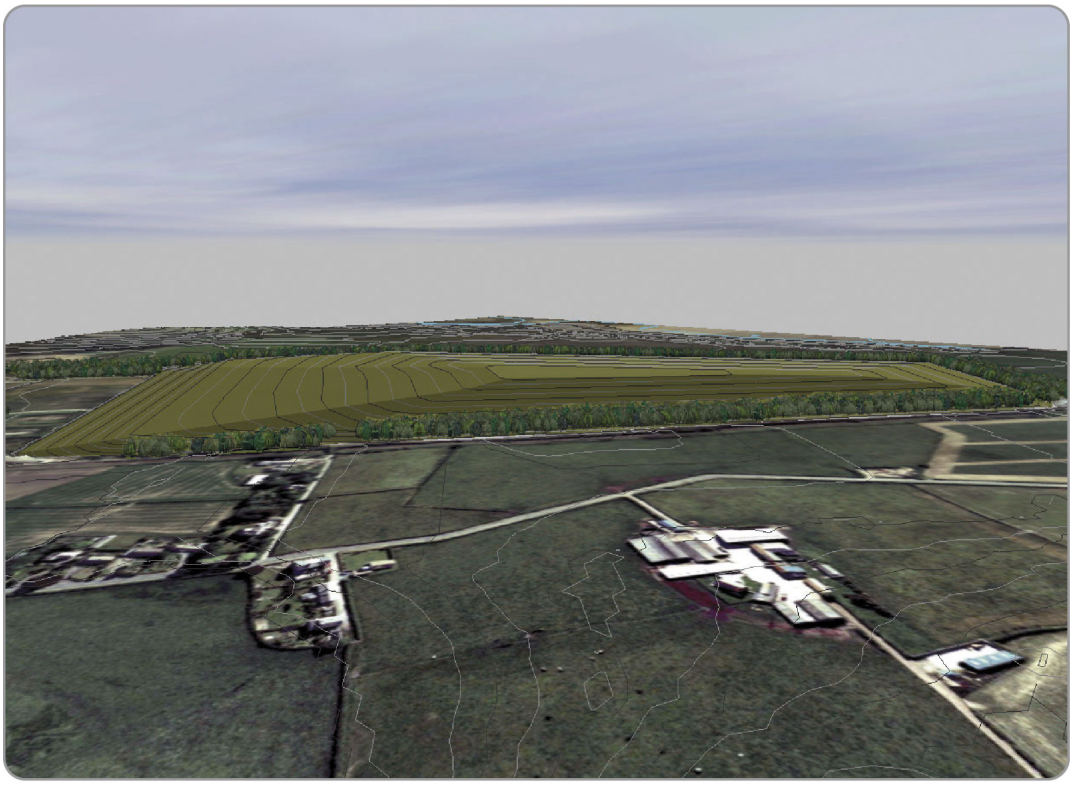

Figure 3.4 Final cap completed over EDA Repository

Table 3.1 ESS: summary of control measures and functions

Control	**Function**
Control of source	
Waste acceptance	Ensure only waste consistent with requirements of Permit, ESC and other constraints is accepted. Controlling impacts directly and indirectly through the effect on the cap of subsidence resulting from voidage
Waste emplacement	Minimise impacts from human intrusion and coastal erosion
Capacity management	Ensure total capacity of repository for hazardous material is not exceeded
Isolation of source	
Interim cap on trenches	Minimise infiltration into trench wastes
Final engineered cap	Minimise infiltration into wastes and possibility of exposure of wastes through erosion, prevent or discourage human intrusion
COW	Minimise infiltration and groundwater flow into wastes
Access restrictions during operations and active institutional control	Prevent intrusion into wastes
Management after active institutional control of land use and records	Minimise likelihood of human habitation on cap and intrusion into wastes
Containment of source	
Wasteform and packaging	Minimise releases during operations and after closure engineering is installed, by providing physical barriers to the release of contaminants
Final engineered cap	Limit impacts from the release of radon
COW	Prevent the release of contaminants to the near-surface environment

Cementitious grout	Retain C-14 (as carbonate) and reduce the releases of certain radionuclides in the groundwater through reduced solubility and provision of a substrate for sorption
Management of residual releases	
Active management (that is, collection and discharge through the Marine Pipeline) of leachate and run-off during operations and active institutional control	Direct discharges to receptor where they will have least impact
Vault drainage design	Direct releases of contaminants via the groundwater pathway down to deeper groundwater and out towards the sea
COW	Direct releases of contaminants via the groundwater pathway down to deeper groundwater and out towards the sea
Environmental monitoring	Re-assurance that the system is behaving as expected
Geosphere	Dilution of any releases in the groundwater. Prevention of the release to the biosphere via the groundwater of short-lived or highly sorbing radionuclides

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4 Environmental Safety Case Arguments

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

– management and dialogue;
– system characterisation and understanding;
– optimisation and SDP;
– assessment.

4.1 Structure of the Arguments

As introduced in Subsection 1.2, the GRA (paragraph 6.2.2 in reference [23]) defines environmental safety case as:

> '*a set of claims concerning the environmental safety of disposals of solid radioactive waste, substantiated by a structured collection of arguments and evidence.*'

At a high level, our case is that:

- We have worked within a sound management framework and firm safety culture, while engaging in dialogue with stakeholders.
- We have characterised and established a sufficient understanding of the LLWR site and facility, and their evolution, relevant to its environmental safety.
- On which basis, we have carried out a comprehensive evaluation of options to arrive at an optimised SDP for the LLWR.
- We have assessed the environmental safety of the SDP, showing that impacts are appropriately low and consistent with regulatory guidance. Using our assessments, we have determined the radiological capacity of the facility and conditions under which waste may be safely accepted and disposed.

This structure of high-level safety arguments, which in summation forms our ESC, is shown schematically in part (a) of Figure 4.1; part (b) of Figure 4.1 shows that each of the Requirements of the GRA [23] can be addressed within the structure. This is confirmed in Section 7, which summarises the relation between the GRA Requirements and our arguments in more detail.

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

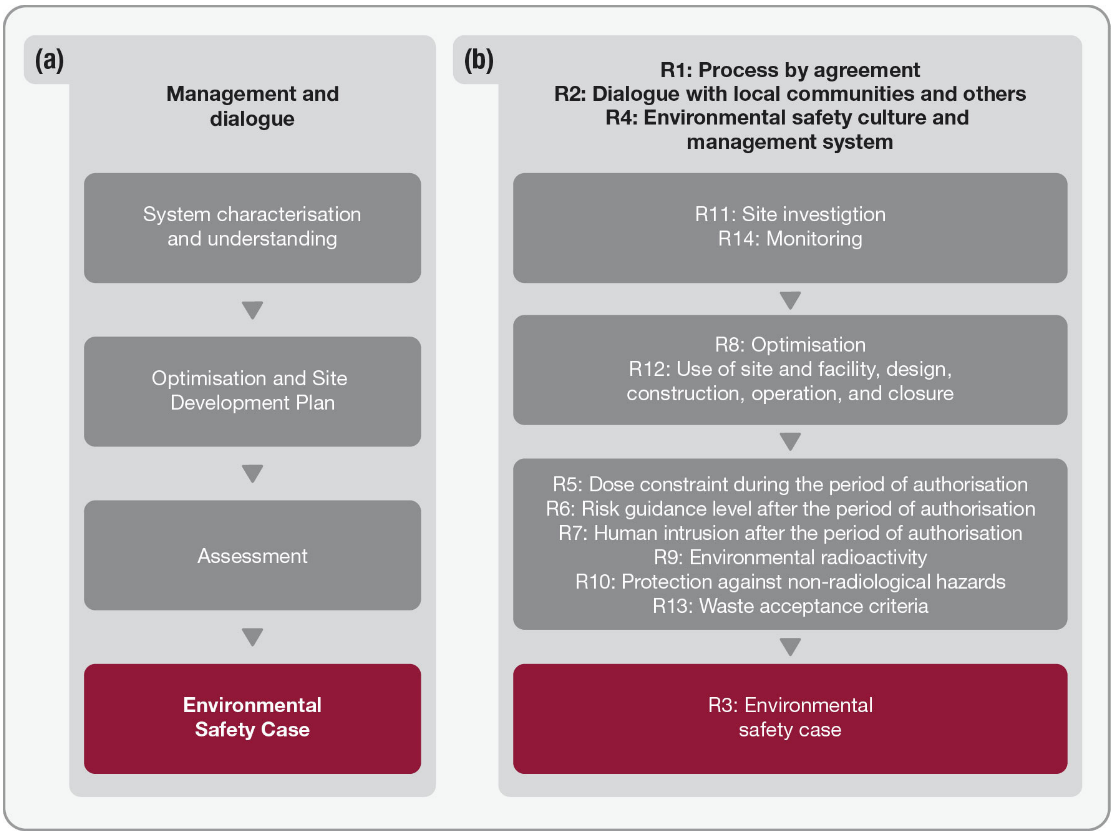

Figure 4.1 Structure of Environmental Safety Case arguments

We observe that:

- sound management, safety culture and dialogue form the essential framework within which all ESC activities are conducted;
- characterising and understanding of all aspects of the system and its evolution form the basis for optimisation and assessment activities that follow;
- iteration occurs because consideration of options and preliminary assessments will identify the need for further characterisation and development of understanding, and because preliminary assessments inform the evaluation of options;
- the figure shows the ESC as the end point of the process; this is true in that, having completed and documented the process, the ESC is complete, but the ESC is also the collection of all the safety arguments (and is itself only one iteration of the Safety Case as the facility develops through its lifecycle).

4.2 Management and Dialogue

We have a sound management system and a positive safety culture, and are committed to dialogue with our regulators, the NDA (the site owner), our waste consigners, and other local, national and international stakeholders. The ESC has been produced by our ESC Project. The Project team planned and undertook a work programme to provide appropriate, accurate and timely information and results to support the development of the ESC, and for LLWR and NDA decision making. The work has been subject to peer review by a standing, independent Peer Review Group from the United Kingdom, by an independent group of experts from other countries, and through review by a team of LLWR staff and contractors.

M1: Management system and safety culture

We have a sound Management System, a positive safety culture and are committed to high standards of environmental safety and quality, as formalised in our Environment, Health, Safety and Quality Policy.

This argument relates to GRA Requirement 4 [23]; further support to this argument is given in Section 4 of the '*Management and Dialogue*' report [2].

We aim to achieve high standards of environmental safety and are committed to the protection of the environment and health and safety of workers and members of the public, now and in the future. Our commitment is formalised in our Environment, Health, Safety and Quality (EHS&Q) Policy, which states that '*nothing is more important than the protection of the environment and the health and safety of the workforce, contractors and the public*' [35]. The Policy also sets out our core values, which are acted upon to encourage a positive safety culture throughout our organisation and across our suppliers and customers. We use a range of media to communicate environmental safety messages, including training courses, meetings, e-mails and posters, as well as formal review and reporting of our performance against key environment, health and safety indicators.

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

The Management System, as documented in the LLWR '*Management System Manual*' [36], comprises the policies, processes, procedures and working instructions needed to deliver the safe, secure, environmentally responsible and cost-effective clean up of the nuclear legacy, the management of storage and disposal of waste on the LLWR site, and the subsequent decommissioning of redundant nuclear plant.

The Management System applies to all activities carried out by LLWR and compliance with its requirements is mandatory. This ensures that we are compliant with:

- LLW Repository Ltd arrangements;
- the Environmental Permitting Regulations (England and Wales) 2010 'Permit for Disposal of Radioactive Waste' and its associated 'Compilation of Environment Agency Requirements' (CEAR) and other consents granted by the Environment Agency;

- our Nuclear Site Licence, regulated by the Office for Nuclear Regulation (ONR) of the HSE;
- permissions and consents granted by the local authorities;
- our contract with the Nuclear Decommissioning Authority (NDA) to operate the site;
- 'BS EN ISO 9001: 2008 – Quality Management Systems – Requirements';
- 'BS EN ISO 14001: 2004 – Environmental Management Systems';
- 'OHSAS 18001:2007 – Occupational Health and Safety Management Systems'.

Our Management System is accredited to international, national and nuclear-facility standards. Internal and external audits are held regularly to improve the effectiveness of the Management System. A detailed review of the management arrangements is held annually, which aims to improve environment, health, safety and quality performance. The recommendations from these reviews are a key input to our '*Improvement Plan*', so this process enables the continuous adaptation of our management arrangements to ensure suitable corporate governance of the organisation throughout the operational and post-closure periods.

M2: Organisation of the ESC Project

Our ESC Project is managed under our Management System. We have carried out our programme of work for the ESC Project according to an ordered plan that provides appropriate, accurate and timely information and results to support decision-making at each stage of development of the ESC. The ESC Project team interacts with other LLWR teams to ensure the consistency of the ESC with other LLWR activities and to ensure other activities are aligned to meet the requirements and needs of the ESC.

This argument relates to paragraph numbers 6.2.22 and 6.2.25 of the GRA [23], which support Requirement 4; further support to this argument is given in Subsections 4.2.3 and 5.2 of the '*Management and Dialogue*' report [2].

The ESC Project has been managed under our integrated Management System. During the development of the ESC, the ESC Project has been managed by an ESC Project team, with the ESC Project Manager reporting directly to the Managing Director. This has ensured appropriate focus on the ESC within the organisation and has involved the deployment of a team with appropriate technical skills.

A phased programme of work for the ESC Project was developed in 2008, based on a detailed review of the Project (then called the Lifetime Project). The detailed review considered the outcomes of the reviews [21] of the 2002 Safety Cases [19,20] by the regulator, and an audit of the Project by a group of experts, and applied the judgement and previous experience of qualified staff in the ESC Project team. The scope, costs, schedules and plans for all activities that supported the development of the ESC were documented or referenced in a Project Execution Plan [37]. Status reviews were held periodically to assess progress, review new information, and identify any required changes to the programme, which were undertaken in accordance with our change control procedures.

The ESC Project Manager is a member of the LLWR management team and attends two weekly team meetings, which help to ensure that company activities and forward plans are consistent with the assumptions and requirements of the ESC. The ESC Project has a project-specific stakeholder engagement plan, which includes scheduled meetings, reporting and review activities and other interface mechanisms, as required, for the following LLWR teams:

- Engineering;
- Projects;
- Environmental and Monitoring;
- Operations;
- Consignor Support;
- LLWR National Strategy Support.

The Consignor Support team provides a link between the ESC Project team and the waste consignors. The Consignor Support team arranges meetings, as needed, with consignors to address specific issues, such as changes to the Repository's Waste Acceptance Criteria (WAC). In addition, an annual consignors and suppliers forum is held, most recently at the Rheged Centre, Penrith. Presentations have been made at the forums in 2009 and 2010 on progress in developing the 2011 ESC.

Presentations to the LLWR's Environment Health and Safety Committee during the preparation of the ESC, along with other meetings, have been used to ensure that internal stakeholders such as the Operations and Maintenance Manager, the Chief Engineer and the Safety Case Manager are aware of the assumptions and results of the ESC and are ready to implement any required changes following the submission of the ESC.

M3: Dialogue with our environmental regulator

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

This argument relates to GRA Requirements 1 and 2 [23]; further support to this argument is given in Section 2 of the '*Management and Dialogue*' report [2].

GRA Requirement 1 '*Process by agreement*' mainly addresses early dialogue and agreement with the regulator at the stage of site selection and prior to issue of a Permit. As the LLWR is not a new development and already holds a Permit, a process by agreement is not needed. As part of our compliance arrangements, however, we have well-established processes for regulatory interactions regarding ongoing operations and proposed developments at the LLWR.

Specifically related to the ESC, we have held monthly liaison meetings, involving the LLWR ESC Project team, Environment Agency, ONR and NDA to discuss progress on the ESC Project. Technical presentations have been made and discussed on many aspects of the ESC as it has been developed. Written communications have also been exchanged requesting information and seeking clarifications on technical issues initiated by both the Agency and LLWR. The LLWR has also held meetings with the Agency's nuclear policy team, to present progress and discuss interpretation of the environment agencies' guidance set out in the GRA.

The structure of the ESC has been presented to the Agency and discussed at the monthly liaison meetings, and the timescales for provision of documents leading to delivery of the ESC to the Agency by 1st May 2011 have been agreed.

M4: Dialogue with our stakeholders

We attach a high priority to stakeholder engagement and the views of our stakeholders are sought and taken into account. We have a dedicated ESC Project stakeholder programme, which uses a variety of engagement mechanisms. We will continue this dialogue to ensure stakeholders understand the conclusions of the 2011 ESC and that any concerns are identified and considered in planning the future development of the ESC.

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

The ESC Project has its own stakeholder engagement plan, which used a variety of mechanisms to engage with the planning authority, local community, other interested parties and the general public during the development of the ESC. Existing forums and communication processes have been used where appropriate and additional specific approaches pursued where necessary. Examples of stakeholder engagement activities include:

- presentations to West Cumbria Sites Stakeholder Group (WCSSG) LLWR Subcommittee meetings;
- liaison meetings with Cumbria County Council (the Planning Authority), the Environment Agency, the ONR and the NDA;
- meetings with Drigg and Carleton Parish Council;
- presentations and discussions at the National LLW Strategy Group meetings;
- site and community open days;
- articles on the LLWR website and in the quarterly site newsletter;
- presentations and discussions with interested local groups;
- presentations at international workshops.

The WCSSG is an independent body that provides opportunities for members of the public and interested parties to comment on and influence future strategies and plans and provide views and comments to the NDA on the future of the nuclear sites in West Cumbria [38]. The LLWR Subcommittee focuses on the operations at, and issues surrounding, the LLWR site. Members of the committee include representatives from our management team, the NDA, the ONR, the Environment Agency, Cumbria County Council, Copeland Borough Council and Drigg and Carleton Parish Council. The committee typically meets quarterly and reports back to the main WCSSG meetings. Meetings are open to members of the public.

Monthly liaison meetings, involving the LLWR ESC Project team, the Environment Agency, ONR and NDA, are held to discuss progress on the ESC Project, as already noted in argument '*M3: Dialogue with our environmental regulator'*. Liaison meetings are also held, usually quarterly, with the LLWR, Environment Agency, ONR, NDA and Cumbria County Council. At these meetings, information is shared and issues are discussed. Past discussions related to the ESC have covered the radiological capacity of the LLWR, coastal erosion, cap design, and climate change. Discussions tend to focus on those issues associated with planning permissions.

In addition to attending the various liaison meetings, the NDA receive regular updates on the ESC Project. These include weekly reports raising any significant issues, fortnightly meetings between our Managing Director and the NDA, and monthly formal progress reports. NDA staff are also involved in technical discussions, for example on the implications of the ESC for waste disposal capacity and the NDA LLW Strategy.

Key aspects of the ESC programme that required focused engagement with external stakeholders have included:

– improving the understanding of the waste inventory in the trenches;
– the future inventory;
– the visual impact of the repository cap design;
– additional capacity for waste emplacement;
– the optimisation of the design for Vault 9;
– the optimisation of the designs for the future vaults and closure engineering;
– changes in the WAC of the LLWR;
– the NDA site end-state consultation [39].

Local stakeholders are engaged through quarterly liaison meetings with the Drigg and Carleton Parish Council, meetings of the LLWR Subcommittee of the WCSSG, site open days and a community newsletter. It is planned that the April 2011 issue of the newsletter will focus on the 2011 ESC.

Following submission of the 2011 ESC to the Environment Agency by 1st May 2011, we will publish the ESC and a '*Non-technical Summary*' on our website [40] and communicate the results to stakeholders according to our plan for stakeholder engagement, to help them understand the conclusions and implications of the ESC. We will welcome any feedback on the ESC, but will emphasise that the Agency will hold formal public consultations on our request for a new Permit, based on the submitted ESC. We will make the Agency aware of any feedback we receive and will take it into account in future updates of the ESC.

M5: Peer review

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

This argument relates to paragraph 6.2.40 of the GRA (in support of Requirement 4); further support to this argument is given in Subsection 4.4.3 of the '*Management and Dialogue'* report [2].

As part of our programme of work leading to the production the 2011 ESC, a Peer Review Group (PRG) was appointed to provide independent challenge of the ESC and constructive advice. The PRG consists of experts of longstanding experience and international reputation, who are independent of the development of the LLWR ESC. The scope of the PRG's work focused on issues that are important to the ESC [41]:

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

The objectives of the PRG were to [41]:

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

Initially, the PRG reviewed the main themes of the ESC and provided high-level comments on the approach to developing the ESC. Meetings were held with the ESC Project team to discuss these reviews. The PRG was also invited to attend one of the monthly liaison meetings with the Environment Agency, ONR and NDA, to discuss the peer review process.

During preparation of the ESC, the Level 1 and 2 documents were reviewed twice by the PRG, with the exception of one [16], which was reviewed once. For each review, the PRG submitted detailed written comments, which were formally addressed by report authors and taken into account in the future development of the documentation. Meeting records, PRG reports and ESC Project responses have been generated as appropriate to provide a clear record of the activities of the PRG and the response. Detailed records are available, and a final report of the PRG, including their view on our treatment of their comments in the final ESC documentation will be issued soon after submission of the ESC to the Environment Agency.

A high-level review of the ESC Project was also commissioned from an international team of peers with experience from other radioactive near-surface waste disposal facilities – the International Peer Review Group (IPRG) [42]. The terms of reference of the IPRG were '*to provide an internationally-based independent review of key technical approaches, arguments, designs, assessments and documents that form components of the developing ESC*' [42]. The focus of this review was the overall strategy for, and approach to, the 2011 ESC and specific issues identified by us (rather than a comprehensive detailed technical review). The review and our response has been documented [43,44].

Opportunities will also be taken to present aspects of the ESC and its underpinning programme of work to a wider technical audience through attendance at conferences.

4.3 System Characterisation and Understanding

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

S1: Characterising and understanding the wastes

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

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

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

This argument relates GRA Paragraphs 5.4.6, 6.2.3, 6.2.34 and 9.9.2 ; further support to this argument is given in the '*Inventory*' report [4].

The evaluation of options for the future management and development of the LLWR, and assessments of its performance, require an understanding of the volume and nature of wastes that have already been disposed to the facility and that could be disposed in the future.

An inventory has been developed for wastes that have already been disposed to the trenches and to Vault 8. Since 1988, waste characterisation has been effective and good records are available. Prior to this time, waste characterisation and record keeping were less effective. Nevertheless, we have developed a good estimate of the disposals of key radionuclides, identified from previous assessments, based on an examination of available disposal records. For other wastes, such as bulk wastes from Sellafield, we have estimated waste stream inventories using volume information from disposal records and the 'fingerprints' (data on the concentration of radionuclides in the wastes) of recent analogous waste streams.

Based on a review of records for key radionuclides, we have produced maps of the distribution of radionuclides in the trenches on a bay-by-bay scale. This has been particularly useful in evaluating the merits of selective remediation, including selective retrieval of wastes.

A series of interviews was conducted with individuals who had operational experience of waste disposals to the LLWR. Such individuals worked at the repository site or at Sellafield. This exercise was conducted in part as a response to stakeholder comments that past consignment practices may not have met appropriate standards. The interviews were recorded using the RECALL system [45], which involved filming and recording information provided by interviewees. A range of issues was identified by the interviewees. Some past practices may not have been fully accounted for in the LLWR's estimated inventory. On the other hand, our approach to estimating past disposals using modern waste fingerprints will have led to over-estimates of radionuclide inventories because of the amount of non-active waste disposed in the past compared with recent practice. Overall, we have concluded that any departures from accepted practice would not have had a significant effect on the estimated trench inventory [46].

