Radioactive Waste
Management

NDA Report no. DSSC/203/01

Geological Disposal

Generic Environmental Safety Case - Main Report

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email: rwmfeedback@nda.gov.uk

Preface

Radioactive Waste Management Limited (RWM) has been established as the delivery organisation responsible for the implementation of a safe, sustainable and publicly acceptable programme for the geological disposal of the higher activity radioactive wastes in the UK. As a pioneer of nuclear technology, the UK has accumulated a legacy of higher activity wastes and material from electricity generation, defence activities and other industrial, medical and research activities. Most of this radioactive waste has already arisen and is being stored on an interim basis at nuclear sites across the UK. More will arise in the future from the continued operation and decommissioning of existing facilities and the operation and subsequent decommissioning of future nuclear power stations.

Geological disposal is the UK Government’s policy for higher activity radioactive wastes. The principle of geological disposal is to isolate these wastes deep underground inside a suitable rock formation, to ensure that no harmful quantities of radioactivity will reach the surface environment. To achieve this, the wastes will be placed in an engineered underground facility – a geological disposal facility (GDF). The facility design will be based on a multi-barrier concept where natural and man-made barriers work together to isolate and contain the radioactive wastes.

To identify potentially suitable sites where the GDF could be located, the Government has developed a consent-based approach, based on working with interested communities that are willing to participate in the siting process. The siting process is on-going and no site has yet been identified for the GDF.

Prior to site identification, RWM is undertaking preparatory studies which consider a number of generic geological host environments and a range of illustrative disposal concepts. As part of this work, RWM maintains a generic Disposal System Safety Case (DSSC). The generic DSSC is an integrated suite of documents which together give confidence that geological disposal can be implemented safely in the UK.

Executive Summary

The UK policy for the long-term management of higher activity waste is deep geological disposal, and a new siting process has been launched to identify a suitable site for the construction of a geological disposal facility (GDF). In terms of long-term environmental safety, a suitable site will be one where the geology and appropriately designed engineered barriers contain the radioactivity, and any potential non-radiological hazards presented by the waste, for as long as required.

In broad terms, three different types of rock are considered as potentially suitable for the construction of a GDF. These are higher strength rock (such as granite), lower strength sedimentary rock (such as clay) and evaporite (halite). Each of these potential 'host' rocks could be overlain by a sequence of cover rocks. The properties of both the host rock and the overlying cover rock are important for long-term safety. This generic environmental safety case (ESC) discusses how, in each geological environment, the geological barriers of a GDF will provide environmental safety functions that support the isolation and containment of radioactive waste.

The environmental safety functions provided by the various wasteforms for geological disposal are also discussed. However, while a location for the GDF is being sought, it is not possible to define a single specific design for an engineered barrier system (EBS) that, in conjunction with the wasteform and the geological environment, will provide the environmental safety functions necessary to ensure that long-term containment is achieved. Instead, a range of illustrative disposal concepts has been studied in order to develop an understanding of the environmental safety functions provided by different types of EBS in the different geological environments. These illustrative disposal concepts are based on those developed in other waste management programmes for disposal of different types of waste in the three potential host rock types.

RWM has therefore established a generic understanding of how a suitably sited and designed GDF can isolate and contain the wastes for the required timescales. This generic understanding is supported by RWM's knowledge base, which captures research and design engineering work undertaken over many decades by RWM and its contractors, relevant international organisations and overseas waste management programmes. Throughout this generic ESC reference is made to the knowledge base (mostly in terms of references to the underpinning research status reports that form part of the generic Disposal System Safety Case suite of documents) to provide the evidence to support the safety arguments presented.

This generic ESC includes a systematic analysis of the environmental safety functions of each combination of geological environment and EBS that provides a sound understanding of the expected evolution (the base scenario) of a GDF constructed in different geological environments. This analysis is based on well-established scientific knowledge regarding the physical and chemical processes governing the evolution of the various components of a GDF and the laws of radioactive decay, expressed in terms of the features, events and processes (FEPs) that are expected to influence system evolution.

The environmental safety functions of the different components of a multi-barrier disposal system must also be shown to be robust to potential variant scenarios defined by unlikely events, such as the occurrence of nuclear criticality in a GDF or inadvertent human intrusion into a GDF. Variant scenarios are identified and analysed by considering the events and processes that could disrupt the environmental safety functions provided by the GDF's natural and engineered barriers.