We have based the inventory for future wastes on the 2007 UKRWI [34] and on additional data collected by NDA for arisings from their sites (in the Waste Inventory Disposal Route Assessment Model, WIDRAM09 [47]). We have reviewed the future inventory focusing on those radionuclides that are key in terms of radiological impact [48]. As a result, certain errors in the inventory were corrected in consultation with waste producers. Uncertainties were also identified. Where uncertainties were identified, the estimated inventory tended to be too high, with the notable exception of Cl-36, where reported concentrations in LLW streams are likely to be too low because the mobility of this radionuclide in reactor circuits has not been properly accounted for. These uncertainties have been taken into account in our assessments of radiological impacts.

We have included all LLW in the UKRWI unless there is good reason to assume it will not be consigned to the LLWR. For example, we have excluded VLLW and Dounreay wastes. However, we have included all ‘orphan’ wastes (with the exception of one waste stream containing large amounts of free mercury), those where no disposal route is identified in the UKRWI, and LLW currently designated for disposal in a future deep disposal facility. This assumption was made with the intention of facilitating future assessment of the optimal route for the disposal of these wastes.

It is necessary to develop an understanding of the non-radiological hazardous nature of the wastes as well as the radiological. Less effort has been focused in the past on understanding the non-radiological hazardous nature of the wastes than the radiological and less information is available on this aspect. We have collated the available information as a basis for our assessment of non-radiological impacts and have identified potential future improvements in this aspect of the inventory, which we are discussing with the NDA.

Overall, we have developed a good knowledge of key disposals to the trenches and the inventories and uncertainties associated with future disposals to the vaults. Certain areas have been identified where the UKRWI could be improved, for example with respect to information on chemotoxic substances. Although uncertainties exist and have been treated in the assessment, assurance that the disposed inventory will not exceed acceptable limits is provided by the identification and implementation of appropriate Waste Acceptance Criteria (see argument ‘*A8: Waste Acceptance Criteria and radiological capacity*’).

S2: Characterisation and understanding of the near field

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

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

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

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

- The repository cap and other engineered barriers will act to reduce the infiltration of water through the trench and vault regions and contribute to the maintenance of partially saturated conditions for several hundred years.

- Chemically reducing conditions will stabilise uranium and technetium in their (IV) oxidation states, leading to lower concentrations in groundwater than would be the case for higher oxidation states.

- Cement grout in the vaults is used to reduce voidage. The grout provides an effective substrate for sorption. C-14 is incorporated in the cement grout by carbonation, reducing the release of C-14 labelled species in gaseous and aqueous media.

- During the PoA, the ISO containers in the vaults are expected to provide substantial containment against water-borne releases. Any leachate accumulating in the repository will be pumped away and disposed via an appropriate authorised discharge route, currently the Marine Pipeline.

- After the end of the PoA, the facility is designed such that any leachate is released to groundwater underneath the site, rather than resulting in local environmental contamination.

A programme of experimental and modelling work has been undertaken in support of the ESC to characterise the key controlling processes relating to these barrier functions and the associated uncertainties.

Elicited parameter uncertainties have been used as input to groundwater flow modelling tools to evaluate the hydrogeological evolution of the system [7].

The engineered features that will be installed as part of the closure of the LLWR will strongly influence the extent of water flow through the near field and its pathway through the wastes – Figure 4.2 provides a simple schematic of the engineered features. A final cap will be installed, and recharge below it will be low initially, leading to a low water table locally; this cap will degrade over hundreds of years, recharge will increase, and the local water table will rise. We have developed an understanding of the physical evolution of the near field based on a number of lines of evidence, including detailed groundwater flow calculations and estimates of physical degradation rates. We have encapsulated this understanding through a series of expert elicitation meetings where degradation rates and evolution processes were discussed [49].

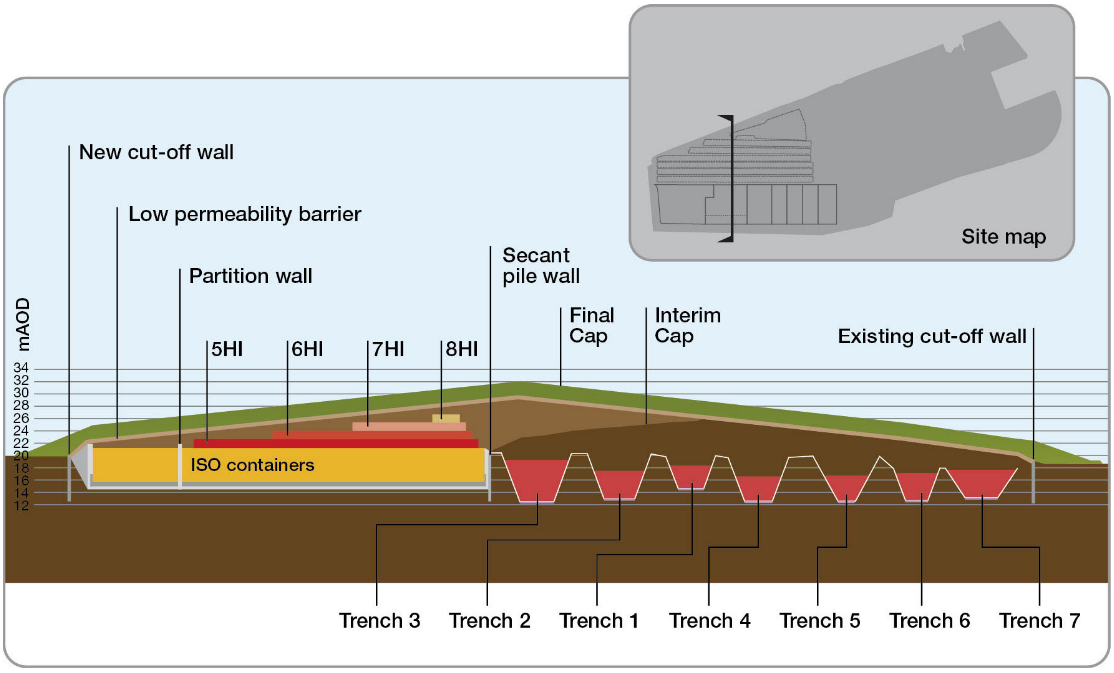

Figure 4.2 Key engineering features

Initially, the vault bases, apart from the base of Vault 8, will have low permeability. After the end of institutional control and after the cap has degraded sufficiently to allow increased infiltration, the water table will rise inside the future vaults until it reaches the top of the one-metre high vault walls. This water will be diverted by drainage blankets over the walls and under the vaults into the underlying geology. Vault 9 will be engineered to ensure it behaves in a similar way. The vault bases and walls will be expected to degrade, allowing more flow through these features. A COW will be constructed around the facility. This will significantly reduce groundwater flows to the vaults and trenches.

The hydrogeological evolution of the near field has been modelled using the program CONNECTFLOW [50], and using a Compartment Flow Model implemented in the program Gold*Sim* [7]. Based on these models, the trench and vault wastes are expected to remain partially saturated for a period up to one thousand years after closure. With the exception of Vault 8, the lower region of the vault waste will be fully saturated up to 1 m above the vault bases, but at higher elevation will be partially saturated.

A conceptual model of the chemical evolution of the trench and vault wastes has been developed, based on a substantial programme of work [6]. Previous near-field research and monitoring has established the role that microbiological processes have in mediating the pH, Eh conditions and gas generation processes in the trenches and has also included experimental studies of the pH conditions resulting from the buffering effect of the cement grout used in the containerised wasteform used in the vaults. In order to underpin the 2011 ESC, further research has been undertaken to examine the physical and chemical nature and leaching behaviour of uranium present in the trenches [51] as well as the sorption of uranium under trench and vault conditions [52]. Modelling approaches have been used to investigate pH buffering and carbonation effects at the scale of an ISO container and more qualitative analysis undertaken of the small-scale chemical interactions between the range of physical and chemical wastes and the cement grout and metal containers [53,54,55]. In developing the conceptual model, we have drawn on monitoring data and built confidence through appropriate validation studies [6].

The chemical evolution of the near field has been examined through the use of the GRM program [6], which models chemical reactions and the transport of contaminants in saturated media. This program has been used to calculate the evolution of Eh and pH, and the effects on uranium and technetium aqueous speciation and solubility, and C-14 partitioning between gas and dissolved species and solid phases. The main chemical processes and phases of evolution that are calculated to occur, are summarised as follows:

- Degradation of cellulose waste in trench disposals leads to mildly acidic and sulphate-reducing conditions for periods lasting up to several thousand years after closure.

- A phase of trench re-oxidation occurs. Re-oxidation occurs first in Trench 1 as a consequence of its smaller size and lower content of metal and cellulose waste. Re-oxidation is initiated about 1,000 years after closure in some regions, dependant on groundwater flow rates and inventory distribution. All the trenches show effects of re-oxidation after 2,000 years of evolution, but some trench regions remain reducing at around 7000 AD (although it is expected that the facility would be eroded by the sea before those times — see argument '*S5: Characterising and understanding the surface environment*'). Uranium concentrations increase significantly during re-oxidation, although the slow release of uranium from some trench wastes such as fluoride residues may limit uranium release under oxidised conditions.

- Degradation and leaching of the vault wastes and wasteform result in the establishment of alkaline and strongly reducing conditions where methanogenesis becomes established. Such conditions are expected to persist until the time when the repository is eroded. The pH of the vaults is affected by the heterogeneous distribution of cellulose-rich wastes, which also influence the extent of CH_4 generation. The chemical conditions of the vaults are less affected by water flow than the conditions in the trenches and alkaline conditions are maintained for several thousand years. Uranium, which is solubility controlled within most regions of the vaults, is maintained at a low concentration. Technetium concentration is controlled by sorption processes at concentrations below the solubility of Tc(IV). The releases of C-14 are mainly in the form of gaseous CH_4 and as dissolved organic species. Peak releases of C-14 occur at around 100 years. C-14 release rate and C-14 concentration is primarily influenced by the inventory distribution and the release rate of C-14 from the mainly metal and graphite waste materials. Typically around 40% of the inventory of C-14 is released as gas and around 10% of the inventory is released to groundwater.

In the '*Engineering Design*' report [5], we have set out the design at a sufficient level of detail to underpin the ESC. The design has been developed taking account of the long-term performance of the site (see argument '*O3: Site engineering*' and reference [10]). Construction will be in accordance with best practice and will utilise appropriate Construction Quality Assurance.

The developed understanding of the evolution of the near field and the specified engineering design are considered an appropriate basis for the development of an assessment model of the near field in the program GoldSim [12] and has been used as the basis for an assessment of waste degradation and subsidence [6]. This model of the near field in Gold*Sim* incorporates:

- models of contaminant release and sorption in both the saturated and unsaturated components of the trenches and vaults;
- a representation of the partitioning of C-14 between gaseous, aqueous and solid phases, based on a factor calculated with the GRM program;
- a compartment flow model to provide a detailed representation of the water flows through the near field;
- a representation of solubility limitation.

The Gold*Sim* model has been used to explore key uncertainties relating to the near field and other parts of the system. In particular, a probabilistic calculation has been undertaken to explore key uncertainties.

Overall, we have developed a sophisticated and comprehensive analysis of the near field with many key aspects including:

- a detailed 3-D groundwater flow model with a representation of the engineered features was used to investigate the detail of flows through the engineered system;
- a model of chemical reaction and contaminant transport was used to investigate the chemical evolution of the near field;
- a more robust model of contaminant release from the unsaturated zone has been developed that is an improvement on previous models;
- in assessment models, water flow through the engineered system was represented using a detailed Compartment Flow Model.

S3: Characterising and understanding the geology and hydrogeology

We have developed a sufficiently detailed and reliable description of the geology and hydrogeology, and the possible evolution of the hydrogeology, to support both our evaluation of options for the development of the facility and assessment calculations.

This work has included site investigations and detailed quantitative modelling. We have obtained an understanding of heterogeneities and of the hydrogeological regime as it may change in response to site developments, climate change, sea-level rise and coastal erosion.

This argument relates to GRA Requirement 11 and also GRA Paragraphs 6.4.7, 6.4.8, 6.4.9, 6.4.10, 6.4.11, and 6.4.13 to 6.4.15; further support to this argument is given in the '*Hydrogeology*' report [7].

We have carried out an extensive programme of site investigation to develop our understanding of the geology and hydrogeology of the site. A conceptual model has been developed for the site (see Figure 4.3) to understand the groundwater flow through the surrounding geosphere and the engineered system. The programme has been led by the requirements of the assessment calculations, which consider the movement of water through the waste and the subsequent transport of contaminants to potential receptors.

By using a combination of intrusive (boreholes, trial pits, environmental sampling, hydrogeological testing) and non-intrusive (geophysics, bathymetry surveys, LiDAR survey, aerial photography) techniques, we have been able to characterise the geology and hydrogeology of the surrounding area. The geology of the area is complex and heterogeneous. Using a lithofacies approach, we have developed a 3-D geological model. The development of the geological model has been led by the need to understand how groundwater moves through the underlying geology. As such, the focus of the geological interpretation has been on the distribution of lithologies and their hydrogeological properties, rather than on understanding the processes that formed them.

The 3-D geological model has been used as a basis for the development of a 3-D groundwater flow model. This has been calibrated against observed heads. It incorporates a detailed representation of the engineered features, allowing details of the flow through the repository to be investigated in support of optimisation and assessment studies.

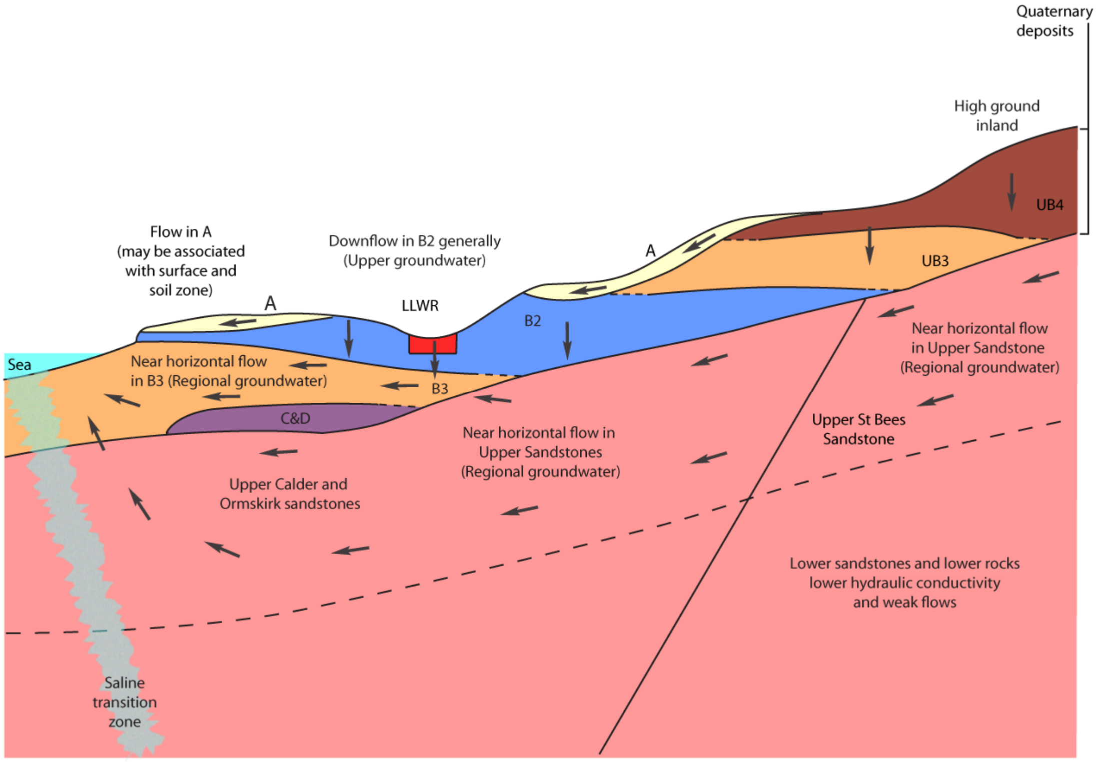

Figure 4.3 Hydrogeological conceptual model. Schematic E-W section

We have been able determine that the movement of water from the repository would be down through the underlying Quaternary geology into the Regional Groundwater with discharges occurring at the coast. Our understanding is underpinned by observations of the movement of tritium in groundwater, observed hydrogeological conditions and through the detailed hydrogeological modelling of the site. Our studies have considered the uncertainty in the hydrogeological properties of the different geological units and the uncertainty in the spatial distribution of the units. Whilst there are variations in flow paths associated with these uncertainties, we can demonstrate that the overall pattern of flow is unaffected and that the representation of the groundwater pathway in the safety assessment is robust.

Hydrogeological modelling has been used to determine how water will pass through the facility taking into account the properties of the engineering components. The models have been used to optimise the design of the facility. Our reference engineering design now incorporates our current best understanding and judgements. It is used as the basis for our detailed assessments of facility performance and radiological and non-radiological impacts within the 2011 ESC.

Our 2010 Hydrogeological Model has been used to consider the long-term behaviour of the site taking into account the expected evolution of climatic conditions and the possible long-term performance of the engineering components. We have undertaken a range of deterministic assessment calculations and a probabilistic calculation based on numerical models of groundwater flow and transport. Detailed 3-D groundwater flow calculations require considerable computing resources, which prohibits modelling large numbers of realisations in probabilistic calculations to address parameter uncertainties. Hence, the 2010 Hydrogeological Model has been augmented by the development of the 2010 Compartment Flow Model of groundwater flow within the immediate environs of the repository. This allows both long-term transients to be modelled as a continuous evolution and the use of a probabilistic approach to assess the implications of uncertainties in the engineering and hydrogeological parameters.

S4: Characterising and understanding the coastal environment

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

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

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

This argument relates to GRA Requirement 11 and also GRA Paragraphs 6.4.14, 7.2.1, 7.3.29 and 7.3.32; further support to this argument is given in the '*Site Evolution'* report [8].

The LLWR site lies mainly between about one half to one kilometre from the coast. At its north-western corner, the site and disposal area is only about 400 m from the high water mark, so that the site is vulnerable to coastal erosion; therefore the characterisation and understanding of the coastal environment is a key concern for the ESC.

Over the last decade, a substantial programme of scientific research and monitoring has been carried out to characterise the current coastal system and to provide a basis for forecasting its future evolution. Data acquisition and characterisation activities have included:

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

- geological characterisation of the Drigg spit and beach using mapping, shallow boreholes and trial pits, to infer Holocene development of the spit and providing beach thickness data used to calibrate coastal recession models.

Work has also been undertaken to understand the implications for sea-level rise of climate change for the LLWR site, using IPCC[4] [56] and BIOCLIM[5] [57] studies and also drawing on studies of long-term climate change for other NDA sites [58,59, 60,61]. The IPCC and BIOCLIM studies indicate a broad envelope of possible future global sea levels, diminished to a small degree by expected tectonic uplift of North-west England. In summary, net sea-level rises are estimated of between about 0.1 to 0.7 m by 2100AD, 1 to 21 m by 3000AD and 7 to 25 m at 5000 AD. The large range relates to uncertainty in future greenhouse gas emissions (according to scenarios considered in BIOCLIM) and uncertainty over the degree of ice loss from the Greenland and Antarctic ice sheets.

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

These rates of sea-level rise are outside the range seen in the Holocene (from about 12,000 years ago to the present). Therefore, extrapolation of currently observed recession or reference to local paleo-evidence is not sufficient to estimate future rates of erosion on the Cumbrian coast. Therefore, two coastal recession models have been applied to estimate erosion of the coast adjacent to the LLWR taking account of the estimated range of future sea-level rises:

- an empirically-based coastal recession model, developed to estimate coastal erosion in the context of coastal forecasting, protection and planning;

- a more detailed process-based model, developed as a research model to describe the erosion of coasts comprised of material such as till and soft rock.

Both models are calibrated from coastal recession data, although mainly from the east of England, against lower rates of sea-level rise and periods of only decades. Both models have been applied for the maximum and minimum bounds of estimated future sea-level rise. The empirical model has been applied to multiple sections from the coast to and through the LLWR disposal area; the process-based model has been applied to a single section along the line of shortest distance between the LLWR disposal area and the coast. Results from these models indicate the timing of erosion and hence the sea level at such times, which is important in determining whether the disposal facility will be undercut, directly eroded at sea level or inundated.

The models indicate a range of times for onset of erosion of the facility (and in the case of the empirically-based model, completion of erosion) that vary with the rate of

[4] Intergovernmental Panel on Climate Change

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

sea-level rise and coast-to-site section modelled. Variation with section is due to differing proportions of gravel along the sections. In summary, times between 300 and 900 years are estimated for onset of erosion with undercutting the far most likely outcome for the vaults. Direct erosion is possible for higher rates of sea-level rise for the more southerly (lower base) vaults and the trenches. Given our understanding of possible biases related to the short-term calibration of the models, we consider that slower and later erosion than estimated by the models is also possible.

Hence, we conclude that the disposal vaults will begin to be eroded on a timescale of a few hundred to a few thousand years, with consequent disruption of the repository, with erosion of the vaults and trenches being complete within one to a few thousand years.

The possibility of the formation of a stable barrier-lagoon system in the Ravenglass Estuary, which was identified by work in support of our 2008 performance assessment [32], has now been ruled out on the basis of estuary modelling and hydraulic arguments.

The programme of work and outcomes from the programme have been reviewed at two workshops convened by the LLWR, bringing in academic and technical experts in coastal processes and modelling not previously engaged in the work we have undertaken. The first workshop, in January 2009, examined the work to date and advised additional work that was subsequently carried out. The second workshop, in March 2010, reviewed the work and outcomes and gave broad support to the approaches and also the conclusions regarding coastal erosion of the LLWR.

S5: Characterising and understanding the surface environment

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

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

This argument relates to GRA Requirement 11 and also GRA Paragraph 6.4.9; further support to this argument is given in the '*Site History and Description*' [3] and '*Hydrogeology*' [7] reports and the various ESC reports that present our assessments [11,12,13,14].

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

- an understanding of the locations of groundwater recharge and discharge and the location of streams, rivers and estuaries now and in the future [7];
- the location of any natural resources, in particular the potential abstraction of water resources for local use (see below and Section 3 of reference [7]);
- local activities and behaviour of people in the vicinity of the site, where this is relevant to the definition of critical or potentially exposed groups (see below);

- the ecosystems and habitats present, which are a basis for the assessment of impacts to non-human biota (see below);
- general aspects of the site such as climate, soil type, potential erosion rates and topography, which provide a general context to our assessments [3];
- those changes over time that are relevant to the assessment.

When defining potentially exposed groups in the future, it is appropriate to consider both generic and local behaviour as the characteristics of the site and local behaviour could change.

As noted in reference [62], the standard approach to assessing the consequences of present-day discharges of radionuclides is to assess the consequence to 'critical groups'. Habits surveys provide information on present-day human habits that could result in exposure via the main pathways, and this is used to define critical groups. In defining the habits of those groups, we have used local information and national statistics to identify high rates of consumption.

Consideration of potential exposures in the future requires an alternative approach in which a wider range of activities is considered (for example, sinking a well into contaminated groundwater and utilisation of the abstracted water). Hypothetical combinations of habits that are expected to lead to the highest exposures from a given source are described in reference [63]. In the assessment of potential radiological consequences during the PoA, these have been used to define 'hypothetical critical groups' for assessment. These complement the critical group assumptions and show that the dose assessment takes account of the possibility of habits changing, which might result in greater exposures. Where appropriate, the hypothetical critical groups also reflect assumptions made for assessments of the post-authorisation phase where radiological impacts to a range of potentially exposed groups are considered. Our approach to the identification of exposed groups has been systematic [63].

Of particular importance is the potential for the future exploitation of water resources by use of a water abstraction well between the facility and the coast. We have examined in some detail the potential for such a well and the likely associated behaviours [12,49].

Assessment of the impacts of non-human biota have been undertaken based on a review of the ecological context of the site and its surroundings [14] (see argument '*A7: Impacts on non-human biota*'). The LLWR site is bordered by farmland to the north and east. However, to the west and south the site is contiguous with or lies close to the Drigg Coast SSSI, which is designated both as an SSSI and a Special Area of Conservation (SAC). The latter is a Natura 2000 classification. A review of relevant habitat types and species was undertaken in support of the assessment and drew on a number of surveys, including those undertaken in association with the construction of Vault 9.

Environmental change is important to the evolution of the LLWR, particularly in the context of coastal evolution (see argument '*S3: Characterising and understanding the geology and hydrogeology*'), which will be the major effect on the topography of the system. Rates of surface erosion will not be sufficiently high to modify the local environment over the timescale of interest. In addition, we have considered the likely evolution of the climate and changes in hydrologically effective rainfall and the possible evolution of the Ravenglass Estuary [8]. There may be evolution of the dune system behind the Drigg beach, but this is not of great significance because the area will continue to be unsuitable for most agricultural purposes. We assume cautiously that agriculture will continue to be the dominant land use around the LLWR.

S6: Monitoring

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

Monitoring results provide evidence of current site performance and provide a basis for forward estimation of performance.

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

This argument relates to GRA Requirement 14; further support to this argument is given in the '*Monitoring*' report [9].

The environmental monitoring programme at the LLWR has undergone significant development in a number of areas in the last two years. The following improvements have been achieved [9]:

- a fully integrated monitoring programme has been produced by drawing together a number of previously disparate monitoring activities;
- substantial objectives-driven reviews of the programme have been undertaken twice, taking account of the technical needs and requirements of the ESC and other users of the data;
- a systematic approach has been implemented to record monitoring data in a reliable way, based on the use of a Geographical Information System.

These enhancements have resulted in a monitoring programme that is focused, fit for purpose and which provides the necessary data to support safety analyses and site management.

Our monitoring programme addresses:

– the concentrations of contaminants in groundwater, surface water and leachate;
– the variation of groundwater levels in the geosphere and within the facility;
– flows relevant to water balance;
– the evolution of the coastline;
– the generation of bulk and radioactive gases;
– meteorological data;

- monitoring related to the condition and subsidence of the cap;
- the concentrations of contaminants in various environmental media;
- measurements of external dose rate around the site;
- the evolution of long-term experiments to investigate the behaviour of the near field;
- monitoring in relation to particular construction projects such as Vault 9.

Baseline monitoring data from before the start of operations in 1959 are not available. However, a baseline has now been established using available monitoring data, including data available from upstream of the site. More specific baselines are developed in relation to specific engineering projects such as the construction of Vault 9.

On the basis of monitoring data, a number of key conclusions can be drawn [9]:

- The concentrations of LLWR-derived radionuclides in groundwater under the site have decreased markedly since the installation of the interim trench cap and the COW between 1989 and 1995. These concentrations are very low and do not give rise to significant radiological doses.

- Tritium has been identified at low concentrations in groundwater between the LLWR and the coast and local to the repository. These concentrations are also in general reducing as a consequence of interim cap and COW construction and do not give rise to significant radiological doses.

- Waste disposal to the LLWR has not resulted in significant contamination of groundwater or surface waters by non-radiological contaminants. Ammonium, arsenic, iron, manganese, nickel, nitrate, nitrite and sulphide are present in groundwater in excess of the relevant standards. However, it seems likely that these substances are present in groundwater (and surface water) as a result of natural processes (rather than as a result of pollution from the LLWR), with the exception of nitrate, which is likely to be present as a result of the use of artificial fertilisers in the area upgradient of the site (see the 'Assessment of Non-radiological Impacts' report [13]).

In the '*Environmental Safety During the Period of Authorisation*' report [11], estimates of performance are based in some cases on observed concentrations of contaminants in environmental media, as well as on the results of models. Data on contaminant concentrations in leachate also show that the assessment models used to estimate environmental impacts generally overestimate the current concentrations of contaminants in pore water in the trenches. This indicates that for current impacts from the groundwater pathway, assessment models are cautious [13]. Monitoring data have also been used as a basis for building confidence in near-field models [6]. For example, data from the Long-Term Trench and Long-Term Vault Experiments have been used to inform our understanding of gas production and corrosion rates [6]. Contaminant concentrations calculated with geochemical models have been compared with measurements of leachate [67].

As noted above, the monitoring programme has been designed to take account of the needs of the ESC as well as other requirements. Monitoring data have been used as a basis of ESC models. For example, flow data have been used as a basis for constructing a water balance model for the interim trench cap [64] and head data have been used to calibrate our 2010 3-D Hydrogeological Model [7].

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

We recognise the need for a programme of long-term monitoring that will continue throughout the PoA. This will need to consider the following aspects:

- providing continued assurance that contaminants are present in the environment at acceptably low concentrations;
- contributing data to future updates of the ESC, which is expected to build confidence in our understanding of system performance.

4.4 Optimisation and Site Development Plan

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

O1: Remediation of past waste disposals

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

This argument relates to GRA Requirement 8; further support to this argument is given in the '*Optimisation and Development Plan*' report [15].

One of the main conclusions of the Environment Agency's review of the safety cases submitted in 2002 by the previous operator was that they contained insufficient consideration of optimisation and risk management to demonstrate that impacts would be ALARA (see Section 6). This conclusion was drawn in the context of the then high calculated doses and risks from existing disposals to the trenches that significantly exceeded regulatory guidance levels. Calculated doses and risks from the trench disposals are now consistent with regulatory guidance levels due to the work we have undertaken to improve our assessments and reduce uncertainties (see argument '*A5: Radiation doses and risks in the long term*'). Nevertheless, in order to demonstrate our SDP is optimised, we have considered a variety of actions that have the potential to achieve reduction in the environmental impact associated with past disposals to the LLWR. These options have been assessed from the perspective of the potential reductions in risk they may be capable of delivering, set against the wider implications that would be associated with their implementation.

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

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

We shall continue to collect information relating to the current performance of the interim cap on the trenches and the potential amount of settlement that remains to be expressed in the trench wastes as part of our ongoing monitoring programme. Further consideration of whether the current interim cap on the trenches is the BAT is planned for 2012, once a year's monitoring data are available from the new drains taking run-off from the trench cap. We anticipate that these data will provide a better view on how the interim cap is performing. Pending the outcome of such information gathering and assessment, we consider current operational leachate management arrangements to be optimal.

Monitoring of the existing COW performance (in order to determine whether it can serve as part of an encircling barrier for the whole facility) will also be used to inform decisions on whether upgrading may be required as part of the control of operational discharges.

O2: Optimisation of future waste disposals

Implementation of the UK Strategy for LLW management will reduce volumes of wastes requiring disposal at the LLWR, through improvements in waste characterisation, segregation and treatment. We are supporting the NDA in the implementation of the UK Strategy. We will also continue to optimise the use of the capacity of the LLWR through improvements in waste packaging, which will increase packing efficiency and reduce the amounts of non-waste materials disposed.

This argument relates to GRA Requirement 8; further support to this argument is given in the '*Optimisation and Development Plan*' report [10].

The NDA's UK Strategy (see Subsection 2.1) seeks to introduce the systematic application of the waste hierarchy into the management of LLW in the UK. Better characterisation and segregation of wastes and increased availability of options for treating wastes, through metal treatment, incineration and compaction, are already reducing the volumes of LLW requiring disposal in the vaults at the LLWR.

We are acting as a strategic partner to the NDA in the implementation of the UK Strategy, partly through providing framework contracts allowing cost-effective access to waste management services and facilities by consignors. We are also using our WAC to encourage the use of best practice amongst our consignors.

Implementation of the UK Strategy will lead to an alteration in the nature of some of the wastes and the concentrations of radioactivity within them. Our assessments take account of the implementation of the UK Strategy using inventory data based on assumptions about the segregation and treatment of LLW. Our assessments show that the resulting wastes can be safely disposed at the LLWR.

We are in the process of improving the efficiency of waste packaging, through improved designs of disposal containers. We also have an objective to increase the packing efficiency of waste within containers. These activities will increase the efficiency of the use of the space in our vaults and reduce the quantity of non-waste materials disposed, including steel and grout.

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

O3: Site engineering

We have examined a range of options for site engineering to promote improved post-closure performance, including for vault design, capping and passive groundwater management. Following consideration of feasibility, effectiveness, impacts during operations and after closure, we have defined the optimised plans for future vaults and site closure adopted in our SDP.

This argument relates to GRA Requirement 8; further support to this argument is given in the '*Optimisation and Development Plan*' report [10] and the site engineering is described in the '*Engineering Design*' report [5].

We have reviewed the basis on which the design for Vault 9 was originally determined, noting that it was specifically intended to underpin the provision of long-term temporary storage. With the perspective of the current ESC firmly on the role of the LLWR as a disposal facility, we have examined a range of aspects of the pre- and post-closure engineering design that will be employed in future development of the site. There are uncertainties associated with providing definitive estimates of long-term engineering performance at the system level, so the main emphasis in comparing engineering options for the purpose of design optimisation was whether there is a preference from the perspective of establishing confidence in demonstrating environmental safety. Having made such a comparison, we then assessed whether that preference would be materially affected by wider considerations.

Our conclusions, on which our SDP for the LLWR is based:

- Future vault design will be based on the principle of providing comprehensive capture and control of leachate during operations and until such time as active control over leachate is ceased. However, no containment function will be assigned to the vault walls, other than to protect against uncontrolled overflow during extreme rainfall events prior to capping. This will help to preserve unsaturated conditions over the majority of the waste column, minimising interaction between infiltrating water and contaminants within the wastes and lending greater confidence to the demonstration of favourable environmental safety performance. Contingency arrangements for the passive discharge of leachate beyond the PoA will be provided by horizontally extensive drainage layers beneath the vault bases.

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

- The profile of the cap is intended to ensure the minimum elevation consistent with providing confidence in long-term performance. The gradient of the cap profile has therefore been minimised to a level that will ensure that its water-shedding and drainage function will persist over the long term under expected rates of settlement. The cap will have a single-dome profile, capable of providing the required structural stability to assure long-term performance. The profiling volume potentially provides additional capacity for waste emplacement (consistent with making optimal use of the available disposal volume). We have assumed higher stacking in the vaults to use this space in our assessments and shown that this will be safe. There is also an opportunity to use VLLW or other inert waste as profiling material above the trenches, but this option has not been considered in the 2011 ESC.

- There is no requirement for an extensive vertical drain to provide contingency against the possibility of near-surface releases, because the design intent is to maintain a very low level of saturation within the wastes beneath the final cap. Moreover, a key mode of potential cap failure has been excluded by the adoption of a single-dome, rather than the previous 'gull wing' design. An encircling COW will be constructed around the whole facility, to a depth of approximately 2 m below the underside of the vault bases, primarily with the aim of minimising the encroachment of saturated conditions within wastes closer to the perimeter of the facility. This will be keyed into the cap and will play an added contingency role in providing reassurance against the possibility of near-surface release of leachate close to the facility.

- A passive gas venting arrangement is incorporated in the design of the final cap to prevent pressurisation of the system by bulk gas production or atmospheric pressure changes. The vent will also facilitate confirmatory monitoring of bulk gas and radioactive gas production during post-operational control of the site. A decision will be made before the end of active control on whether to close the vent prior to final site closure.

O4: Waste emplacement strategies

We have examined the advantages and disadvantages of waste emplacement strategies and identified an appropriate course of action.

This argument relates to GRA Requirement 8; further support to this argument is given in the '*Optimisation and Development Plan*' [10] and '*Waste Acceptance*' reports [15].

We have examined a wide range of potential enhancements to our approach to waste emplacement within future disposal vaults. In general, our conclusions are that detriments associated with implementation (for example, in terms of cost and complexity, and impacts on efficient operation of the facility) would significantly outweigh any advantages they might offer in terms of risk reduction over existing waste emplacement arrangements. In most cases, the potential benefits are assessed to be marginal.

We have, however, identified a number of strategies that do offer sufficient benefit to be implemented. These include emplacement of packages to limit the impacts that might result from human intrusion or coastal erosion, loads on materials containing absorbed liquids, and the effects of settlement on the cap. We intend to implement the identified strategies. These strategies will, for example, result in waste packages containing relatively large amounts of radium being placed away from the top of the waste stacks, to limit the potential for impacts from the release of radon through a damaged cap; and limits on the local concentrations of biodegradable materials that might lead to voidage and differential settlement.

O5: Management of run-off and leachate

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

This argument relates to GRA Requirement 8; further support to this argument is given in the '*Optimisation and Development Plan*' report [10].

During operations, rainwater run-off from the open vaults and leachate from the trenches and vaults (in the latter case once they start to be capped) will continue to be managed as now, by the collection, monitoring and controlled discharge to sea via the MHT and Marine Pipeline, subject to the terms of our Permit. We plan to construct the final cap progressively in strips, which will reduce infiltration to the trenches and run-off from the vault slabs. This will ensure that the current leachate management systems remains capable of handling run-off from most storm events.

Flexibility is incorporated in our plans to allow for the possibility that the current interim cap may not continue to remain the optimum barrier to infiltration over the medium term.

The assumption in our SDP is that leachate will continue to be actively managed while waste emplacement continues and up until the end of the PoA and final site closure. This assumption is based on our current understanding of the regulatory requirement, which is that leachate collection and monitoring will be necessary until surrender of the Permit.

After final capping, the maintenance of pumps used to remove leachate collected within the vault sumps will be undertaken with the support of engineered man-access penetrations in the western side of the cap. A decision will be made later on how to manage the collected leachate after final capping is completed.

The assumption of continued active management and monitoring is consistent with established practice for landfill operations. However, based on current understanding of cap performance and estimated likely rates of leachate generation, we expect that the vaults and trenches will be effectively de-saturated within two decades after the completion of final waste emplacement, with very low ongoing rates of leachate generation.

Monitoring will continue into the post-operational period with the objective of confirming performance in relation to leachate management.

O6: Management during closure

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

This argument relates to GRA Requirement 8; further support to this argument is given in the '*Optimisation and Development Plan*' report [10].

Following the end of waste emplacement the cap will be completed and a period of institutional control will follow in which the facility will continue to be monitored and managed until it is finally closed. We expect the site will continue under regulatory control during this period and hence the PoA will finish when the site is finally closed.

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

Our assessment calculations demonstrate that intrusion hazards associated with shorter-lived radionuclides are expected to fall substantially over the first 100 years following the end of disposals and much less rapidly thereafter. Our assessment suggests that the site could be safely released from control after 100 years from this perspective. Our assessment of the groundwater pathway has produced estimates of risk consistent with guidance levels assuming a 100-year period of active leachate management (although the implications of a shorter period of management have been investigated). Our current assessment for the release of C-14 labelled gas suggests, however, that some control will be required for up to about 300 years to ensure risks are consistent with the regulatory guidance. We believe that this assessment is cautious, however, and that we will be able to justify a shorter period. The last two hundred years of this period would only require sufficient control to prevent agriculture and hence the PoA could safely end 100 years after the completion of disposals. Further information is provided in argument '*A5: Radiation doses and risks in the long term*'.

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

4.5 Assessment

We have carried out assessments of the performance and safety of the LLWR during disposal operations, while under management following completion of disposals, and after the end of management and regulatory control of the site. Radiological risks and doses to members of the public, the impacts from chemotoxic substances and radiation doses to non-human species have all been considered. The final assessments were undertaken on the basis of the SDP (see Subsection 3.4). We have thus demonstrated the environmental safety of the facility under the Plan and, also, derived the radiological capacity and conditions under which waste may be safely disposed at the facility under the Plan.

A1: Qualitative understanding and safety functions

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

– potential radiological and non-radiological hazards;

– safety functions, for example, isolation of the waste, containment of contaminants and attenuation of releases;

– features, events and processes that provide, promote or reduce those functions.

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

This argument relates to GRA paragraphs 7.2.6, 7.3.3; further support to this argument is given in the '*Environmental Safety During the Period of Authorisation*' and '*Assessment of Long-term Radiological Impacts*' reports [11,12].

The detailed characterisation and understanding of the wastes, disposal system and its environment is discussed in Subsection 4.3. This argument, A1, addresses the qualitative synthesis of that understanding in terms of its implications for system performance, which has informed the development of our SDP (see Subsections 3.3 and 3.4) and is the basis for quantitative modelling and assessments (see argument '*A2: Quantitative analysis and modelling*').

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

The control measures envisaged within our ESS and SDP, and the functions that they fulfil, have been introduced in Table 3.1. Here we set out an account of the expected evolution of the LLWR and the safety functions and dispersion processes that are expected to operate over the lifetime of the disposal facility.

Period of Authorisation – site development, controls and safety functions

At the present day, aqueous and aerial discharges are made under the terms of our Permit. Releases of contaminants (mainly tritium) to groundwater have occurred in the past and are likely to be continuing, albeit to a lesser degree today.

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

Discharges occur of dust, for example, from the LLWR Grouting Facility, and of gases (notably radon and C-14 labelled gases, but also tritium) from the disposed waste in the trenches and vaults. The Grouting Facility includes dust abatement and control features. Gaseous discharges, notably of radon, are reduced by the present trench cap and by the grouting in the case of the vaults.

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

After filling of the last vault, the final cap will be completed. The cap includes a vent to protect the cap from atmospheric pressure differentials and to allow the dissipation of gas from waste degradation. A COW will be constructed around the disposal area to below the depth of the vault bases, to limit shallow groundwater inflow to the disposal area and prevent contaminant migration from the disposal area to shallow groundwater. Trench and vault leachate and drainage management will continue up until the end of site management to reduce the potential for release of leachate to groundwater.

A key feature of the LLWR, and other near-surface disposal facilities, is that substantial radioactive decay of shorter-lived radionuclides, and hence diminution of radiological hazard, occurs between the time of disposal and the end of the period management control. During this time, unauthorised access to the disposal site and waste is prevented, and hence direct exposure to the waste, human intrusion into the waste and deleterious actions or uses of the site area are all prevented.

In the first 100 years following the end of disposals, that is, between 2080 and 2180 (for the reference case inventory and assuming disposal only in the RDA), the radiological hazard posed by direct exposure to the wastes in the vaults will reduce by about an order of magnitude, with a further 30% diminution in the next 200 years. For the trenches, a factor of three diminution will have already occurred between 1996 and 2080, that is, before the end of vault disposals, but thereafter will decline by only a small factor, being maintained by the impact of long-lived radionuclides, primarily Th-232 [65].

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

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

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

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

Migration in groundwater

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

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

Migration with gas

Methane and carbon dioxide will be generated from the degradation of organic wastes mainly within the first few hundred years, after which readily degradable organic material is exhausted. These gases can provide a vector for release of C-14 labelled gas. CO_2 may be taken up as carbonate within the cement grout in the vaults, so mainly CH_4 is evolved; both CH_4 and CO_2 will be evolved in the trenches, but the inventory of C-14 in the trenches is much less than that in the vaults. C-14 labelled methane is expected to migrate by diffusion, aided by buoyancy, within the unsaturated vaults and profiling to beneath the cap, and thence diffuse through the cap.

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

A key feature of this pathway is that production of C-14-labelled methane from the vaults requires both degradation of organic materials and that C-14 is at the same time being released from the waste. Hence, organic C-14 waste streams can have a greater impact on release than C-14 waste streams from which C-14 is only slowly released, such as graphite and activated steels.

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

Once the cap is complete, radon generated from radium-bearing waste will be of little concern, because it will decay within the wastes or profiling. Radon might cause an impact if the cap were substantially damaged or radium-bearing waste were excavated by human intrusions. We assess such cases and also other exposure modes resulting from human intrusions (see arguments '*A2: Quantitative analysis and modelling*' and 'A5: *Radiation doses and risks in the long term*'), but we do not regard it as part of the 'expected evolution' of the disposal system. Rather, as described in argument '*O6: Management during closure*', a sustainable use of the site will be established and records placed to deter future human intrusion and developments that might be detrimental to repository performance.

Longer-term evolution and coastal erosion

Over hundreds to thousands of years, the properties of the cap and COW and vault bases will degrade so that infiltration through both trench and vault wastes will increase. Over the same timescale, sea level will rise and the coast erode, such that the groundwater flow path to the tidal zone will shorten. More significantly, sea-level rise will reduce the hydraulic head difference between the site and the coast. With a sea-level rise of about 10 metres, and allowing that the COW will be degraded, there is a potential for contaminated groundwater from the site to migrate southwards from the disposal area into a future East-West/Drigg Stream and thence to the estuary. At this time, with sea-level rise and coastal erosion, the estuary is liable to have developed into a more open tidal bay, and the Drigg Stream will have become tidal.

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

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

The ultimate fate of all solid material eroded from the LLWR will be distribution in sediments along the West Cumbrian coast and, in the longer term, dispersion and burial in the Irish Sea. More mobile contaminants will be carried in marine solution and dispersed in the Irish Sea and beyond.

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

A2: Quantitative analysis and modelling

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

We assess these pathways and interactions between them for defined scenarios focusing on the expected evolution of the disposal facility and its environment. We apply appropriate models to analyse each of the above pathways for the defined scenarios, representing the uncertainties related to each pathway, and assessing each pathway cautiously. We compare assessment results from each pathway, the timing and location of impacts, and hence whether an individual could be exposed via multiple pathways.

This argument relates to GRA Requirements 5 to 7 and 9 and 10; further support to this argument is given, in particular, in the ‘*Environmental Safety During the Period of Authorisation*’ and ‘*Assessment of Long-term Radiological Impacts*’ reports [11,12].

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

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

For long-term assessments, we identify four pathways:

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

We recognise that there is interaction, correlation, and the potential for addition, between the pathways. For example, changing vault or environmental conditions will simultaneously affect migration in more than one pathway, damage due to human intrusion might affect releases by other pathways, and an individual could be simultaneously exposed to more than one pathway. We address this as follows:

- *We first define environmental scenarios that present a coherent context within which all the pathways will be analysed.*

  Considering the evidence, as discussed in Subsection 4.3, we have defined a single 'Expected Natural Evolution Scenario'. In this scenario, the facility and engineered barriers degrade within the envelope defined from elicitation studies, and the climate and landform evolves taking account of the possible range of future climate and sea-level change and consequent coastal erosion, such that the disposal facility will be eroded within a few hundreds to a few thousand years after present.