At this generic stage of the geological disposal programme, whilst a location for the GDF is being sought and in the absence of a detailed GDF design, detailed total system modelling to evaluate base and variant scenarios is not possible. Instead, for this generic ESC,

relatively simple total system models have been developed based on illustrative examples of different geological environments and disposal concepts. These examples are not related to any specific site, but have been developed to illustrate the range of geological environments and GDF designs being considered and the evolving containment functions provided by the barrier components of each concept.

An understanding of the set of environmental safety functions provided by a system of natural and engineered barriers and how the disposal system is expected to evolve also forms the basis of a framework for considering the potential implications of waste packaging proposals as part of the Disposability Assessment process. A waste packaging proposal can be considered in terms of its features and the environmental safety functions that they provide and the potential impacts of the waste package on the environmental safety functions provided by other components of the barrier system. If any potential negative impacts on one or more environmental safety functions are identified, then these are assessed further to determine whether there is sufficient compensation from other complementary environmental safety functions to ensure that long-term containment is not compromised. Where complementary environmental safety functions are judged to work together to maintain the overall safety arguments, the waste package may be assessed to be suitable for disposal. Alternatively, it may be necessary to consider package design modifications in order to build confidence in waste package disposability.

The understanding of safety presented in this generic ESC provides the underpinning for future work in the siting of the GDF and the development of a site-specific GDF design. Once a location for the GDF has been identified, consideration of the required environmental safety functions will enable engineered barriers to be developed that complement the environmental safety functions provided by the different wasteforms and the selected geological environment. At that time, it will be possible to develop a site-specific ESC, based on the GDF design and knowledge of the geological environment. Understanding of the characteristics of the geological environment will be expressed in terms of a site descriptive model, which will include a detailed description of hydrogeological and geochemical conditions at the site. The site descriptive model will be used as the basis for developing an understanding of radionuclide and non-radiological contaminant migration behaviour in the geological environment of the GDF, which will provide information for the development of a model for evaluating the performance of the total disposal system.

However, until there is sufficient confidence in a site-specific ESC, the generic ESC will be maintained. Maintenance of the generic ESC (in parallel with the development of a future site-specific ESC) will enable waste package disposability assessments encompassing a broad range of potential disposal facility designs to continue to be undertaken. In other words, maintenance of the generic ESC prevents the premature foreclosure of disposal options by maintaining the flexibility to design, build and operate a GDF in a wide variety of geological environments.

In summary, this generic ESC provides confidence that a GDF could be constructed in a way that provides long-term environmental safety in a range of geological environments. Long-term safety will be assured by the presence of a system of natural and engineered barriers and the complementary environmental safety functions that they provide. The understanding of barrier system behaviour and safety functions demonstrated in this generic ESC, based on an illustrative assessment approach, provides an underpinning for future site-specific work. Once a disposal site is identified, more detailed site-specific modelling and assessments will be undertaken to support an application for the geological disposal of radioactive wastes under the Environmental Permitting Regulations.

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1 Introduction

1.1 The generic Disposal System Safety Case

RWM has been established as the delivery organisation responsible for the implementation of a safe, sustainable and publicly acceptable programme for geological disposal of the UK's higher activity radioactive waste. Information on the approach of the UK Government and devolved administrations of Wales and Northern Ireland[1] to implementing geological disposal, and RWM's role in the process, is included in an overview of the generic Disposal System Safety Case (the Overview) [1].

A geological disposal facility (GDF) will be a highly-engineered facility, located deep underground, where the waste will be isolated within a multi-barrier system of engineered and natural barriers designed to prevent the release of harmful quantities of radioactivity and non-radioactive contaminants to the surface environment. To identify potentially suitable sites where a GDF could be located, the Government is developing a consent-based approach based on working with interested communities that are willing to participate in the siting process [2]. Development of the siting process is ongoing and no site has yet been identified for a GDF.