  We define an additional scenario of 'Delayed Coastal Erosion'. From the scientific evidence, we do not think that this scenario is credible. Nevertheless, we analyse it because it allows study of the longer-term performance of the facility including the effect of long-term in-growth of radioactive progeny from disposed parent radionuclides. It also covers the circumstance of *'what if either we or the science are wrong?'*, noting that the view on the effects of climate and coastal erosion at the LLWR has changed over the last ten years.

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

  Each of the pathways is analysed and modelled independently, taking account of the range of uncertainties for the defined scenarios and uncertainties related to the contaminant release, migration and exposure processes for each pathway. Models are developed to present a cautiously realistic representation of the real world features and processes. That is, we apply our knowledge to develop models of physical and chemical processes that are realistic where possible, but where there are uncertainties we adopt cautious interpretations and model representations.

  We also check for interactions and correlations. For example, we use the same detailed near-field model to investigate the biogeochemical evolution of the disposal facility and consequent generation of C-14 labelled gases and release of contaminants, including C-14, to groundwater.

- *We assess each pathway cautiously, including that the contaminant inventory is not depleted due to migration or losses via the other pathways.*

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

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

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

A3: Uncertainty management

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

This includes the development of a register of significant uncertainties.

This argument relates to GRA Paragraphs 7.2.4 and 7.3.10; further support to this argument is given, in particular, in the '*Near Field*', '*Hydrogeology*' and '*Assessment of Long-term Radiological impacts*' reports [6,7,12].

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

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

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

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

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

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

As part of this ESC, we have:

- defined an Expected Natural Evolution Scenario, which encompasses the broadly expected evolution of the LLWR and its environment, and a Delayed Coastal Erosion Scenario, which we consider relatively unlikely [12];
- defined a realistic and foreseeable set human intrusion events that are assessed assuming that they occur;
- considered whether alternative models of the system are appropriate, for example, in relation to the conceptual hydrogeological model [7];
- identified the key uncertainties relating to different parts of the system [6,7,8];
- explored the implications of those key uncertainties in terms of estimated radiological impacts by undertaking variant calculations or by means of system understanding [66,67,68,69,70,71];
- explored other uncertainties by undertaking underpinning technical studies [6,7], for example, in relation to heterogeneity in the wastes and in the geosphere;
- undertaken probabilistic calculations for radiological impacts for the groundwater pathway, based in part on a set of elicited probability density functions for key parameters [12,49,66];

- used our understanding of the key uncertainties as a major input to the development of the technical programme that we have put in place in support of the 2011 ESC [72];

- identified those uncertainties and biases that still warrant further work (see Section 5);

- established a FEP database that includes a register of uncertainties, which indicates how uncertainties have been addressed and the extent to which further data gathering, calculations or decisions are needed [73].

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

- the time at which the facility will be eroded by the sea, sea level at the time of erosion and rate of release of radionuclides from eroded material into marine waters;

- the primary release rate of C-14 from key wasteforms, the degradation rate of cellulose and the assumption of uniform biogeochemical conditions in the GRM model;

- the effective dilution factor of water entering the Regional Groundwater from the repository, linked to the degradation of the engineered features;

- uncertainties related to the heterogeneous nature of the Quaternary sediments and consequent flow path characteristics and dilution;

- assumptions on future human activities on the site, especially those giving rise to exposure to radon in buildings constructed on the site or excavated waste.

The implications of these key uncertainties are explored in the '*Assessment of Long-term Radiological Impacts*' report [12].

A4: Radiation doses during the Period of Authorisation

Environmental safety during the Period of Authorisation is managed, and impacts controlled and monitored, through a SDP, such that doses to members of the public are as low as reasonably achievable.

We define critical groups assuming cautious habits based on those of the local population. We have estimated the radiation doses to these groups based on monitoring data and assessment calculations. These estimates take account of present-day conditions and site developments up to the end of regulatory control of the site, including the effect of uncertainties in releases to the environment.

The sum of cautiously estimated annual effective doses via all pathways is less than the applicable dose constraint. The doses are expected to reduce as the progressive capping of the disposal area proceeds, and after completion of capping will be reduced to very low levels.

This argument relates to GRA Requirement 5; further support to this argument is given in the '*Environmental Safety During the Period of Authorisation*' report [11].

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

Environmental safety in this period is managed through an optimised SDP derived under our ESS (see Subsection 3.2). The SDP provides for:

- engineering to minimise the generation of contaminants in effluents, and collection and controlled discharge of those that arise, using existing engineered measures, appropriate future vault design, and early implementation of closure engineering features such as the final cap and the COW;
- the use of site management controls, in particular controls on access to prevent inadvertent exposure to the highest concentrations of radionuclides (in particular preventing human intrusion and access to the cap area);
- the collection of information on effluents, discharges, and environmental concentrations, which provide information on the functioning of the engineered barriers and management controls, as well as providing a baseline against which future performance can be gauged.

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

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

- radioactivity in the Drigg Stream, which relates to discharges to the stream prior to upgrading of leachate collection and discharge arrangements;
- radioactivity in groundwater (if abstracted in the future), which at present day is mainly related to loss of leachate to groundwater that occurred before upgrading of construction of the interim trench cap and current COW.

We have assessed each of the above pathways using a combination of monitoring data (in respect of present discharges via the Marine Pipeline, off-site external exposures, discharges of dust, and residual radioactivity in the Drigg Stream), results from long-term assessment models (in respect of projected releases to groundwater), and models specific to the PoA assessment (in respect of discharges of radioactive gases).

In the assessments we assume cautious locations and behaviours for exposed persons according to 'critical group' assessment principles, for example, applying high occupancy times and local foodstuff consumptions rates. The estimated annual effective doses are thus liable to be overestimates for exposures at the present day and also into the future. Our summary results are given Table 4.1, which are to be compared to a source-related dose constraint of 0.3 mSv (300 µSv) set in the GRA.

Dose estimates are made incorporating assumptions that are cautious with respect to each exposure route, such that the doses cannot all be received by the same individual. At the present day, the cautiously estimated maximum annual dose related to the LLWR is less than 100 µSv (0.1 mSv); future annual doses depend on assumed future habits and locations, but are unlikely to be significantly higher. The number of individuals that could be exposed at this level is very small, a few to tens at most dwelling very close to the operating disposal area. A larger number of individuals may be exposed as a result of marine discharges, although only a few will have habits such as to experience the calculated doses based on critical group habits.

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

The potential for radionuclide releases, and thus doses, will reduce as capping proceeds. This is due to shielding of exposed wastes and hold up of migrating gas in the cap structure, with consequent decay of radon. Following completion of the final cap, annual doses will be of the order of not more than a few µSv.

Table 4.1 Estimated annual effective doses during the PoA

Estimated annual effective doses during the PoA (µSv)		
Discharge or release path	Estimated annual doses for present day	Estimated peak during future operations
Discharges to sea	0.3 µSv calculated from current LLWR discharges (compared with 150 µSv from nuclear industry based on measurements [74])	Peak of 0.8 µSv at about 2026 from estimated future peak discharge
Release to groundwater	3 µSv if well assumed to be present; pre-1991 contamination*	3 µSv if well assumed to be present; pre-1991 contamination
Drigg Stream	3 µSv from pre-1991 contamination	3 µSv from pre-1991 contamination
Discharges to air	Dust 12 µSv (Vault 8 operations) Tritium (if HTO*) 4 µSv Carbon-14 (if CO_2) <0.6 µSv Radon approximately 50 µSv	Dust 17 µSv (Vault 9 operations) Tritium (if HTO**) 5 µSv Carbon-14 (if CO_2) 0.6 µSv Radon approximately 50 µSv
Off-site external irradiation	12 µSv for coal yard worker	7 µSv for periodic passer-by (No residence or occupied locations along the Site to SSSI boundary.)

*Pre-1991 contamination refers to effects of discharges to the Drigg Stream and releases to groundwater prior to interim capping of Trenches 1 to 6 and the upgrading of leachate collection and discharge arrangements all completed in 1991

** HTO is tritiated water

A5: Radiation doses and risks in the long term

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

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

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

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

We currently calculate levels of carbon-14 labelled gas flux from the vaults at 100 years after completion of disposals that would imply a conditional risk to a self-sufficient smallholder that are substantially above the risk guidance level. There are, however, overly-cautious assumptions in our current models, and we believe that through improved modelling we will be able to substantially reduce our current estimates of risk.

The only action required to prevent the carbon-14 labelled gas pathway leading to risks inconsistent with the guidance level would be to place restrictions on the use of the cap for agriculture or kitchen gardening. This could be readily achieved through land ownership and land covenants.

This argument relates to GRA Requirement 6 and Requirement 7; further support to this argument is given in the '*Assessment of Long-term Radiological Impacts*' report [12].

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

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

Each of the pathways is assessed for the expected natural evolution scenario and the delayed coastal erosion scenario (A2) and four inventory cases.

Table 4.2 presents a summary of the assessed risk via each of the 'natural' pathways, which may be compared with the risk guidance level of 10^{-6} y^{-1}. Results are presented for the groundwater well probabilistic case and for reference deterministic cases and exposed groups. Human intrusion is assessed against a dose guidance level range and not included in the table. Further details are provided in the text below.

Table 4.2 Summary of assessed risks from reference cases

<table>
<tr><th rowspan="2"></th><th colspan="2">Risk, y^{-1}</th><th rowspan="2">Time approx.
Year (yPVC[1])</th><th rowspan="2">Key radionuclides</th></tr>
<tr><th>Trenches</th><th>Vaults</th></tr>
<tr><td colspan="5">Groundwater</td></tr>
<tr><td>Well – probabilistic case</td><td colspan="2">$1\ 10^{-7}$</td><td>2230 (150)</td><td>C-14 / Cl-36</td></tr>
<tr><td>Well – deterministic case</td><td colspan="2">$4\ 10^{-8}$</td><td>2250 (170)</td><td>Cl-36 / C-14 / I-129</td></tr>
<tr><td>Marine release</td><td colspan="2">$2\ 10^{-9}$</td><td>2220 (140)</td><td>C-14</td></tr>
<tr><td>Estuary release</td><td colspan="2">$2\ 10^{-9}$</td><td>2220 (140)</td><td>C-14</td></tr>
<tr><td>Stream release</td><td colspan="2">$5\ 10^{-10}$</td><td>3180 (1100)</td><td>Cl-36 / Ca-41 / Mo-93</td></tr>
<tr><td colspan="5">Carbon-14 labelled gas</td></tr>
<tr><td rowspan="3">Smallholder</td><td>$9\ 10^{-7}$</td><td>$4\ 10^{-5}$</td><td>2180 (100)</td><td>C-14</td></tr>
<tr><td>$4\ 10^{-7}$</td><td>$5\ 10^{-6}$</td><td>2280 (200)</td><td>C-14</td></tr>
<tr><td>$3\ 10^{-7}$</td><td>$2\ 10^{-6}$</td><td>2380 (300)</td><td>C-14</td></tr>
<tr><td colspan="5">Coastal erosion</td></tr>
<tr><td>Local recreational beach user</td><td>$1\ 10^{-6}$</td><td>$7\ 10^{-7}$</td><td>3700 for trenches
3260 for vaults</td><td>Th-232 for trenches
Ra-226 for vaults</td></tr>
<tr><td>Coastal occupational user</td><td colspan="2">$7\ 10^{-7}$</td><td>3800</td><td>Th-232 / Ra-226</td></tr>
<tr><td>Marine foodstuffs</td><td colspan="2">$7\ 10^{-7}$</td><td>3400</td><td>Ra-226 (Pb/Po-210)</td></tr>
</table>

[1] yPVC is years after closure of the final vault of the RDA, which occurs at 2080

Groundwater pathway

The hydrogeological models have been used to consider the long-term behaviour of the site taking into account the expected evolution of climatic conditions and the possible long-term performance of the engineering components. We have undertaken a range of deterministic calculations and a probabilistic calculation based on numerical models of groundwater flow and transport. As mentioned in argument '*S3: Characterising and understanding the geology and hydrogeology*', the 2010 Hydrogeological model is computationally intensive and, also, not suited to capture the full range of behaviours that may occur, given the significant uncertainties in the evolution of the engineering components. A simplified Compartment Flow Model has therefore been developed to carry out the large numbers of probabilistic cases required. The Compartment Flow Model allows the simulation of flows and water levels in hundreds of alternative realisations.

A reference case calculation case is defined, based on inventory Case A, the expected natural evolution scenario, and a near-field model in which radionuclides in saturated regions of the trenches and vaults are assumed to be immediately available for dissolution, except for C-14, which is given a more realistic treatment based on GRM results (termed near-field Model C). Risks are assessed for four biosphere paths: a water abstraction well between the disposal facility and the coast, and natural discharges to the marine environment, the estuary or a stream. Potentially exposed groups receive external exposure, inhale and ingest dust, and consume contaminated products consistent with the biosphere path, for example, drinking water, garden produce, marine foodstuffs, animal products etc.

In the reference case deterministic case, the highest peak risk is from the well pathway, with a peak annual risk of about 4 10^{-08} occurring around 2250 (that is, about 170 years after completion of the final cap); the key radionuclides are C-14 and Cl-36. Peak risks via other biosphere paths are typically an order of magnitude lower. For the delayed coastal erosion scenario, peak risks may increase somewhat and occur later and are contributed to by additional radionuclides, notably Pb-210 for the well and stream biosphere paths.

The probabilistic calculation, representing inventory Case A, the expected natural evolution scenario, and near-field Model C, showed a peak mean risk for the well biosphere path of about 4 10^{-07} at about 2220; that is, also about half an order of magnitude below the risk guidance level, dominated by the contributions from C-14 and Cl-36.

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

Gas pathway

The gases of key concern are:

- C-14 labelled methane and carbon dioxide, generated from C-14 bearing wastes in the presence of degrading organic wastes;
- Rn-222 (radon) generated from Ra-226-bearing wastes.

Carbon-14

The assessment of C-14 is based on a detailed biogeochemical model that is used to calculate the evolution of C-14 labelled gases from the trenches and vaults, and a model of entry of C-14 to biomass and human foodstuffs in the biosphere, and thence doses to humans. Processes of gas migration in the profiling and cap have been considered and modelled; although they provide some lateral spreading and mixing of fluxes, they do not provide any reliable attenuation of the total flux.

The biogeochemical model (GRM) models the repository on a 30 m x 30 m grid taking account of spatially-variable conditions of groundwater flows in the repository and flows between grid cells. The model represents a saturated environment, taking no credit for containment of wastes, only delaying the release of radionuclides into the near field according to a primary release rate from the wasteform. Different wasteforms and waste associations can be modelled but, in practice, information on the form of C-14 in LLW waste streams is lacking. Thus, in the reference case, credit for wasteform is only applied to graphite waste streams, with C-14 in all other waste streams being rapidly released into the biogeochemical model. The biogeochemical model calculates the chemical evolution of the environment including the degradation of cellulosics and other organic material and consequent partitioning of biogeochemically-available carbon between gas, groundwater, biomass and mineral phases. The partitioning of C-14 follows the partitioning of stable biogeochemically-available carbon (specific activity model). Thence, the model calculates fluxes of C-14 labelled gases from the repository as a function of time and space; this is CO_2 and CH_4 from the trenches and mainly CH_4 from the vaults.

The biosphere model takes fluxes of C-14, from individual GRM cells or from arrays of cells (for example, representing an individual vault), and assumes all such gas is metabolised to C-14 labelled carbon dioxide in the soil overlying the cap. It then represents the processes of mixing of C-14 labelled carbon dioxide in the plant canopy atmosphere and uptake into vegetation by photosynthesis. Different vegetation heights or crop types can be represented. Specific concentrations (Bq kg[C]$^{-1}$) of C-14 in plant foodstuffs or animal fodder and hence animal products, and dose via consumption of these products, are calculated. Doses are calculated for alternative PEGs defined on the basis of areas cultivated, crops grown and animals grazed. The reference PEG is a smallholder self-sufficient in vegetables and fruit grown on the cap, and with milk from goats grazed on the cap.

The C-14 inventory of the trenches is relatively low (total of 0.1 TBq), and in all cases C-14 releases from the trenches are such that the annual dose to a reference PEG on the cap above the trenches are lower than 20 µSv, which for an assumed annual probability of one corresponds to the risk guidance level of 10^{-6} y^{-1}.

Much larger C-14 inventories are found in future LLW streams that, according to our ESC inventory assumptions, are destined to be disposed mainly in Vaults 10 and 14 in the Reference Disposal Area (RDA) and Vaults 15 to 20 of the Extended Disposal Area (EDA). The total C-14 inventories are 5.5 TBq in the RDA (Vaults 8 to 14) and 18.9 TBq in the EDA (Vaults 15 to 20). Assessments are made for the RDA and for the EDA, assuming final vault closure engineering at 2080 and 2130, respectively. The GRM model begins simulation at these times, that is, no account is taken of degradation of organic wastes of loss of C-14 in groundwater or gas before that time.

For the RDA and reference model assumptions, annual doses are calculated of 680 µSv at 100 years after closure (2180) and 30 µSv at 300 years after closure (2380).

For the EDA and reference model assumptions, annual doses are calculated of 520 µSv at 100 years after closure (2230) and 1 µSv at 300 years after closure (2430).

These results indicate that the EDA vaults are assessed as performing substantially better that the RDA vaults. Expressed as Bq m^{-2} y^{-1} of C-14 in evolved gas per Bq m^{-2} of C-14 in the vault, the EDA performs better than the RDA by a factor of 10 at

100 years, 20 at 200 years and 100 at 300 years after engineering closure. This can be traced to the different amounts of organic wastes in the RDA and EDA vaults, and hence different biogeochemical evolutions.

Alternative GRM model cases have been run to understand sensitivities of the modelled system in general and, also, to investigate the effect if credit is taken for delayed primary release from C-14 bearing wasteforms. In particular, the greater part of the future inventory of C-14 bearing wastes is associated with reactor steels and slags from metal smelting. In the case of reactor steels, a significant part of the C-14 is expected to be within the metal and released at a rate controlled by corrosion; the disposition of C-14 with the slags is uncertain at present but is liable to offer some degree of retention.

The sensitivity calculations reveal that, although the cumulative amounts of C-14 released as gas change, the fluxes of C-14 released as gas at times of 100 years and later change rather less. The results and understanding of the GRM model lead to the conclusion that the reason for the difference in performance is mainly the higher levels of cellulosic and organic wastes in general in the RDA. This leads to biogeochemical conditions in which larger fractions of carbon are partitioning to the gas phase, and prolongs those conditions. Since, in GRM, no credit is given for packaging or separation of inorganic C-14 wastes (such as the steels, slags and graphite) from the reactive organic environment, taking account of primary release rate is insufficient to reduce calculated C-14 labelled gas fluxes.

We conclude that we will be able to demonstrate substantially improved performance of the RDA, if we can assure conditions around inorganic C-14 bearing wastes in the RDA that are similar to those seen by wastes in the EDA. We believe this is possible through:

- development of a physical and biogeochemical model at the single vault scale to address features and processes not included in the GRM model. This could include taking account of effects of packaging, spatial allocation of wastes and degree of saturation;
- using the model to investigate the effect of more robust packaging for C-14 bearing wastes, for example, grouted concrete boxes, or emplacement strategies or creation of subvaults;
- review of information on the disposition of C-14 in key waste forms, especially steels and slags, including its behaviour in the smelting process, to better determine primary release characteristics.

We believe that by these means we will be able to substantially improve our estimates of C-14 labelled gas release, and show with greater confidence that the assessed doses and risks are consistent with the risk guidance level.

Radon

Rn-222 (half-life 3.8 days) is produced from the decay of Ra-226, which is present mainly in thorium process wastes in the trenches and site remediation wastes in the vaults. Impacts from radon are only important if there is a relatively fast path for migration from the waste to a building on the cap in which radon and its progeny may accumulate.

Various cases and possibilities have been investigated but none result in the establishment of a sufficiently fast path for gas migration as a result of natural evolution. The only cases of concern are human intrusion events in which either Ra-bearing wastes are excavated, or a building or its services makes connection to the gas collection layer beneath the low permeability cap layers. These cases are considered under human intrusion.

Natural disruption and dispersion – coastal erosion

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

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

The calculated concentrations of radionuclides in different parts of the shore environment change with time as different parts of the LLWR, containing different wastes, are eroded. The calculated concentrations reproduce the dilution of waste with co-eroded materials and the foreshore/offshore sediment tidal mixing. Thus, for example, the radionuclide concentration in the foreshore sands is a factor of about 50 less than that at the cliffs. Assessed annual doses to potentially exposed groups (PEGs) take account of exposure to the different parts of the local coastal environment and more widely dispersed radionuclides. Locally, the dominant exposure pathway is external irradiation to wastes present on the beach and foreshore; along the coast, external exposure to more generally dispersed contamination and doses via marine foodstuffs are important.

Three reference PEGs are considered as being present at all times:

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

The reference case considers erosion of the vaults by undercutting, beginning at 1000 years after present, and passing through the facility on a front aligned parallel to the general alignment of the coast, and hence parallel to the line of the vaults and then each trench in turn.

The reference calculation case yields a peak annual dose of 19 µSv for the locally-based recreational exposure group, principally due to progeny from Th-232 in Trenches 4 and 5. The peak annual dose to this group from the vaults of 12 µSv occurs earlier and is mainly due to disposed Ra-226 and its progeny. The peak annual dose to the inshore fisherman PEG is 11 µSv, contributed to by radionuclides from both the trenches and the vaults. Calculations of potential dose from the ingestion of marine foods lead to an annual dose of 12 µSv, dominated by Pb-210 and Po-210 supported by disposed Ra-226 from the future vaults.

Annual doses to the locally-based recreational PEG show peaks as specific wastes are eroded. Doses to the occupational PEG show an increase with time and peak when erosion of the significant waste disposals are complete; this is due to the accumulation of activity in the coastal sediments. Doses to the marine foodstuff PEG show a composite pattern with some impact from radionuclide release from wastes as they are eroded and a decreasing tail due to desorption from coastal sediments.

Variant cases have investigated the impact of uncertainties related to: the timing of erosion, whether the vaults and trenches are eroded by undercutting or directly at sea level, the alignment of the erosion front, and alternative inventory cases. The implications of the specific waste form associations of key radionuclides and the extent of degradation of waste have also been investigated.

Times of onset of erosion of 300 and 3000 years after present have been investigated, which is considered an appropriate range for assessment. Under the case assumptions, the early onset of erosion implies a faster rate of erosion that is continued through the repository; similarly, a late onset of erosion implies a slower rate of erosion that is continued through the repository. The effect is that the same wastes and radionuclides are passed through the cliff, beach and foreshore more rapidly or slowly, but concentrations are the same except for the effect of radioactive decay. Thus, peak doses, to the local recreational group, which are dominated by Ra-226 from the vaults and Th-232 from the trenches, show a limited variation due to the decay of Ra-226. Peak doses to the coastal occupational group, reach a peak when all dose-contributing radionuclides have been eroded and distributed along the coast and thus show a similar limited variation due to decay of Ra-226. On the other hand, the dose to the marine foodstuff consuming group depend on the rate at which eroded radionuclides are entering marine water. Thus, the annual dose to this group increases to 47 µSv for the early erosion case and reduces to 3 µSv for the late erosion case.

The two oblique erosion cases are based on two alternative hypotheses for the direction and rate of erosion developed in [75]. Compared with the reference case, these show lower peak doses to local recreational group and similar peak doses to the coastal occupational group. These cases are possibly more realistic than the reference case, but the vault/trench parallel case is preferred as the reference case, because it enables us to separately resolve the impacts from the vaults and the trenches.

Direct erosion, which could occur if sea-level rise is more rapid (or erosion slower), provides lower dilution with natural materials as the cliff erodes. This only affects the peak doses to the local recreational group; the peak doses to the coastal occupational and marine foodstuff groups are unchanged.

The study of waste form associations shows the key radionuclides, Ra-226 and Th-232, are not associated with materials that would be differentiated from natural materials such as will be co-eroding from the cliff and form the beach and foreshore. Large items that are present in the LLWR, and might remain on the beach for longer periods of time, are generally surface-contaminated items. Surface corrosion before erosion, and wave and sand action after erosion from the cliff, are liable to have removed the major part of such contamination. Discrete items such as low-activity sources containers, and individual sources, have also been considered; the risk associated with finding such an item is shown to be very low [76].

Overall, we consider that the reference case (see above) is a reasonable central base for deterministic estimate of radiological impacts from coastal erosion and observe that it yields annual doses, and hence conditional risks, that are consistent with the risk guidance level. Cases can be identified, such as direct erosion and reduced degradation, that yield higher doses (by about a factor of two). Other cases can be identified, such as oblique erosion, which yield lower peak doses.

We do not feel able to define probability density functions for some of the key parameters, for example, related to sea-level rise, or rate and direction of coastal erosion, so that we do not consider that a probabilistic assessment of coastal erosion is supportable at this point. We observe, however, that the effect of any such simulation would be to yield a mean annual risk as a function of time that would lie below the highest peak conditional risks obtained from deterministic simulations. Hence, we consider the results from variant cases also indicate consistency with the risk guidance level.

Since the LLWR will be eroded and dispersed into the sea within a period of a few hundred to a few thousand years, it is relevant to ask what is the total impact of the erosion of the LLWR on the levels of radionuclides that are naturally present in the Irish Sea or in more local Cumbrian coastal waters. A comparison has been made that shows:

- The LLWR inventory would initially contribute about 20% to the naturally-occurring inventory of uranium, plus 6% and 3% of the naturally-occurring inventories of Ra-226 and Th-232, respectively, in sediments of the Cumbrian coastal waters.

- In the longer term, assuming the activity is dispersed by movement of resuspended sediments, the LLWR inventory would contribute about 2% to the naturally-occurring inventory of uranium, and a fraction of a percent to the naturally-occurring inventories of Ra-226 and Th-232 in sediments of the Eastern Irish Sea.

In both cases, these contributions will be added over a period of a few hundred to a thousand years. In this time, additional natural geological materials will be eroded into Cumbrian coastal waters and into the Irish Sea, with consequent burial of older sediments and dilution with freshly eroded material. The comparison is thus very cautious neglecting both losses by burial and losses from the Eastern Irish Sea area.

Human intrusion

The guidance in the GRA [23] requires that human intrusion into a near-surface disposal facility after the end of management control of the site is to be assessed on the basis that it occurs, and against a dose guidance level in the range of around 3 mSv y^{-1} for exposures continuing over a period of years to around 20 mSv y^{-1} for exposures that are only short term.

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

For events that may occur after the end of management control of the site, but before erosion of the site begins, exposure situations fall into two groups.

- For those involved in geotechnical investigations, calculated doses are typically less than 0.05 mSv, and even making pessimistic assumptions on location of intrusion not higher that 0.5 mSv; that is, a fraction of the 20 mSv dose guidance level that is applicable to these relatively short-term exposures.

- For those that occupy a house, or a dwelling and agricultural smallholding, based on land that has been contaminated by spoil from a prior excavation, calculated annual doses are in the range 0.5 to 4.0 mSv depending on the location over the vaults. Doses over most of the trench area are zero since the cap and profiling material is sufficiently thick to prevent any excavation penetrating to the waste. The doses are dominated by exposure to radon that may accumulate in a building due to Ra-226 in the contaminated spoil on which it is built. The potential for such doses depends on the interception of Ra-226-bearing wastes, which under our emplacement strategy will not be placed in upper stack positions in the vaults. With application of that strategy, calculated doses will be consistent with the 3 mSv y^{-1} dose guidance level that is applicable to exposures continuing over a period of years.

The cases assessed for the period during which the site is being eroded are that of an individual making frequent informal visits to inspect the waste cliff and the case of local contractors involved in a campaign of material recovery. At most times during the erosion of the facility, calculated doses are less than 0.7 mSv y^{-1}, whether to the individual inspecting the cliff or the contractor recovering materials. At the time when thorium mineral sands present in the trenches are being eroded, and assuming these bays are targeted, doses of up to about 2 mSv in a year may occur to a contractor attempting to recover material from those bays. All of the calculated doses are less than the applicable dose guidance level.

Criticality

We have undertaken a criticality assessment for the repository and concluded that the possibility of criticality is so remote that it can be discounted [77].

A6: Non-radiological impacts

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

We have made estimates of the non-radiological impacts to the environment in the PoA, and thereafter. During the PoA, the estimated non-radiological impacts are demonstrated to be low. After the PoA, some impacts are higher than relevant groundwater standards, but the level of protection is no different from that provided by a typical landfill.

This argument relates to GRA Requirement 10; further support to this argument is given in the '*Assessment of Non-radiological Impacts*' report [13]. The regulatory guidance notes that standards for the disposal of hazardous waste may not be suitable to apply to waste that presents both radiological and non-radiological hazards. It goes on to say that, '*Accordingly, these standards need not necessarily be applied, but a level of protection should be provided against the non-radiological hazards that is no less stringent than would be provided if the standards were applied.*' The argument in relation to this requirement is presented below. Of further relevance is the removal of the exemption under the Groundwater Regulations for discharges containing radioactive substances [78]. As a result, the LLWR must take '*all measures deemed necessary and reasonable to avoid the entry of hazardous substances to groundwater*' and non-hazardous substances should be present at concentrations below the relevant standards. However, it is noted that there is '*a practical limit to what can realistically be achieved ...', '... when considering what measures are 'reasonable', the radiation protection principle of optimisation should be observed'* and that *'... absolute and indefinite containment of pollutants within a disposal facility will not be achievable*' [79].

Design Aspects

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

- the waste in the vaults is contained in ISO containers, which will provide substantial containment during the PoA;
- given the persistence of the ISO containers, pumping of leachate will be highly effective in limiting releases to groundwater during the PoA;
- the low sidewalls in the future vaults [5] will make local discharge to the surface environment much less likely than would be the case with a landfill;
- wastes in the vaults are grouted to reduce voidage, promoting the stability of the cap;

- the period of active institutional control will be substantial, far longer than is planned for any landfill, allowing monitoring of the evolution of the engineered features.

For the trenches, post-emplacement engineering included the installation of an interim cap and a cut-off wall, which act to reduce the non-radiological impacts of the disposed inventory by limiting release of both gaseous and aqueous contaminants into the environment.

Assessment Approach

In assessing the impacts from non-radiological contaminants, we have drawn on data from the current monitoring programme [9] and on the results of assessment calculations.

We believe that it is appropriate to assess the potential non-radiological impacts arising from the LLWR in a manner that is consistent as possible with the approach that we have followed with respect to radiological impacts. Consideration has been given to the use of approaches involving LandSim [80], but these are considered inappropriate because:

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

We have assessed non-radiological impacts for the groundwater pathway using a systems assessment model developed using the program Gold*Sim* [13].

Concentrations of contaminants in groundwater have been calculated underneath the LLWR and between the LLWR and the coast (where groundwater might be exploited using a water abstraction well). Calculated concentrations have been compared with assessment standards, which are usually based on the more restrictive limit of the UK Drinking Water Standard or the Environmental Quality Standard for freshwater [9]. The use of such standards ensures the protection of people and the environment.

We have followed a more comprehensive approach to the assessment of non-radiological hazards than would be the case for a landfill. In particular, we consider what will happen to the facility after the end of management control and extend our assessment to long times in the future.

It is noted that a number of aspects of our assessment models are cautious. In particular, we have compared estimated leachate concentrations from our groundwater pathway assessment model with monitoring data for leachate. We have found that the assessment model for the PoA generally predicts higher contaminant concentrations than we currently measure in leachate.

Impacts during the PoA

Monitoring data for non-radiological contaminants in groundwater have been reviewed recently [81,82]. The levels of non-radiological contaminants leaving the LLWR at present are sufficiently low that their impact is indiscernible from background concentrations. Where concentrations exceed the relevant assessment standards, these substances are considered to be present in groundwater as a result of natural processes or agricultural activities up-stream of the site. Monitoring will continue during the PoA to provide reassurance that concentrations of non-radiological contaminants remain low.

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

Impacts after the Period of Authorisation

For the groundwater underneath the vaults and after the end of the PoA, predicted concentrations of chromium are approximately equal to, for lead about half an order of magnitude higher than, and for molybdenum and nickel up to about an order of magnitude higher than, the relevant assessment standard. For groundwater underneath the trenches and after the end of the PoA, predictions for chromium are approximately equal to, for lead, molybdenum and zinc about an order of magnitude higher than, and for nickel about two orders of magnitude higher than, the relevant assessment standard.

A simple assessment has been performed of potential non-radiological impacts arising from human intrusion. The same conceptual model has been used as for radiological impacts. An intrusion associated with a smallholding has been considered and it is assumed that the smallholder grows crops on land contaminated as a result of an intrusion associated with the smallholding. Concentrations of contaminants in soils were compared with Soil Guideline Values [13]. A number of contaminants were found to be present in excess of these values, in particular iron (a factor of about two above), chromium (about an order of magnitude above), lead (less than a factor of two above), molybdenum (about an order of magnitude above), nickel (a factor of about thirty above) and uranium (a factor of about five above). However, the model used was simple and assumed that metals would be released into the soil instantaneously, rather than remaining for a period within uncorroded metal. Leaching of contaminants from the soil has not been represented.

Concentrations of contaminants in beach sediments were calculated, subsequent to the occurrence of coastal erosion. These were compared with concentration measures based on acceptable intakes, and assuming inhalation of dust and inadvertent ingestion of sediment. It was found that concentrations of chromium (a few percent above) and copper (a factor of three above) were above the relevant concentration measures. At this stage, we have not assessed the potential impacts that might arise via marine pathways.

We considered the impacts that might arise from toxic or flammable gases and concluded that such impacts will be very low.

Assessment models suggest that a number of metals would be present in the environment, after the end of the PoA, at concentrations exceeding the standards that we have set out. The exceedances relate to substances present in steels, common alloys and copper, rather than to hazardous substances. We consider that the performance provided by the LLWR would be similar to that provided by any landfill after the end of the period of management and note that assessments are not required or conventionally undertaken for a landfill after this period. In terms of broad consistency with policy for the management of landfill wastes, we suggest that the proposed disposals of these materials to the LLWR are acceptable.

Waste Acceptance Aspects

In our judgment, there are a number of areas where disposals of chemotoxic substances should be limited. Further details and justification are provided in the '*Waste Acceptance*' report [15]. A brief summary is provided in the following paragraphs.

For specific contaminants identified:

- as hazardous under the Hazardous Waste regime;
- as hazardous pollutants in relation to the Environmental Permitting regime;
- as non-hazardous pollutants, but present in a soluble form.

we propose to undertake assessments to determine if substances can be disposed to the facility. Without such an assessment, such substances would not be disposed. In addition, and pending discussion of these issues with the Environment Agency, we propose to retain controls on lead.

There is a potential for asbestos to become exposed on the beach as a result of coastal erosion. Given the hazard with the potential exposure of asbestos on the beach, we consider it prudent to ensure that disposed asbestos is conditioned or treated in such a way that it presents an acceptable hazard when present on the beach. This is a more restrictive approach than required by the current WAC. Some asbestos has already been disposed to the facility; we consider that the analysis set out in argument '*O1: Remediation of past waste disposals*' applies.

A7: Impacts on non-human biota

We have made estimates of the radiation doses to the non-human biota in the vicinity of the LLWR at the present day and into the future. In almost all cases, the absorbed dose rates are below a cautious screening level of 10 $\mu Gy\ h^{-1}$ recommended by the Environment Agency, for which no significant radiological effects are expected in even of the most sensitive types of organisms present.

Absorbed dose rates related to groundwater are typically factors of 1000 lower than the screening level; those due to C-14 gas release over the cap can approach but remain below the screening level even at time shortly after vault closure. Absorbed dose rates above the screening level are calculated in the case of biota residing permanently and gaining all sustenance in the cliff and beach areas during erosion of the wastes, but the most irradiated organisms are relatively insensitive to radiation.

Furthermore, the cliff and beach are transient environments with continual turnover, migration and movement of organisms. Hence, there is no potential for significant harm to local populations.

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

Although there is no evidence that there might be a threat to populations of non-human species from the authorised release of radioactive substances if people are protected (see paragraph 6.3.72 in [23]), we must also protect biota in areas and habitats that are not extensively exploited by people, or where no people are present. Furthermore, it is necessary to demonstrate that non-human species are protected under legislation related to conservation, for example that derived from the EC Habitats Directive (EC 1992) [83]. Therefore, we have assessed the impacts of waste disposal at the LLWR on non-human biota that are present in the vicinity of the LLWR today, or that could be present in future.

We have carried out the assessment using the ERICA methodology and software Tool ERICA [84], which is a method supported and used by the Environment Agency.

The ERICA Tool considers reference organisms characterised by their dimensions, the concentrations of radionuclides that they exhibit relative to the environmental media in which they reside, and the fractions of the time that they are present within, or at the surface of, these media. The whole-body dose rate to each selected reference organism is calculated based on radionuclide concentrations in the environmental media in which they reside. These dose rates are compared to threshold dose rates below which no significant effects are observed in populations of the most sensitive types of organisms so exposed. The Environment Agency has advised that evaluation against a generic screening threshold of 10 $\mu Gy\ h^{-1}$ will generally be sufficient; this is more restrictive than the value of 40 $\mu Gy\ h^{-1}$ that has previously been used in the UK.

Only if dose rates exceed the screening threshold is a more detailed assessment required, which may draw on specific organism behaviour and conditions of exposure and evidence of radio-sensitivity for the organisms exposed.

As described in Subsection 2.3, the western boundary of the northern part of LLWR site is contiguous with the Drigg Coast SSSI, which is also designated a Special Area of Conservation (SAC), and to which we pay special attention in the present day [6]. For this area, detailed evaluations of the implications of observed radionuclide concentrations have been published in the literature, including an assessment using the ERICA Tool and a comparative assessment using ERICA and the other biota assessment models. All the model studies conclude that dose rates to non-human biota are generally less than 1 μGy h^{-1} and are very unlikely to exceed the screening threshold of 10 μGy h^{-1}.

To assess future impacts to non-human biota, we have estimated dose rates to reference organisms due to radionuclide concentrations as calculated by the same models as used to assess human exposures. We have considered the environmental concentrations thus arising as a result of releases via groundwater and gas pathways, and as will occur during erosion of the facility. We do not consider environmental contamination that may arise during and following human intrusion cases, because the contamination would be localised, and thus present little potential for ecological harm.

For the groundwater pathway, the highest dose rates are assessed for freshwater biota in the Drigg Stream. Even very cautiously calculated, the dose rates are more than three orders of magnitude below the screening dose rate of 10 μGy h^{-1}. For land irrigated by contaminated groundwater from a well, the maximum dose rate is also more than three orders of magnitude below the threshold dose rate.

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

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

Taking account of the habitats and organisms present, the highest dose rates are of the order of 80 μGy h^{-1} for molluscs and crustaceans inhabiting and gaining sustenance from the storm beach area. Doses to small mammals and birds using the cliff and beach area were first identified as a concern, but fall below the screening level when their habits and sources of sustenance are factored in. That is mammals and birds will spend time on, and gain their sustenance mainly from, the foreshore or inland heath. Invertebrates and insects permanently residing on the cliff and beach could receive absorbed dose up to about 100 μGy h^{-1}, but such organisms are relatively insensitive to radiation.

The cliff and beach are, furthermore, transient environments with continual turnover, migration and movement of organisms between the potentially contaminated area adjacent to the LLWR, other areas of beach and further afield. Thus, even if there is

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

potential for radiological detriment to individual organisms, there is no potential for significant harm to local populations, or at local colony levels.

A8: Waste Acceptance Criteria and radiological capacity

We have systematically derived WAC that will ensure that waste will only be accepted consistent with the assumptions and results of the ESC. We have also derived the radiological capacity of the repository and will ensure that this is not exceeded. The derived radiological criteria and capacity are consistent with the limits and guidance levels for dose and risk given in the GRA. Our WAC also take account of other waste characteristics, including their physical properties, ability to affect biogeochemistry, potential to create voidage as a result of degradation, and chemotoxic properties.

This argument relates to GRA Requirement 13; further support to this argument is given in the '*Waste Acceptance*' report [15].

Emphasis has been placed on developing an approach to waste acceptance in accordance with regulatory guidance and requirements. In deriving the approach, we have taken into account guidance and requirements specific to the LLWR provided by the Environment Agency in response to previous submissions, and best practice guidance based on international experience.

We have systematically reviewed the assumptions and results of the ESC to ensure that our new WAC and approach to capacity management are comprehensive and soundly based. Where possible, our WAC are quantitative. WAC for radionuclides are based on the application of the 'sum of fractions' approach, which is recognised as a safe way of dealing with contributions to radiological impact from potentially more than one radionuclide.

We have:

- considered whether any requirements need to be placed on the containers or wasteform (to ensure consistency with the ESC);
- placed limits on the quantities of biodegradable waste and inaccessible voidage in the waste (that cannot be accessed by grout) in order to limit subsidence;
- derived limits on the acceptance of complexing agents;
- calculated a radiological capacity for the repository, based on application of the sum of fractions methodology;
- derived additional consignment limits to control activity concentrations, which can be implemented through emplacement strategies;
- specified what spent sealed sources are appropriate for disposal;
- considered what limits are necessary on the acceptance of fissile materials;
- set out a framework for controlling the disposal of chemotoxic substances.

Procedures are already in place to ensure that consigned wastes are compliant with current WAC and our Permit and to identify and assess waste streams or consignments that may challenge our different safety cases or Permit conditions.

Verification procedures are in place to ensure the wastes received match their declared characteristics.

Subsequent to submission of the 2011 ESC, detailed finalisation of the new WAC will be undertaken. We will consult with our waste consignors and the Environment Agency as appropriate. We will review our waste acceptance arrangements and revise them as necessary to take account of the new WAC and approach to capacity management, as well as our implementation of waste emplacement strategies, described in argument '*O4: Waste emplacement strategies*'.

Our current Permit includes some limitations on what wastes we are allowed to dispose and includes annual limits on the amounts of some radionuclides that can be accepted for disposal. Our assessment suggests that the requirement in our Permit not to accept complexing agents can be relaxed for some agents. We are also proposing that the annual limits on radionuclides can be replaced by our new approach to capacity management. We will discuss our proposals with the Environment Agency. We will, however, continue to meet the requirements of our Permit until such time as it is varied or revised.

A9: Extended capacity

We have assessed the safety of disposal of additional LLW on the LLWR site beyond the disposal area and waste volume considered in our reference SDP and established that such additional disposals could be accomplished consistent with current regulatory guidance and within the radiological capacity of the site.

Allocation of this additional area to future disposals would, subject to the necessary planning consents and regulatory permissions, allow the LLWR to continue to serve as the primary disposal facility for UK LLW up until 2130.

Argument A9 relates to the same GRA Requirements as those listed above for assessment arguments A1 to A8; further support to this argument is given in the '*Assessment of an Extended Repository*' report [16].

A set of assessment calculations, very similar to those for the Reference Disposal Area (RDA), has been undertaken to assess the impact of additional disposals to vaults in an Extended Disposal Area (EDA). The purpose of the work was to provide an improved understanding of the capacity of the site as input to the NDA and LLW Repository Ltd in further developing plans for radioactive waste management in the UK.

The inventory of wastes considered included all LLW in the UKRWI [34] – inventory Case A (the reference case) – and also a case including LLW arising from new nuclear build – inventory Case B – representing wastes from eight new reactors. Based on the results for the RDA assessments, these two cases are sufficient to draw conclusions about the capacity of the site for waste management planning purposes. The additional wastes would require the construction of six extra vaults, which we designate Vaults 15 to 20. We describe this extended repository as the EDA repository. It comprises Trenches 1 to 7 and Vaults 8 to 20.

The assessment calculations demonstrate that the additional wastes can be safely disposed in the EDA. Estimated doses and risks are consistent with the relevant constraints and guidance levels.

Inventory

The composition of the waste that would be disposed in Vaults 15 to 20 will be different from that disposed in the RDA repository. This is because Vaults 15 to 20 would take most of the final stage decommissioning wastes from the existing reactors. These wastes will be dominated by concrete and metals, with substantially less organic materials than in the RDA repository. 79% of the total graphite inventory in the EDA repository will be in Vaults 15 to 20. The C-14 inventory of the EDA repository is 4.4 times that of the RDA repository; the Cl-36 inventory is 1.7 times that of the RDA repository. The difference between the EDA and RDA inventories of other radionuclides of potential importance to long-term safety is less than 10%. Thus, we have paid particular attention in the EDA assessment to the risks that arise from C-14 and Cl-36.

For inventory reference case, Case A, the additional vaults will need to accommodate an additional 573,000 m^3 of packaged waste. For inventory Case B, which accounts for new nuclear build, an additional 730,000 m^3 of packaged wastes must be accommodated.

Siting

As described in argument '*A1: Qualitative understanding and safety functions*', we have a detailed understanding of the evolution of the LLWR and its environment. Using this understanding, potential locations on the LLWR site for the additional disposal vaults to accommodate the above defined volumes of waste were considered. Two possible siting areas were identified: an area directly adjacent to the RDA area, and an area on the south-eastern portion of the LLWR site, south and east of the East-West and Drigg streams. The area adjacent to the existing trenches and Vault 14 was chosen as the preferred site for a number of reasons: including commonalities in structures with the RDA repository (such as drainage and final cap), waste capacity, local hydrogeological environment and cost [85].

Design

The engineering design principles, safety functions, design detail and component optimisations for additional vaults for the EDA repository (Vaults 15 to 20) are the same as those for the RDA vaults. The key functions of the engineered barrier systems are:

- to minimise water flow through the disposal system for as long as is practicable;
- to control gases and leachate that may be produced within the facility;
- to direct releases that may occur so as to minimise their impact.

Each of Vaults 15 to 20 would serve for around 10 years at typical waste consignment rates, allowing suitable time for engineering works for capping each previous vault and constructing the subsequent vault. The simplest practicable layout has been adopted to match the constraints of site topography, including the existing trenches and the Vaults 8 to 14. The RDA vault layouts are unaltered and the EDA cap profile is kept consistent with that of the RDA – mainly 1 in 25 and 1 in 10 at the edges. The different inventory cases could be accommodated by varying the stack heights under this profile.

Assessments

The assessment models developed to assess the potential exposure pathways (groundwater, gas, coastal erosion and human intrusion) for the RDA repository (see argument '*A2: Quantitative analysis and modelling*') were used in the assessment of the EDA. Assessment calculations were undertaken for the PoA (see argument '*A4: Radiation doses during the Period of Authorisation*') and for the longer term. The long-term impacts are calculated for radiological and non-radiological contaminants (see arguments '*A5: Radiation doses and risks in the long term*' and '*A6: Non-radiological impacts*'). An assessment of the impacts to non-human biota (see argument '*A7: Impacts on non-human biota*') was also carried out. As with the RDA assessments, the calculations take account of a range of uncertainties (see '*A3: Uncertainty management*'), although not as extensive as considered for the RDA.

Each of the four potential exposure pathways was assessed for the Expected Natural Evolution Scenario, in which the LLWR site is expected to be eroded within a few hundred to few thousand years (see argument '*S4: Characterising and understanding the coastal environment*'). We also carried out calculations based on the Delayed Coastal Erosion Scenario. This is an unlikely scenario, but enables us to assess the performance of the repository over longer timescales. Assessment calculations were performed for inventory Cases A and B. The implications of the extra inventory and disposal vaults on the waste acceptance criteria (WAC) and proposed emplacement strategies were also considered.

Period of Authorisation

This argument relates to GRA Requirement 5 and argument '*A4: Radiation doses during the Period of Authorisation*'.

The PoA refers to the time period during which an Authorisation (now Permit) is held by LLWR. This includes the present-day operations, the future disposals, the period in which the final closure engineering is built and the phase of reassurance monitoring and active leachate management.

We have assessed the impacts to members of the public for several exposure pathways: direct radiation, discharges to air and surface water, and releases to groundwater. The assessment used a combination of environmental monitoring data, modelling and scaling of results. We conclude that peak annual doses for the EDA repository are not significantly different from those of the RDA repository. In particular, the peak combined annual dose to a critical group living to the east of the site remains at around 100 µSv. The doses from the EDA repository are therefore below the source-related dose constraint of 0.3 mSv per year [86].

Long-term risks

This argument relates to GRA Requirement 5 and Requirement 6 and Argument *A5: Radiation doses and risks in the long term*.

Groundwater pathway

The assessment model used information from the 2010 Hydrogeological Model (see argument '*S3: Characterising and understanding the geology and hydrogeology*') to model the transport of radionuclides in the groundwater. Deterministic calculation cases were based on two environmental evolution scenarios, two inventory cases and two near-field models, as discussed above (see argument '*A5: Radiation doses *and risks in the long term*' for more details). A probabilistic calculation case was undertaken using elicited distributions for key parameters. Risks were calculated for four biosphere paths, considering releases to a well between the disposal facility and the coast, the marine environment, the estuary and a local stream.

The assessed risk for all biosphere pathways for the EDA repository are below the risk guidance level of 10^{-6} yr^{-1}. For the Well pathway, results from the EDA and RDA assessments are broadly similar. Risks for the Marine, Estuary and Stream pathways are about one to two orders of magnitude higher for the EDA repository than for the RDA repository. The greatest increase is for the Stream pathway modelled using the Expected Natural Evolution Scenario (a factor of approximately 180). The increase is due to the modelled overtopping of Vaults 18, 19 and 20, causing radionuclides to be transported to the Drigg Stream towards the end of the simulation.

Gas pathway

C-14 labelled gases – methane (CH_4) and carbon dioxide (CO_2) – and Rn-222 were considered.

The assessment of C-14 labelled gases showed that Vaults 15 to 20 perform significantly better than Vaults 8 to 14 in an EDA repository. This is because of the lower amounts of organic waste present and, hence, lower gas production. Doses to the reference PEG from Vaults 15 to 20 are cautiously calculated to be 520 µSv at 2230AD (100 years after closure of the final vault) and 1 µSv at 2430 (300 years after closure). Corresponding annual doses for Vaults 8 to 14 are calculated to be 1,020 µSv at 2230 and 24 µSv at 2430. For comparison, the corresponding annual doses from Vaults 8 to 14 in the RDA repository are calculated to be 680 µSv at 100 years after closure (2180AD) and 30 µSv at 300 years after closure.

The change in impact from the RDA vaults when the EDA vaults are also considered is related to changes in groundwater flows through the repository.

Impacts from radon are only important if the gas can reach the surface in a relatively short time. Therefore, whilst the cap is intact the impacts from Rn-222 are negligible.

Coastal erosion

The LLWR is expected to be eroded on a time scales of a few hundreds to a few thousands of years, resulting in the exposure of wastes in the cliff, on the beach and dispersal in the marine environment (see argument '*S4: Characterising and understanding the coastal environment*'). Exposes may occur by a variety of pathways; most important are external irradiation from wastes in the cliff and on the beach and foreshore, and internal irradiation via the consumption of marine foodstuffs. Three potentially exposed groups were defined with the same characteristics as assumed for the RDA assessment; a recreational user of the local beach, an occupational user of the coast and high-rate consumer of local marine foodstuffs.

The highest calculated peak annual dose is 18 µSv, to the local recreational beach user. This arises principally from disposals of Th-232 in Trenches 4 and 5. The key radionuclides that dominate for coastal erosion are Th-232 and Ra-226 (see Table 4.2). The inventories of these radionuclides in the EDA vaults are very low, such that exposure is dominated by the impact from the RDA and the peak doses for the EDA and RDA repositories are almost[7] the same [87].

Human intrusion

The assessment of human intrusion considered the same intrusion events that were considered for the assessment of the RDA. The events fall into two categories: those that could occur any time after the end of the PoA (such as site investigations or occupancy following such events), and those that can only occur after wastes are exposed by coastal erosion (such as scavenging and material recovery).

For the additional vaults (Vaults 15 to 20) of the EDA repository, all doses for short-term intrusion events are substantially below the dose guidance level of 20 mSv/year. For longer-term exposures, the highest calculated dose rate is 5.4 mSv/y to a smallholder growing crops on land contaminated by an intrusion into the part of Vaults 15 to 20 having the highest C-14 activity. This calculation is cautious, however, as it neglects losses of C-14 and Cl-36 from the waste before excavation and from the contaminated land it is excavated onto.

Non-radiological impacts

This argument relates to GRA Requirement 10 and also argument '*A6: Non-radiological impacts*'. The assessment of non-radiological hazards is consistent with the approach that we have followed with respect to assessing radiological impacts. Risks resulting from non-radiological hazards are calculated for three pathways: groundwater, coastal erosion and human intrusion. In all cases, and for both the PoA and the long term, the impact of the additional vaults (Vaults 15 to 20) is small compared with impacts from the RDA repository.

Impacts on non-human biota

This argument relates to GRA Requirement 9 and also argument '*A7: Impacts on non-human biota*'.

Our environmental monitoring programme demonstrates that present-day dose rates to non-human biota in the vicinity of the LLWR are generally less than 1 μGy h^{-1} and are very unlikely to exceed the screening threshold of 10 μGy h^{-1}. For the time after the PoA, total dose rates to non-human biota from the EDA repository are below the screening threshold of 10 μGy h^{-1} for most pathways situations. The exception is that, following coastal erosion, invertebrates and insects dwelling in the eroding cliff or beach could receive dose rates up to about 20 μGy h^{-1}. The evidence is that such organisms are relatively insensitive to radiation. The maximum dose rates for the EDA case are only slightly higher than that for the RDA case.

Radiological capacity and waste acceptance

This argument relates to GRA Requirement 13 and argument '*A8: Waste Acceptance Criteria and radiological capacity*'.

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[77] There is a small difference between annual doses for the local recreational beach user for the RDA and EDA assessment (19 μSv and 18 μSv respectively). This is due to a model change made to accommodate the different geometries and varying frontage of the eroding repositories between the two cases.

We are confident that the EDA repository can safely accept the identified LLW within the UKRWI. This is demonstrated by the estimated doses and risks, which are consistent with the relevant constraints and guidance levels.

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5 Future Programme

In this section, we provide an overview of a planned future programme of work that will be undertaken to ensure effective maintenance and application of the ESC and to further reduce uncertainties. This programme is preliminary in that we will not make final decisions on its longer-term aspects until we have seen the outcome of the Environment Agency's review of our ESC and taken appropriate account of requirements in any revised or new Permit. We will also take note of the final report on the 2011 ESC by our independent Peer Review Group (PRG) (see argument '*M5: Peer review*' in Subsection 4.2). The programme will be adapted to take account of new evidence arising or external factors, such as changes in LLW management in the UK.

Implementation of the ESC

A number of activities are required in order to implement the ESC that we have submitted. Of course, such implementation will initially be governed by the conditions in the LLWR's current Permit and subsequently by the conditions in any revised or new Permit. In other words, we will implement the conclusions of the ESC where these do not conflict with the requirements in our current Permit. Such conclusions cover the areas of:

- WAC;
- waste emplacement strategies;
- capacity management.

From the WAC set out in our ESC, we will need to derive a set of 'Customer WAC' that will be provided to customers and which will guide their decisions and applications for disposal, helping to ensure best practice. We will consult with our consignors before the revised WAC are adopted. Current processes will need to be amended to implement our revised WAC.

A number of waste streams will arise that may not be acceptable for disposal. We will ensure the involvement of staff with appropriate understanding of the ESC in assessing such waste streams.

New management processes will also be required to manage the acceptance of wastes against the radiological capacity of the site. Initially, at least, the new approach to capacity management will need to operate in parallel with the meeting of the annual limits on the acceptance of particular radionuclides required by our current Permit.

The ESC sets out emplacement strategies for certain categories of waste, including for those containing relatively large amounts of Ra-226 or cellulosic materials. New processes are required to manage these emplacement strategies and will be put in place.

We will undertake an annual review of waste acceptance to:

- ensure that the types and quantities of wastes that we are accepting are consistent with the overall assumptions of the ESC;

- understand the fraction of the total capacity that has been utilised.

We envisage that these activities will take place within about twelve months of the submission of our ESC. Further, we envisage that there will be dialogue with the Environment Agency about any future changes to the WAC, following issue of any new Permit, and how and when they might be implemented. This would lead to a further phase of implementation.

Maintenance of the ESC

It is necessary to ensure that the ESC is maintained so that it continues to be an applicable tool for making decisions about the regulation, management and development of the site.

A suitably qualified and experience team will be retained to maintain the ESC. Ongoing maintenance of the ESC will itself help ensure that appropriate expertise is maintained and developed amongst the responsible staff.

A formal change control process will be implemented in order to manage the maintenance, under our overall process for managing change control of safety cases.

Maintenance of the ESC will involve updating assessment models to take account of significant changes in:

– the actual or projected disposal inventory;

– the approach to waste disposal, for example, waste packaging;

– the engineering design;

– the understanding of the site.

We envisage a review process where changes to the system are reviewed and a decision is made as to whether a revised assessment model is required. For changes to the waste inventory, approach to disposal or design, there is likely to be an iterative approach in which major proposed changes are assessed before implementation (see below in this section under '*Decision making and optimisation*').

Major updates to the ESC will also be produced in accordance with dates specified by the Environment Agency (as required by our Permit) and possibly as required by any major changes in radioactive waste management at the national level. The next appropriate date may be before the construction of the next vault (expected to be about ten years from now), to inform the planning permission process.

Decision making and optimisation

The ESC will be a tool for future decision-making concerning the repository operation and design and the acceptance of wastes. Use of a maintained ESC will continue to ensure that the SDP evolves taking account of environmental performance, and that the Plan continues to be optimised.

The ESC will be of key use in assessing:

- any implications arising from changes to the characteristics of the wastes disposed, noting that those wastes must be consistent with the requirements set out in any Permit;

- any proposed changes to the treatment of the wastes;
- any proposed disposals that may not be consistent with the WAC;
- any proposed operational or design changes.

Any changes or proposals of this nature will be assessed at an appropriate level of detail, under our change control process.

The 2011 ESC has assumed the use of containers similar to the half-height ISO containers that have been used in Vault 8 since 1988. An optimisation study is underway to develop a new waste disposal container. The design of the new waste container will be optimised having taken account of environmental considerations on the basis of the ESC. The final proposed design will also be assessed against the requirements of the ESC, using LLWR's change control process.

We are continuing to evaluate the performance of the interim cap over the trenches and are expecting sufficient data to be available in 2012 to support an optimisation study to consider the best strategy for managing the interim cap, prior the installation of the final cap.

We will consider further the role and design of the gas vent in the cap, and whether it should be left open or closed before the end of active institutional control.

In addition, the ESC could be used as an input to optimisation studies at the national level, for example, in relation to the management of graphite, LLW destined for disposal to the Geological Disposal Facility and orphan wastes.

Inventory

We had to use the 2007 UKRWI [34] as an input to the ESC because the 2010 inventory only became available in late March 2011, just prior to the submission of the ESC. Following submission of the ESC, we will initiate a review to consider the implications of the updated inventory for our ESC and provide these to the Environment Agency.

Overall, we consider that further work is unlikely to significantly reduce uncertainties in the inventory of wastes disposed to the trenches, noting that we have developed a good understanding of the key disposals and radionuclides. There are uncertainties in the future LLWR disposal inventory, including:

- accuracy of volume estimates for individual streams;
- information on non-radiological materials present in the wastes;
- management decisions affecting the treatment and timing, for example, in relation to final stage reactor decommissioning wastes;
- uncertainties associated with C-14 and Cl-36 activation and the extent to which the inventory of Cl-36 in core graphite might have entered LLW streams.

Currently, there are efforts to reduce uncertainties in future wastes through the NDA's National Waste Programme, but this is focused on physical volumes and bulk material properties, rather than radiological and non-radiological aspects. We consider that it would be beneficial to engage with the NDA and waste producers and other users of data to focus efforts on collecting the data of most importance to users including ourselves, leading to the development of a suitably enhanced UKRWI [34].

We intend to develop a tool for analysing potential changes to our inventory, in order to facilitate assessments of new waste management proposals. This development will build on the experience of developing the PIER (Projected Inventory Evaluation Routine) tool [88] for the 2011 ESC.

Near field

Our priority concerning the near field will be to address technical issues that have a direct bearing on waste acceptance.

The behaviour of C-14 including its release from different wasteforms is of key importance in determining the flux of C-14 labelled gas from the facility. A better understanding of the release characteristics would increase confidence in our waste acceptance criteria and might enable some relaxation of the criteria to be proposed. Further work might involve:

- a review of the available literature;
- focused experiments on particular types of waste, such as different types of cellulose;
- carefully designed long-term experiments;
- improved, possibly simpler, modelling of gas generation and other near-filed processes.

This activity would also address general uncertainties in the degradation behaviour of different types of cellulose, which affect our estimates of waste subsidence.

There are a range of other near-field uncertainties that are important, including those related to the release of contaminants (key radionuclides and non-radiological contaminants) from different waste types and the model of the unsaturated zone behaviour used in the assessments. These may be amenable to study through carefully designed experiments.

There will be opportunities to improve our understanding of the evolution of the properties of the engineered barriers, for example, through monitoring the performance of the existing COW and the final cap and extended COW once they start to be constructed; and possibly from experience in other countries.

Our first step will be to commission a review task to establish the best way of reducing these key near-field uncertainties.

Geology and hydrogeology

There are some analyses that would usefully be performed in relation to currently available data, including further consideration of the elevated groundwater levels immediately to the west of the site [7], to analyse the implications of new geological data on the location of discharges; and an analysis of the head data collected in order to monitor the effects of the construction of Vault 9.

Additional further work will largely result from changes at the site. These might arise from needs to:

- analyse the consequences or behaviour of new engineered features;
- analyse new data, for example on water balance for the trenches;
- address any issues identified by the monitoring programme.

We have been considering the utility of long-term tracer tests to build confidence in our understanding of contaminant transport (see reference [89]). Such tests would need to be extensive and sophisticated, to take account of the effects of spatial variability. We will review the potential and value of such experiments, following delivery of the ESC.

Coastal processes

Our objective with coastal processes is to continue to monitor the coastline in order to confirm our understanding of the evolution of the coast and mechanisms involved. A watching brief will be maintained on developments in the science and predictions of climate change and coastal erosion. If there were significant developments in forward projections of climate change and sea-level rise, or in modelling capabilities in relation to coastal erosion, then we would consider the merits of developing further site-specific and physically-based models and consider any assessment implications.

Our assessments of radiological impact arising from coastal erosion depend on the way in which wastes degrade on the beach, the leaching of contaminants from those wastes and the behaviour of wastes and sediments dispersed in the near shore environment and along the coast. There is scope for a more realistic treatment in our models of the processes of contaminant release, local sedimentary processes and uptake by marine biota that could be applied to the impacts of both radionuclides and non-radiological contaminants. We will consider developing these aspects of our ESC.

Monitoring

We need to keep our programme of monitoring under review [9]. We intend to undertake an annual review of our approach, based on the outcome of the programme for the previous year and planned developments. It is appropriate to make this review particularly broad in the current year, in order to consider all of the findings and implications of the ESC. As a result of these reviews, the programme will be adjusted as necessary to take account of new monitoring data and other information. There will be particular needs associated with the construction of new engineered features, such as the future vaults and final cap.

Assessments

We intend to review our biosphere model of the impact of C-14. With the exceptions of this aspect and those identified above, we do not consider that further enhancements to the assessment methodology are required at present. Rather, the focus should be on using the ESC and the supporting assessment models as a management tool (see '*Decision Making and Optimisation*' above). Consideration will be given to adapting, and possibly simplifying, assessment models, for use in assessing wastes for acceptance and management and operational changes. We will, however, continue our active involvement in international projects, such as

BIOPROTA [90] and the IAEA's PRISM [91], and will take account of new information as it becomes available. The outcomes of comparisons of different biosphere models of the impact of C-14 in the BIOPROTA project are likely to be of particular interest.

Programme and review

We will develop a more detailed programme based on the views set out above and discuss it with the Environment Agency after submission of the ESC. The views set out above are based on our current understanding. As noted at the beginning of this section, we will update our programme as necessary, taking account of any comments received from the Agency on the ESC and any conditions or requirements set out in any future Permit, and the views of our independent PRG. We will also, in any case, review the status of the ESC and any required work on a yearly basis. It is important that the ESC is updated in a timely way in response to changes in requirements or to the repository system.

6 Progress in Developing the ESC

The previous environmental safety case for the LLWR was submitted by the previous operator in September 2002 in two parts: an '*Operational Environmental Safety Case*' [19] and a '*Post-closure Safety Case*' (PCSC) [20]. The Environment Agency undertook a thorough review of these cases [21], which, together with input from public consultation, informed its '*Decision Document*' for future regulation of the LLWR [22] and Authorisation for the site [92], both issued in 2006.

We have studied the Environment Agency's review and addressed the review comments in our work programme since 2006. Below are noted the key deficiencies identified by the Environment Agency's review. These are recorded in the '*Explanatory Document*' produced to assist the public consultation [93], as follows (the numbers refer to paragraphs in the document).

> '*8.2 We have concluded that all the time the repository site is being managed in compliance with our regulatory controls, the impact from all the disposals on the LLWR will be very low.*
>
> *8.3 We also consider that the 2002 PCRSA*[8] *provides a more thorough evaluation of the potential future impacts of the LLW repository than previous post-closure assessments. We believe that the assessment provides a broad indication of the impact of the repository. However, we have concluded that the 2002 safety cases fail to make a robust argument for continued disposals of LLW because:*
>
> *(i) Estimates of doses and risks from existing disposals to members of the public in the future significantly exceed current regulatory targets;*
>
> *(ii) The assessment predicts that the repository could be destroyed by coastal erosion in 500 to 5,000 years;*
>
> *(iii) The 2002 safety cases include insufficient consideration of optimisation and risk management, to demonstrate that impacts will be as low as reasonably achievable (ALARA).*
>
> *8.4 We recognise that it would be unreasonable to expect historical practices to fully comply with present day guidance and modern standards, but there may be reasonable options to optimise the performance of the site as a whole and BNGSL*[9] *needs to demonstrate it has considered, and implemented them where appropriate.*
>
> *8.5 BNGSL should focus further work to improve the safety cases on a thorough evaluation of a range of realistic risk management options. BNGSL should ensure an appropriate level of regulatory and stakeholder involvement in its options appraisal.*'

We have also considered feedback from the Environment Agency [94,95,96,97,98] on our interim submission to the Environment Agency in 2008 [29,30,31,32,33], made in response to Requirement 2 in Schedule 9 of our Permit.

[8] Post-closure Radiological Safety Assessment, a key element of the PCSC.
[9] British Nuclear Group Sellafield Ltd, then operator of the LLWR.

In the rest of this section, we summarise the improvements that have been made since the 2002 Safety Cases.

Estimates of doses and risks exceeding regulatory targets

Key examples of where the doses and risks presented in the 2002 PCSC exceeded regulatory targets included:

- to occupational groups using the Drigg shore in the period during which the repository was assumed to be eroding, and
- due to concentrations of radon gas in dwellings constructed on excavated wastes from the facility (human intrusion case).

We undertook a review of the 2002 PCSC calculations and results and identified several overly cautious or inappropriate assumptions, modelling approaches and uses of data. In preliminary assessments [33] in support of our submission to the Environment Agency to meet Requirement 2 of Schedule 9, we went some way towards improving models and correcting unreasonably cautious assumptions, and indicated that lower impacts were more likely, although these assessments lacked a comprehensive examination of uncertainties. In this work, we also considered the radiological impacts that would arise to users of a water abstraction well located between the facility and the coast. Conditional risks associated with such a well were found to exceed the risk guidance level, although the assessment identified a number of cautious aspects of the calculation. As a consequence, further analysis has been undertaken for the ESC.

The post-closure assessments carried out in support of the 2011 ESC build on the 2008 preliminary assessments and incorporate substantial improvements, compared with the 2002 PCSC and the 2008 assessments, in the underlying technical basis and in our approach to estimating radiological impacts. These include:

- Since 2002, we have substantially improved our understanding of the inventory of disposed materials and radionuclides [4], drawing on:
    - an improved understanding of the inventory in the trenches and its distribution, based on an analysis of disposal records for key disposals and the use of ‘fingerprints’ for analogous waste streams;
    - detailed review of our understanding of the inventories of key radionuclides, such as C-14 and Cl-36;
    - review of disposal practices during the early phases of disposal, to confirm that no significant unexpected or unrecorded disposals are likely to have occurred;
    - consideration of the implications different waste management practices might have for the disposed inventory as the UK Strategy for LLW management is implemented;
    - use of the new 2007 UKRWI [34] and Issue 3 of WIDRAM [47], as the latest available data at the time of data freeze for the assessments.
- A programme of work has been undertaken on the evolution of the near field [6], including:

- an improved model of contaminant transport and chemical reaction in the near field has been developed using the program GRM and applied to understanding the evolution of chemical conditions and radionuclide releases to the groundwater;
- the GRM model has been used to provide estimates of the generation rates of bulk and C-14 labelled gases and to calculate the partitioning of C-14 between, gas, groundwater and carbonate solids;
- the evolution of the engineered barriers has been considered and uncertainties evaluated, based on process understanding and a series of facilitated expert elicitation meetings.

- Substantial improvements and improved confidence have been achieved in our understanding of the site hydrogeology [7], based on:
  - acquisition of additional site data, including the drilling of a set of boreholes between the LLWR and the coast;
  - the development and revision of a lithofacies model of the geology, which was used as a basis for the definition of hydrogeological units;
  - the development of a 3-D groundwater flow model that is calibrated against observed heads and provides a detailed representation of the engineered features;
  - development of a conceptual model for water flow and contaminant transport in unsaturated waste, which was used as a basis for a simple assessment representation.

We have also made a number of significant improvements in terms of calculations of radiological and non-radiological impacts, including:

- An improved model for representing a well has been developed, which takes account of the probability of occurrence, as required to estimate radiological risk.

- There is an improved understanding of coastal processes, allowing a physically-based model of radiological impacts during coastal erosion of the site to be developed. This model incorporates more appropriate assumptions on beach and foreshore occupancy and use than previous models.

- A detailed analysis of the relation between radon in dwellings and radium and radon activity in the underlying ground has been performed, which has led to an empirically-based model for the assessment of radon in dwellings. This model is considered to be more reliable than previous physically-based models that incorporated some poorly known parameters.

- A much more comprehensive assessment of non-radiological impacts has been undertaken.

Taking account of these and other improvements, and also having carried out a fuller investigation of uncertainties, we consider that the results from our current assessments are substantially more reliable and realistic than previous assessments of the LLWR. Importantly, the dose and risk estimates are consistent with regulatory guidance levels.

Predicted destruction of the repository by coastal erosion

Over the last decade, a substantial programme of scientific research and monitoring has been carried out to characterise the West Cumbrian coastal system and to provide a basis for forecasting its future evolution [8]. Based on qualitative evidence and quantitative modelling studies, and taking account of an envelope of projected forecasts for long-term sea-level rise resulting from global warming, we conclude that the site will be eroded on a timescale of a few hundred to a few thousand years, with consequent disruption of the repository.

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

Insufficient consideration of optimisation and risk management

We have addressed optimisation as a major component of our ESC.

Options assessments have been undertaken in four main areas:

- Management controls and interventions relating to the disposed inventory from past operations of the LLWR. We have considered a wide variety of actions that have the potential to achieve significant reduction in the environmental impact associated with past disposals to the LLWR. These options have been assessed from the perspective of the potential reductions in dose and risk that they may be capable of delivering, set against the wider implications that would be associated with their implementation. Consideration has included estimation of potential doses, from human intrusion and consequent on coastal erosion, that could be averted by selective waste retrieval. Significant effort has been expended in understanding the work that would be required to undertake partial retrieval or other remediation measures.

- Management and engineering controls over future waste disposals to the LLWR, including acceptance criteria, treatment and packaging, and methods for waste emplacement.

- Passive engineering controls over the environmental safety performance of the LLWR during the PoA and beyond, taking account of the functional role of engineering features in overall safety strategy, as well as their design and timing of implementation. We have reviewed the basis on which the design for Vault 9 was originally determined, noting that it was specifically intended to underpin the provision of temporary storage. With the perspective of the current ESC firmly on the role of the LLWR as a disposal facility, we have examined a range of aspects of the pre- and post-closure engineering design that will be employed in future development of the site.

- Active management controls over environmental safety performance, including implications for discharges during the PoA and for post-closure management control over the LLWR site.

Summary

The 2011 ESC rectifies the deficiencies of the 2002 safety cases identified by the Environment Agency. Our estimates of doses and risks are now consistent with regulatory guidance and ALARA, we have assessed the impact from coastal erosion and shown it to be consistent with regulatory guidance, and we have given a sufficient consideration of optimisation and risk management.

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7 Addressing the Regulatory Guidance

The Environment Agency's Guidance on Requirements for Authorisation for near-surface disposal facilities – the GRA – sets out a fundamental protection objective (see Subsection 3.1), five Principles for solid radioactive waste disposal and fourteen Requirements – see Figure 7.1.

Our ESC must demonstrate compliance with all the relevant Requirements of the GRA and show consistency with the supporting guidance therein. We do not have to separately show adherence to the five Principles, although we observe that all the Principles set out in the GRA have, effectively, been incorporated in our Environmental Safety Strategy (ESS), as discussed in Subsection 3.2.

As noted in Subsection 1.2, we have decided to develop and present our ESC according to our approach to arriving at our proposal for safe, optimised development of the LLWR. We then show that the arguments and evidence we have advanced satisfy the requirements of the GRA. To this end, Table 7.1 lists the GRA Requirements and shows how our safety case arguments, as set out in Section 4, correspond to each of the Requirements. There is not a one-to-one correspondence, rather, many of our safety case arguments are building blocks that underpin our claim to have met a given Requirement.

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

A more detailed analysis covering the fourteen Requirements, and the much larger number of guidance paragraphs of the GRA that can be interpreted as essential conditions, is set out in the '*Addressing the GRA*' report [17]. That report systematically sets out our high-level response to each of the guidance paragraphs and identifies where in the ESC documentation more detail can be found to show how the guidance has been interpreted and addressed in our ESC.

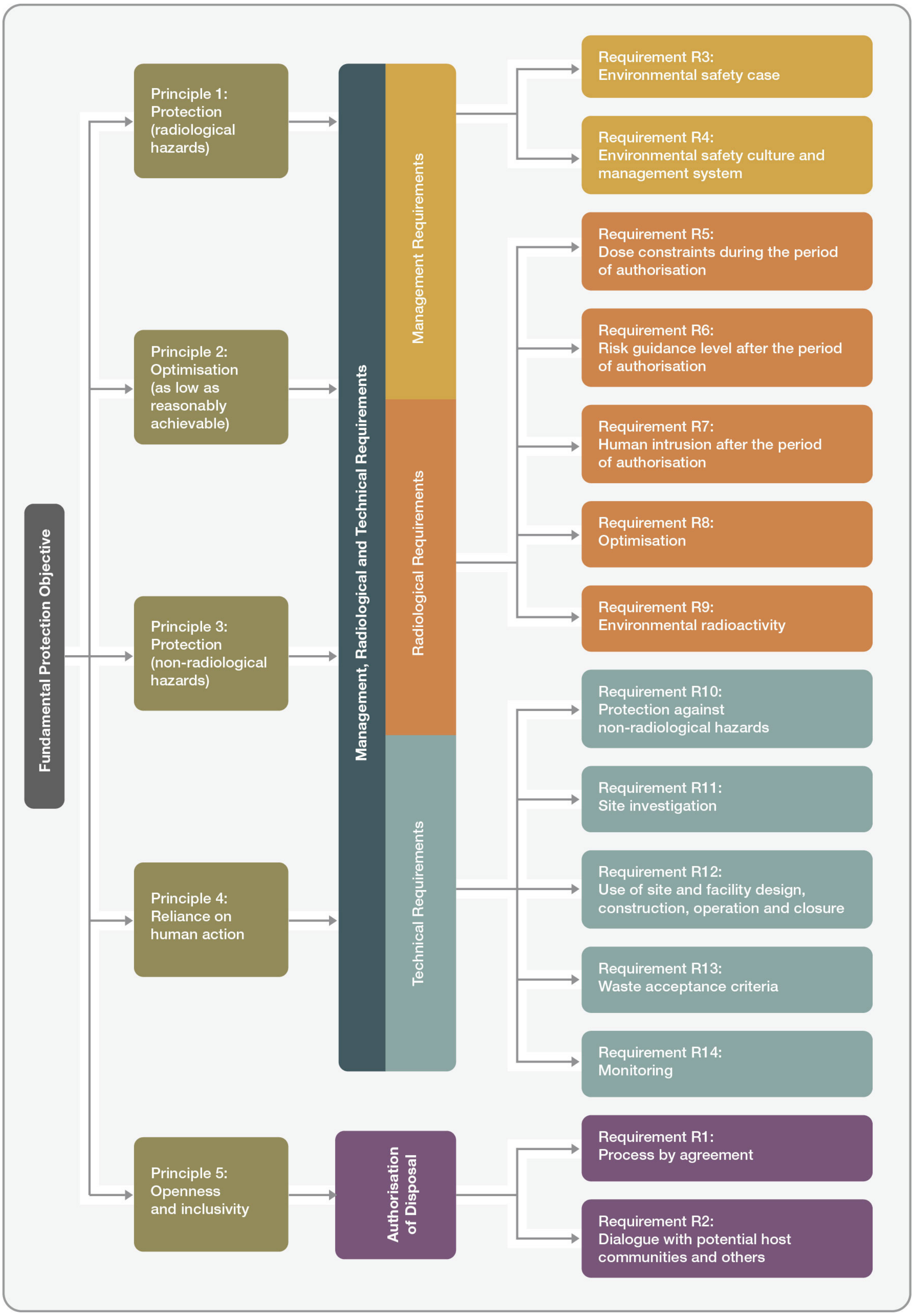

Figure 7.1 Relationship between principles and requirements in the GRA [23]

Table 7.1 The GRA Requirements and corresponding ESC arguments

GRA Requirement	Main related safety case arguments (and comments)
R1: Process by agreement	This requirement is mainly directed at the early stage of repository development, whereas the LLWR is an operating facility. It is mostly not directly applicable to our ESC. Relevant points are developed under '*M3*'.
R2: Dialogue with local communities and others	'*M3: Dialogue with our environmental regulator*' '*M4: Dialogue with our stakeholders*'
R3: Environmental safety case	All our safety arguments contribute to satisfying R3. This document and the Level 2 reports constitute the LLWR's ESC.
R4: Environmental safety culture and management system	'*M1: Management system and safety culture*' '*M2: Organisation of the ESC Project*' '*M3: Dialogue with our environmental regulator*' '*M4: Dialogue with our stakeholders*' '*M5: Peer review*'
R5: Dose constraints during the period of authorisation	'*A4: Radiation doses during the Period of Authorisation*' '*A9: Extended capacity*' (Underpinned by '*S1*', '*S2*', '*S3*', '*S4*', '*S5*', '*S6*', '*O5*', '*A1*', '*A2*', '*A3*')
R6: Risk guidance level after the period of authorisation	'*A5: Radiation doses and risks in the long term*' '*A9: Extended capacity*' (Underpinned by '*S1*', '*S2*', '*S3*', '*S4*', '*S5*', '*A1*', '*A2*', '*A3*')
R7: Human intrusion after the period of authorisation	'*A5: Radiation doses and risks in the long term*' '*A9: Extended capacity*' (Underpinned by '*S1*', '*S2*', '*S3*', '*S4*', '*S5*', '*A1*', '*A2*', '*A3*')

GRA Requirement	Main related safety case arguments (and comments)
R8: Optimisation	'*O1: Remediation of past waste disposals*' '*O2: Optimisation of future waste disposals*' '*O3: Site engineering*' '*O4: Waste emplacement strategies*' '*O5: Management of run-off and leachate*' '*O5: Management during closure*' '*A9: Extended capacity*' (Underpinned by '*S1*', '*S2*', '*S3*', '*S4*', '*S5*', '*S6*', '*A1*', '*A2*', '*A3*')
R9: Environmental radioactivity	'*A7: Impacts on non-human biota*' '*A9: Extended capacity*' (Underpinned by '*S1*', '*S2*', '*S3*', '*S4*', '*S5*', '*S6*', '*A1*', '*A2*', '*A3*')
R10: Protection against non-radiological hazards	'*A6: Non-radiological impacts*' '*A9: Extended capacity* (Underpinned by '*S1*', '*S2*', '*S3*', '*S4*', '*S5*', '*S6*', '*A1*', '*A2*', '*A3*')
R11: Site investigation	'*S3: Characterising and understanding the geology and hydrogeology*' '*S4: Characterising and understanding the coastal environment*' '*S5: Characterising and understanding the surface environment*' (Underpinned and guided by '*A1*')
R12: Use of site and facility design, construction, operation and closure	'*O3: Site engineering*' '*O4: Waste emplacement strategies*' '*O5: Management of run-off and leachate*' '*A9: Extended capacity*'
R13: Waste acceptance criteria	'*A8: Waste Acceptance Criteria and radiological capacity*' '*A9: Extended capacity*'
R14: Monitoring	'*S6: Monitoring*'

8 Concluding Statements

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

- the national policy and NDA UK Strategy for the management of LLW, which sets the objective of the LLWR;

- the history, current conditions and environmental context of the facility and site.

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

The ESC sets out our environmental safety arguments and supporting evidence that we believe justify the use of the LLWR to dispose of LLW and ideally only that requiring disposal in vaults.

At a high level, our case is that:

- We have worked within a sound management framework and firm safety culture, while engaging in dialogue with stakeholders.

- We have characterised and established a sufficient understanding of the LLWR site and facility, and their evolution, relevant to its environmental safety.

- On which basis, we have carried out a comprehensive evaluation of options to arrive at an optimised SDP for the LLWR.

- We have assessed the environmental safety of the SDP, showing that impacts are appropriately low and consistent with regulatory guidance. Using our assessments, we have determined the radiological capacity of the facility and conditions under which waste may be safely accepted and disposed.

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

The 2011 ESC addresses the deficiencies identified by the Environment Agency in the safety cases presented by the previous operator of the LLWR in 2002. We have described how this has been done.

We have shown how the ESC has addressed the requirements set out in the regulatory guidance.

The ESC will now be implemented, in accordance with our current Permit.

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Appendix 1: List of Acronyms

AOD	Above Ordnance Datum (levels, normally in metres, m AOD)
ALARA	As low as reasonably achievable
BNFL	British Nuclear Fuels Limited
CEAR	Compilation of Environment Agency Requirements, Approvals and Specifications
COW	Cut-off wall
CRM	Coastal Recession Model
EDA	Extended Disposal Area
EHS&Q	Environment, Health, Safety and Quality
ESS	Environmental Safety Strategy
FEPs	Features, events and processes
GRA	Guidance on Requirements for Authorisation for Near-Surface Disposal Facilities on Land for Solid Radioactive Wastes
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
IPRG	International Peer Review Group
ISO	International Organization for Standardization
LLW	Low-level waste
LLWR	Low Level Waste Repository
MHT	Marine Holding Tanks
NDA	Nuclear Decommissioning Authority
ONR	Office for Nuclear Regulation
PEG	Potentially exposed groups
PIER	Projected Inventory Evaluation Routine
POA	Period of Authorisation
PRG	Peer Review Group
RDA	Reference Disposal Area
ROF	Royal Ordnance Factory
RSA	Radioactive Substances Act
SAC	Special Area of Conservation
SEA	Strategic environmental assessment
SEAR	Significant Environmental Aspects Register
SDP	Site Development Plan
SLC	Site Licence Company
SSSI	Site of Special Scientific Interest

TNT	Trinitrotoluene
UKRWI	UK Radioactive Waste Inventory
VLLW	Very-low-level Waste
WAC	Waste Acceptance Criteria
WAMAC	Waste Monitoring and Compaction Plant
WCSSG	West Cumbria Sites Stakeholder Group
WIDRAM	Waste Inventory Disposition Route Assessment Model

Appendix 2: ESC Glossary

This appendix provides a glossary of important and general terms, which are used across several ESC reports. The appendix does not provide a comprehensive glossary of technical terms. Terms are ordered by logical connection, not alphabetically. Further specialist technical definitions may be found in:

- the IAEA '*Safety Glossary*', 2007 Edition;
- documents available on the Environment Agency website, especially the Glossary in '*Near-surface Disposal Facilities on Land for Solid Radioactive Wastes. Guidance on Requirements for Authorisation*' [23]:

Organisations

Cumbria County Council

Cumbria County Council is a local government authority. Development (planning) control is one of the responsibilities of local government. Development control for the LLWR is shared by Cumbria County Council and Copeland Borough Council, with Cumbria County Council having responsibility for all development associated with waste management.

Environment Agency

In England, the Environment Agency is an executive non-departmental public body responsible to the Secretary of State for Environment, Food and Rural Affairs. Its principal aims are to protect and improve the environment and to promote sustainable development. In the context of LLWR, the Environment Agency regulates the disposal of radioactive waste.

LLW Repository Ltd

LLW Repository Ltd is the Site Licence Company that manages and operates the *LLWR* on behalf of *NDA*. The Parent Body Organisation (PBO) of LLW Repository Ltd is UK Nuclear Waste Management Ltd (UKNWM).

Nuclear Decommissioning Authority (NDA)

The Nuclear Decommissioning Authority is a non-departmental public body created under the Energy Act 2004. It owns the 19 civil nuclear sites and associated nuclear liabilities and assets that were previously under the control of the United Kingdom Atomic Energy Authority and British Nuclear Fuels Ltd. The NDA owns the *LLWR*.

Office for Nuclear Regulation

The Office for Nuclear Regulation is an agency of the Health and Safety Executive (HSE). It regulates the safety and security of nuclear sites and, from summer 2011, the transport of radioactive substances by road, rail and inland waterways. It issues a *nuclear site licence* for each *nuclear-licensed site*, and regulates operations at each site through the site licence conditions.

Terms related to legislation and regulation

Authorisation

The *LLWR* operates under the terms of an Authorisation granted by the *Environment Agency* that took effect in May 2006 under the terms of the Radioactive Substances Act 1993. The Authorisation sets requirements and conditions for, amongst other things, disposal of radioactive waste, radioactive discharges, site management and improvements and reporting to the *Environment Agency*. The *LLWR*'s Authorisation has now been replaced by an *environmental Permit.*

Environmental Permit

Under the *Environmental Permitting (England and Wales) Regulations 2010* our existing *Authorisation* automatically became an environmental Permit on 6 April 2010. This did not change the technical requirements to be met; it was a change of name related to the standardisation of environmental regulation and controls. Hence, the 2011 *Environmental Safety Case* will present the basis for our application for an environmental Permit that will authorise disposal of radioactive waste under determined conditions.

Nuclear Site Licence

Where appropriate, nuclear sites, such as the *LLWR*, are issued with a Nuclear Site Licence before any activities commence on the site. The Nuclear Site Licence requires the Licensee (the 'Site Licence Company', *LLW Repository Ltd* in the case of the *LLWR*) to make and implement adequate arrangements for work at the site. The Nuclear Site Licence contains 36 Licence Conditions, which cover aspects such as: documentation; training; emergency arrangements; safety documentation; quality assurance; radiological protection; control and supervision of operations; disposal of radioactive waste; control of radioactive material and radioactive waste. The Nuclear Site Licence is issued by the *Office of Nuclear Regulation*.

Nuclear licensed site

The nuclear-licensed site is the area of ground covered by the *Nuclear Site Licence*. Licence Condition 2 requires the licensee to make and implement adequate arrangements to prevent unauthorised persons from entering the site. Hence, the perimeter of the *LLWR* nuclear-licensed site is marked by a security fence.

Environmental Permitting Regulations 2010

The Environmental Permitting Regulations (England and Wales) 2010 (EPR2010) were introduced on 6 April 2010, replacing the 2007 Regulations. The Regulations combined the Pollution Prevention and Control and Waste Management Licensing regulations in 2007. Their scope has since been widened to include water discharge and groundwater activities, radioactive substances and provision for a number of Directives. An *environmental Permit* that would authorise disposal of radioactive waste at *LLWR* will be issued under EPR2010.

Guidance on Requirements for Authorisation for near-surface disposal facilities on land for solid radioactive waste (GRA)

The GRA was issued by the UK environment agencies, including the *Environment Agency*, in February 2009. The guidance sets out the framework within which

Environment Agency regulates near-surface disposal facilities, and the intended regulatory approach. It is written mainly for the developers and operators of these facilities. The guidance sets out five principles for solid radioactive waste disposal and fourteen specific requirements, which, if fulfilled proportionately to the hazard presented by the waste, should ensure that the principles are properly applied.

Terms related to radioactive waste management

Consignment

A consignment is a container or item of waste sent by a *consignor* to a *disposal* facility (such as *LLWR*).

Consignor

A consignor is an organisation or person that sends waste to a facility for disposal.

Low Level Waste (LLW)

In Government policy, low-level waste is defined as radioactive waste having a radioactive content not exceeding four gigabecquerels per tonne (GBq te^{-1}) of alpha or 12 GBq te^{-1} of beta/gamma activity.

UK Strategy – i.e. the NDA LLW Strategy

In March 2007, UK Government published a new policy for the long-term management of solid low-level radioactive waste in the UK. The *NDA* subsequently developed a strategy to implement this policy, '*UK Strategy for the Management of Solid Low Level Radioactive Waste from the Nuclear Industry*', August 2010.

United Kingdom Radioactive Waste Inventory (UKRWI)

The UKRWI is provided by the Department of Energy and Climate Change and the *NDA*. The Inventory is routinely updated and published in the public domain, currently on a three-yearly cycle. The 2010 UKRWI is the latest public record of information on radioactive waste present in the UK. It describes the sources, quantities and properties of radioactive waste that existed at 1 April 2010 in the UK and that was forecast to arise in the future. The 2010 UKRWI was published too late for application in the 2011 ESC, which is based on the 2007 UKRWI.

Very Low Level Waste (VLLW)

VLLW is LLW with concentrations of radioactivity above that defined as exempt in the *Environmental Permitting Regulations*. It arises from a variety of sources, including the nuclear industry and hospitals and the wider non-nuclear industry. It is suitable for disposal, subject to specified conditions, with ordinary waste in facilities not specifically designed for radioactive waste disposal, or, in the case of larger volumes of waste that arise from the nuclear industry, in landfill-type facilities.

Waste hierarchy

The waste hierarchy was first introduced in 1975 in EU waste policy in the Waste Framework Directive for non-radioactive waste. It is an integral part of the development of integrated waste strategies at both nuclear and non-nuclear. Application of the waste hierarchy is central to the *UK Strategy* for LLW management. Application of the waste hierarchy ensures waste creation is avoided or minimised as much as possible. Where it is not possible to avoid the creation of waste, or it already exists, the objective is to reuse or recycle the waste and only dispose of the waste as a last resort.

Waste stream

The fundamental designation used in the *UK Radioactive Waste Inventory* is that of the waste stream. Waste streams are designated to summarise waste or a collection of waste items at a particular site, usually in a particular facility or from particular processes or operations. A waste stream is often distinguishable by its radionuclide content and in many cases also by its physical and chemical characteristics.

WIDRAM09

WIDRAM (Waste Inventory Disposition Route Assessment Model) contains inventory data for currently stored and forecast *LLW* arisings for all UK nuclear sites. It provides information on the source of individual waste streams, their composition in radiological and non-radiological terms, and the volume of material arising as a function of time. WIDRAM is derived from information in the 2007 *UK Radioactive Waste Inventory* and other information provided by NDA sites. The latest version is WIDRAM09.

Terms related to the LLWR repository

Closure

The term *vault closure* is used to denote the time when the capping is complete over a given vault. At this time, active leachate management will be ongoing. 'Final closure' of the facility and site is used to denote the time when we complete all closure engineering. This includes decommissioning the active leachate management system and possibly closing the cap vent. In the 2011 ESC, it is assumed that active leachate management will continue up to the end of the *Period of Authorisation*. Hence, for *LLWR*, the end of the *Period of Authorisation*, the end of *active institutional control* and final closure all occur at the same time. Even after final closure, the site will remain under *passive institutional control.*

Disposal

Disposal is the *emplacement* of waste in a specialised land disposal facility without intent to retrieve it at a later time. Retrieval may be possible but, if intended, the appropriate term is *storage*.

Emplacement

Emplacement is the placement of a waste package in a designated location for disposal, with no intent to reposition or retrieve it subsequently.

Emplacement strategy

An emplacement strategy is a strategy to control the locations in which certain waste streams and waste consignments are emplaced in the vaults, for example, not placing certain wastes in the upper stacks in the vaults. This would have the effect of reducing the probability of inadvertent human intrusion into such wastes. An emplacement strategy may be necessary in order that dose constraints and dose guidance levels are met, or might be an optimisation measure to minimise the environmental impact of disposals to the *LLWR*.

ISO containers

A steel container built to standard dimensions, which can be loaded and unloaded, stacked and transported efficiently over long distances without being opened. Currently, wastes for disposal in the vaults at *LLWR* are mostly placed in half height ISO containers. The 2011 ESC assumes that this will continue to be the case.

LLWR facility

The LLWR facility consists of the engineering for the *disposal* of solid radioactive wastes. The LLWR facility includes the *trenches* (Trenches 1 to 7), existing *vaults* (Vaults 8 and 9) and future *vaults*, in which *LLW* is or will be emplaced, and the associated post-closure engineering. It also includes additional plant such as the *LLWR Grouting Facility* and the leachate management system.

Low Level Waste Repository (LLWR)

The LLWR is the UK's national facility for the disposal of LLW. It is situated near the village of Drigg in Cumbria. Operated since 1959, the LLWR is now owned by the *NDA* and currently operated on its behalf by the Site Licence Company: *LLW Repository Ltd*.

LLWR site

The LLWR site is the *nuclear-licensed site* on which the *LLWR facility* is constructed and operated. The site is designated under the Nuclear Installations Act 1965 (as amended).

Monitoring

Monitoring consists of taking measurements so as to be aware of the state of the disposal system and any changes to that state. This may include measuring levels of radioactivity in samples taken from the environment, and also measuring geological, physical and chemical parameters that are relevant to environmental safety and which might change as a result of construction of the disposal facility, waste emplacement and closure. A comprehensive monitoring programme has been established at *LLWR*. An important objective of this programme is to provide data to underpin and increase confidence in the conceptual and numerical models of the *LLWR* system that are used in the *Environmental Safety Case*, particularly relating to models of groundwater flow and contaminant transport. An annual review of the monitoring programme is prepared for *Environment Agency*.

Royal Ordnance Factory (ROF)

The site of the *LLWR* was first developed in 1940 as a Royal Ordnance Factory (ROF Drigg) for the production of TNT. The first TNT was produced in March 1941. Ownership of the site later passed to the United Kingdom Atomic Energy Authority (UKAEA), which was granted planning consent in 1957 for the disposal of *Low Level Waste* in the northern 40 ha of the site.

Storage

Storage is the placing of waste in a suitable facility with the intent to retrieve it at a later date.

Waste Acceptance Criteria (WAC)

Waste Acceptance Criteria define the quantitative and qualitative criteria, specified by the operator of a disposal facility, for solid radioactive waste to be accepted for disposal. WAC form part of the set of waste acceptance arrangements that ensure the safety of waste disposal at the site.

Terms related to the 2011 Environmental Safety Case

ESC Project

The ESC Project is the project to produce the 2011 *Environmental Safety Case* for *LLWR*. The 2011 *Environmental Safety Case* will be submitted to the Environment Agency by 1st May 2011.

Environmental safety

Environmental safety is defined as the safety of people and the environment both during and after the Period and Authorisation. In the context of *LLWR*, the view taken in the 2011 *Environmental Safety Case* is that the *LLWR facility* is liable to be disrupted by coastal erosion within a time frame of a few hundred to a few thousand years, with consequent dispersal of wastes into the coastal environment. This informs our decisions on the future timescales over which environmental safety is considered.

Environmental Safety Case (ESC)

An *environmental safety case* is a set of claims concerning the environmental safety of disposals of solid radioactive waste, substantiated by a structured collection of arguments and evidence. It should demonstrate that the health of members of the public and the integrity of the environment are adequately protected. It will be provided by the developer/operator of the disposal facility and should be designed to demonstrate consistency with the principles set out in the UK environment agencies' '*Near-surface Disposal Facilities on Land for Solid Radioactive Wastes Guidance on Requirements for Authorisation*'. It is important to recognise that an *environmental safety case* is broader than the safety assessment calculations. It will also include a range of more qualitative arguments to demonstrate safety.

Environmental Safety Strategy

The Environmental Safety Strategy (ESS) lays out our approach to achieving the continuing environmental safety of the *LLWR*. The ESS is the process and means by which we achieve this primary objective in a demonstrably environmentally safe way. Our ESS leads to an optimised *Site Development Plan*, our plan for developing the site consistent with our strategy.

International Peer Review Group (IPRG)

In addition to the UK-based *Peer Review Group*, a team of peers with experience from other radioactive waste disposal facilities was appointed. This 'International

Peer Review Group' (IPRG) provided an independent review of key technical approaches, arguments, designs, assessments and documents that form components of the developing *Environmental Safety Case*. The focus of this review was the overall strategy for, and approach to, the 2011 *Environmental Safety Case* rather than a comprehensive detailed technical review.

Optimisation

Optimisation is the principle of ensuring that radiation exposures are as low as reasonably achievable (ALARA) in the given circumstances. It is a key principle of radiation protection recommended by the International Commission on Radiological Protection (ICRP) and incorporated into UK legislation. Optimisation is about finding the best way forward where many different considerations need to be balanced. Relevant considerations include economic and societal factors and the requirement to manage any non-radiological hazards. Although reducing radiological risk is important, it should not be given a weight out of proportion to other considerations. The best way forward is not necessarily the one that offers the lowest radiological risk. It is through this process that we have developed our *Site Development Plan*.

Peer Review Group (PRG)

As part of the *ESC Project*, a Peer Review Group (PRG) was appointed to provide independent challenge of the *Environmental Safety Case* and constructive advice. The PRG consists of experts of longstanding experience and international reputation who are independent of the development of the *LLWR's Environmental Safety Case*. The scope of the PRG's work focused on issues that are important to: environmental risks; development and evaluation of options; and clear presentation of evidence and arguments. The PRG works in such a way that it can be demonstrated to stakeholders that an effective and proportionate process of independent technical review and scrutiny is operating.

Radiological capacity

The radiological capacity of a disposal facility is defined as an inventory of radioactive material that the facility is capable of accepting based on the environmental safety case. Radionuclide-specific radiological capacity values for LLWR are calculated based on selected *calculation cases* for the *Period of Authorisation* and the period thereafter. The radiological capacity for any particular radionuclide is calculated using a Sum of Fractions methodology, as recommended by the IAEA.

Site Development Plan (SDP)

The Site Development Plan (SDP) is developed from the *Environmental Safety Strategy*. An optimised SDP forms the basis of our assessments of repository performance, an important part of our demonstration of environmental safety. For the 2011 *Environmental Safety Case* for *LLWR*, the SDP sets out our proposals and assumptions on operations, remedial activities, vault design, capacity and future waste disposal practice, closure design and management up to the end of the *Period of Authorisation*. The Plan is flexible, however, and will be amended as necessary in the light of UK radioactive waste management needs, operating experience, results of monitoring, future iterations of the *Environmental Safety Case*, regulatory and planning decisions and stakeholder views.

Terms related to radiological safety

Critical group

A group of members of the public that is reasonably homogeneous with respect to its exposure for a given radiation source, such as a near-surface disposal facility, and is typical of individuals receiving the highest effective dose or equivalent dose (as applicable) from the given source.

Dose constraint

The dose constraint is a prospective restriction on the individual dose delivered by a source, and serves as an upper bound on the dose in optimisation of protection and safety for the source. The concept of dose constraint is applicable to the *Period of Authorisation* of a disposal facility. In this period, the effective dose to a representative member of the *critical group* should not exceed a source-related dose constraint of 0.3 mSv per year and a site-related dose constraint of 0.5 mSv per year.

Dose guidance level

In the context of near-surface disposal facilities, the dose guidance level is the dose standard against which the radiological consequences of *human intrusion* are assessed. It indicates the standard of *environmental safety* expected, but does not suggest that there is an absolute requirement for this level to be met. The assessed effective dose to any person during and after the assumed intrusion should not exceed a dose guidance level in the range of around 3 mSv per year to around 20 mSv per year. Values towards the lower end of this range are applicable to assessed exposures continuing over a period of years (prolonged exposures), while values towards the upper end of the range are applicable to assessed exposures that are only short term (transitory exposures).

Passive safety

Passive safety is safety that is achieved without placing reliance on active safety systems (i.e. systems whose functioning depends on an external input such as actuation, mechanical movement or supply of power) and human intervention.

Potentially exposed group (PEG)

For a given source, such as a near-surface disposal facility, an exposed group is any group of people within which the exposure to radiation is reasonably homogeneous. Where the exposure is not certain to occur, the term 'potentially exposed group' is used.

Radiation dose

Radiation dose is a measure of the energy deposited by radiation in a target, in this case humans and non-human biota. The quantity 'annual dose' is calculated as the sum of effective doses received from external sources in a year, together with the sum of committed effective doses incurred from intakes (ingestion and inhalation) during the same year. In some cases we calculate 'dose from the event', by which we mean the sum of effective doses from external sources during the event, plus the sum of committed effective doses from intakes arising from the event.

Radiation risk

Radiation risk is the probability per unit time that an individual will suffer a serious radiation-induced health effect as a result of the presence of a radiation source, for example, a disposal facility. In this context, a serious radiation-induced health effect is a fatal cancer or a severe hereditary defect. Radiation risk can only be assessed and not measured.

Risk guidance level

The risk guidance level is the level of radiological risk from a disposal facility that provides a numerical standard for assessing the environmental safety of the facility after the *Period of Authorisation*. For a disposal facility, the risk guidance level is 10^{-6} per year.

Terms related to the groundwater pathway

Drigg Stream

The *LLWR site* is located in a small surface water catchment area. The catchment is drained by the Drigg Stream, which rises immediately to the south of Vault 8, and the *East-West Stream*, which rises to the north-east of the site in farmland and is a tributary to the Drigg Stream on the site. Across the *LLWR site* these streams are fed by numerous drains, for example, the railway drain, which is located parallel to the north-eastern edge of the trenches. The Drigg Stream discharges into the tidal section of the River Irt. Regular monitoring of stream flows and surface water quality is carried out by *LLWR*.

East-West Stream

The East-West Stream rises to the north-east of the LLWR site in farmland and is a tributary to the *Drigg Stream* on the site.

Leachate

In the context of LLWR, leachate is liquid present within the *trenches* and *vaults*. It arises as a result of the infiltration of rainwater or groundwater. Where the water contacts waste, it can leach soluble components and become contaminated. An active leachate management system is currently in operation at *LLWR* to limit the amount of leachate that enters the underlying Quaternary strata.

Lithofacies unit

The Quaternary geology of west Cumbria is complex. The geological conceptual model is that Quaternary strata with similar hydraulic properties can be grouped together into ‘lithofacies units’. Knowledge of the locations and geometry of the lithofacies units allows the development of a regional 3-D geological model. The improved level of confidence in the interpretation of the Late Quaternary site- and regional-scale glacigenic deposits has allowed a single, integrated lithofacies framework (A, B2, B3, B4, C and D) to be proposed at *LLWR*.

Regional Groundwater

Regional Groundwater occurs within the deeper Quaternary deposits and the underlying bedrock. It is distinguished from the *Upper Groundwater* by the lack of a significant vertical gradient in the measured heads. The transition from *Upper Groundwater* to Regional Groundwater occurs roughly at 4 m AOD and is generally coincident with the interface between *lithofacies unit* B2, which has low vertical hydraulic conductivity, and *lithofacies unit* B3, which has a relatively high hydraulic conductivity.

Upper Groundwater

Upper Groundwater lies in the upper part of the Quaternary deposits between the *Regional Groundwater* and the surface and soil zone. It is distinguished from *Regional Groundwater* by a significant downwards-directed vertical gradient in the measured heads.

Unsaturated

A volume of material is unsaturated when some or all of the pore space is filled with air. At LLWR, unsaturated rock or soil occurs above the *Upper Groundwater* (the 'surface and soil' zone) and in some areas of site between *Regional Groundwater* and *Upper Groundwate*r. The intention of the Reference Design at the *LLWR* is to keep the waste as unsaturated as possible.

Terms related to LLWR site management

Active Institutional Control

The period of active institutional control is the time during which active measures will be taken by *LLW Repository Ltd* to control the disposal site. For the *LLWR*, the term is synonymous with *Period of Authorisation*. The *LLWR site* will remain under active institutional control for a period of 100 years after closure of the last vault. During this time, a site boundary will be maintained to prevent access by the public. Land use will be controlled. Active leachate collection and management will continue up to 100 years after closure of the final vault. Monitoring to meet regulatory requirements and to provide reassurance that the facility is performing safely and as expected will continue during active institutional control. Remedial actions, such as addressing any problems with the interim trench cap, will be taken if required.

Extended Disposal Area (EDA)

The Extended Disposal Area is an extended area, beyond the *Reference Disposal Area*, which is considered in the *Environmental Safety Case* to assess the capacity of the site to take all waste requiring vault disposal in the *United Kingdom Radioactive Waste Inventory*.

Lifetime Plan

NDA requires each Site Licence Company to produce a Lifetime Plan for the site. The Lifetime Plan is updated annually. The Lifetime Plan describes all the activities in terms of scope, schedule and cost to be undertaken on the site in the remaining period of its lifecycle.

Passive institutional control

During the period of *active institutional control*, measures will be put in place to encourage sustainable and appropriate uses of the site in the longer term. Hence, longer-term controls may remain over the site in the form of covenants, planning controls and record keeping, in order to deter, or prevent, inappropriate site uses. These measures do not require the presence of an dedicated organisation or ongoing actions to be taken by the operator. We term such measures passive institutional control.

Period of Authorisation

The regulatory guidance on the authorisation of near-surface disposal facilities for radioactive waste includes several requirements that relate to the environmental safety of the site until the cessation of active institutional control. The period up until the cessation of active institutional control is referred to as the Period of Authorisation.

Reference Disposal Area (RDA)

The Reference Disposal Area is the area assumed to be occupied by disposal units (*trenches* and *vaults*) in the 2011 ESC *Reference Design*. It corresponds to the area formerly known as the ‘consented area’, a term that now has no force.

Site release

Our safety case is that one hundred years after closure of the last vault, it will be safe to release the site from operator management and regulatory control. Site release is the presumed release of the site from regulatory control, including withdrawal of the *environmental Permit*. This marks the end of the period of *active institutional control*.

Terms related to LLWR repository engineering

Cut-off wall (COW)

The cut-off wall (COW) will provide a low permeability vertical barrier around the *LLWR trenches* and *vaults*. Its main functions are to minimise lateral infiltration of groundwater (including water shed by the cap) into the waste and to direct any *leachate* preferentially downwards. A cut-off wall along the northern and eastern sides of the *trenches* was constructed in between 1988 and 1995; it is a bentonite-cement structure, designed to be keyed into underlying clay (COW depth is between 7.3 m and 9.4 m). The existing COW will be extended round the whole facility. However, hydrogeological modelling has demonstrated that to achieve the design objectives, it need only extend slightly deeper than the base of the vaults.

Final cap

The final cap will have a single dome profile and will provide a suitable long-term landform, physical cover and low permeability surface barrier. It will be installed in sections over the *trenches* and *vaults* after waste *emplacement* is complete, such that only two vault areas will be open at any given time. The final cap is a passive barrier that will: restrict infiltration to encourage run-off; isolate the waste; control release of landfill and radioactive labelled gases; resist damage due to movement, settlement and erosion, and address the visual impact of the site.

Grout

The grout used to fill residual voidage in the *ISO containers* comprises a 3:1 mix of PFA and Ordinary Portland Cement with a super-plasticiser and an initial water/solids ratio of about 0.4. The mix was selected to ensure that the grout exhibited suitable viscosity, flow, setting, bleed and strength characteristics.

Interim cap

The interim cap covers the *LLWR trenches*, and is designed to limit infiltration to the trenches and hence reduce leachate production. It was placed over Trenches 1 to 6 in 1989 to 1990 and over Trench 7 in 1995. It is comprised a soil mound, with 1:25 gradient and typically around 1 m thick (excluding profiling material), with an integral geomembrane. The interim cap will be incorporated within the final repository closure design.

LLWR Grouting Facility

On arrival at the *LLWR site*, the *ISO containers* are transferred to the LLWR Grouting Facility, where any residual voidage within the containers is filled with grout. This facility can handle up to four containers at one time. During grouting, the containers are tilted to help ensure that residual air voids are able to escape and are returned to the horizontal for the final filling.

Marine Holding Tanks (MHT)

Leachate from the *LLWR trenches* and run-off from the open vaults is directed to the Marine Holding Tanks (MHT), where it is monitored prior to discharge under consent via the *Marine Pipeline* to the sea. The MHT system has a consent to discharge 6,500 m^3 per day; future quantities are anticipated to continue to be well within this.

Marine Pipeline

The Marine Pipeline is used to discharge *leachate* from the *LLWR* to the sea via the *Marine Holding Tanks*.

Reference Design

The Reference Design is the engineering design arrived at through optimisation studies within the 2011 *Environmental Safety Case*. It is used as the basis for our detailed assessments of facility performance and radiological and non-radiological impacts within the 2011 *Environmental Safety Case*. The design incorporates our current best understanding and judgements. It may, however, be amended in the light of construction and operating experience, monitoring, iterations of the *Environmental Safety Case*, and regulatory and planning decisions.

Trench

Trench disposals commenced at *LLWR* in July 1959. The first trench (Trench 1) was filled by the end of 1963. In the years that followed a further six trenches (Trenches 2 to 7) were constructed, excavated in the glacial sequence beneath the site. Each trench was founded predominantly within an underlying natural clay layer, which was intended to form a low hydraulic conductivity base. Bentonite was rotovated into the base of trenches in less clayey areas, at least in the case of the later trenches. The trenches were designed with drainage systems and the run-off water originally entered a ditch, which discharged into the *Drigg Stream*. An active effluent management system is now in operation: leachates are directed to the *Marine Holding Tanks* and then discharged to sea via the *Marine Pipeline*. During operation, the trenches were progressively filled by tipping loose wastes from the top of the previously filled area into the excavated trench. Trench disposal began to be phased out in 1988 when Vault 8 commenced operation. Disposals to Trench 7 were completed in 1995 and this was then capped. An *interim cap* now covers all of Trenches 1 to 7 to limit infiltration and leachate production.

Vault

The first disposal vault (Vault 8) at *LLWR* commenced operations in May 1988. Vault 9 is currently being filled. The design of future vaults is described in the *Reference Design*. The bulk of wastes emplaced in the vaults are grouted into *ISO containers*, which are then stacked in the vaults. Large items that will not fit into a container will be placed or grouted in place. The vaults are constructed with reinforced concrete base slabs and walls. The future vaults will also include drainage materials, which are designed to delay the onset of saturated conditions in the vaults after *vault closure* and to promote drainage into underlying Quaternary strata. Active leachate management systems are in place in each vault.

Terms related to environmental assessments

Calculation case

A calculation case is a specified combination of events, circumstances, conditions or their evolution, including specification of model boundary conditions and data, which represents a particular realisation of the disposal system, its evolutions and radionuclide or contaminant release, migration and exposures. A large number of cases may be required to adequately explore aspects of, or uncertainties within, a *scenario*. Where the meaning is clear the abbreviated term, 'case', is used.

Deterministic analysis

A deterministic analysis is one in which parameters have single numerical values, taken to have a probability of one, leading to a single value for the result. Typically, deterministic analysis is used with either ‘realistic’ or ‘cautious’ values, based on expert judgment and knowledge of the phenomena being modelled. Many of the *calculation cases* that we present in the 2011 *Environmental Safety Case* are based on deterministic analysis.

Human intrusion

We define human intrusion as human actions taken after withdrawal of *active institutional control* that penetrate into or expose the disposed waste, or significantly damage the barriers that are intended to isolate and contain the waste. The regulatory guidance requires that we assess inadvertent human intrusion; that is, actions taken without full knowledge of the facility or potential hazards that the waste therein may present. Actions taken with full knowledge of the facility and associated hazard are taken to be reasoned actions that are the responsibility of those that undertake the action.

Inventory case

Inventory cases represent alternative assumptions for future waste arisings and treatments. These are illustrative of possible *LLWR site* use. They are not fixed proposals for long-term site use.

Model

A model is the assembly of features, events, process and interactions that are treated in a given case or set of assessment cases. We distinguish: (i) conceptual model – the scientific understanding and descriptive presentation of the model; (ii) mathematical model – the model as represented by given mathematical equations, and; (iii) computer model – the model as implemented in given software.

Near field, geosphere and biosphere

Near field, geosphere and biosphere are terms denoting domains that are considered within models used in performance and safety assessments of disposal systems. The definition of each domain may vary between assessment programmes. In the context of the assessments in support of the *LLWR's Environmental Safety Case* we consider that:

- the near field consists of the waste and engineered barriers, and relevant processes therein;

- the geosphere consists of the Quaternary strata and bedrock around the LLWR facility, and relevant processes therein. The geosphere provides a groundwater pathway, through which potential contaminants migrate;

- the biosphere denotes the accessible environment and relevant processes therein including human practices for use of that environment, for example, farming, fishing, recreational uses, not disturbing the facility.

Pathway

Pathways are different routes or mechanisms by which contaminants may be released from the *LLWR facility*. These releases may give rise to exposure to humans or non-human biota. We identify four pathways: groundwater; gas; natural disruption; human intrusion.

Probabilistic analysis

A probabilistic analysis is one in which key parameters are treated as uncertain. Our 2011 *Environmental Safety Case* considers a probabilistic *calculation case* for the groundwater pathway. Probability density functions were defined for: radionuclide inventories; *near-field* and *geosphere* sorption coefficients; groundwater flow rates and dispersion; infiltration through the cap; hydraulic conductivity of engineered barriers; well probability. Probability distribution functions of key flow and transport parameters were derived through formal expert elicitations.

Safety arguments

A safety argument provides a link between the safety evidence and a safety claim, showing that the safety evidence is sufficient to support the claim. For the 2011 *Environmental Safety Case* for the *LLWR*, they include descriptions of our management framework, system understanding, design and management choices and assessments.

Scenario

Scenarios are the broad alternative future events, circumstances, conditions or their evolution that are characteristically different and provide a framework for analysis that is useful in providing an understanding of the environmental safety of the disposal system. We define relatively few scenarios in the 2011 *Environmental Safety Case*. They are related to assumptions over the natural development of the site and human actions after site release.

Uncertainty

Uncertainty is lack of complete knowledge, which precludes an exact or complete description of past, present or future. We recognise three types of uncertainty: scenario uncertainty, which is uncertainty in the broad future evolution of the disposal facility and its environment; conceptual model uncertainty, where scientific understanding of the process being represented is uncertain, and parameter certainty, where the quantitative value of a parameter is uncertain. We have addressed scenario and conceptual model uncertainty through a range of *deterministic calculation* cases. Parameter uncertainty has been addressed through both *deterministic calculation* cases and *probabilistic calculation* cases.

'What-if' case

A *case* put forward to explore the consequences of a defined set of assumptions.