In order to progress the programme for geological disposal while potential disposal sites are being sought, RWM has developed illustrative disposal concepts for three types of host rock. These host rocks are typical of those being considered in other countries, and have been chosen because they represent the range that may need to be addressed when developing a GDF in the UK. The host rocks considered are:

- higher strength rock, for example, granite
- lower strength sedimentary rock, for example, clay
- evaporite rock, for example, halite

The inventory for disposal in the GDF is defined in the Government White Paper on implementing geological disposal [2]. The inventory includes the higher activity radioactive wastes and nuclear materials that could, potentially, be declared as wastes in the future. For the purposes of developing disposal concepts, these wastes have been grouped as follows:

- High heat generating wastes (HHGW): that is, spent fuel from existing and future power stations and High Level Waste (HLW) from spent fuel reprocessing. High fissile activity wastes, that is, plutonium (Pu) and highly enriched uranium (HEU), are also included in this group. These have similar disposal requirements, even though they don't generate significant amounts of heat.
- Low heat generating wastes (LHGW): that is, Intermediate Level Waste (ILW) arising from the operation and decommissioning of reactors and other nuclear facilities, together with a small amount of Low Level Waste (LLW) unsuitable for near surface disposal, and stocks of depleted, natural and low-enriched uranium (DNLEU).

RWM has developed six illustrative disposal concepts, comprising separate concepts for HHGW and LHGW for each of the three host rock types. Designs and safety assessments for the GDF are based on these illustrative disposal concepts.

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[1] Hereafter, references to Government mean the UK Government including the devolved administrations of Wales and Northern Ireland. Scottish Government policy is that the long term management of higher activity radioactive waste should be in near-surface facilities and that these should be located as near as possible to the site where the waste is produced.

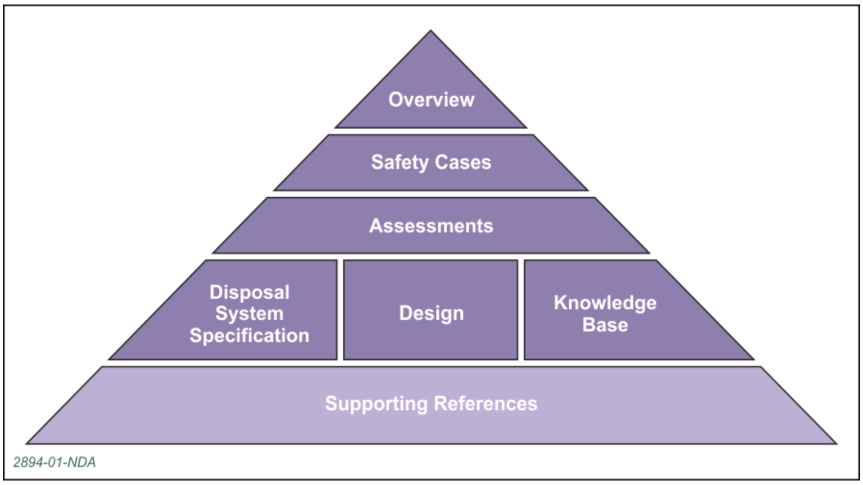
High level information on the inventory for disposal, the illustrative disposal concepts and other aspects of the disposal system is collated in a technical background document (the Technical Background) [3] that supports this generic Disposal System Safety Case.

The generic Disposal System Safety Case (DSSC) plays a key role in the iterative development of a geological disposal system. This iterative development process starts with the identification of the requirements for the disposal system, from which a disposal system specification is developed. Designs, based on the illustrative disposal concepts, are developed to meet these requirements, which are then assessed for safety and environmental impacts. An ongoing programme of research and development informs these activities. Conclusions from the safety and environmental assessments identify where further research is needed, and these advances in understanding feed back into the disposal system specification and facility designs.

The generic DSSC provides a demonstration that geological disposal can be implemented safely. The generic DSSC also forms a benchmark against which RWM provides advice to waste producers on the packaging of wastes for disposal.

Document types that make up the generic DSSC are shown in Figure 1. The Overview provides a point of entry to the suite of DSSC documents and presents an overview of the safety arguments that support geological disposal. The safety cases present the safety arguments for the transportation of radioactive wastes to the GDF, for the operation of the facility, and for long-term safety following facility closure. The assessments support the safety cases and also address non-radiological, health and socio-economic considerations. The disposal system specification, design and knowledge base provide the basis for these assessments. Underpinning these documents is an extensive set of supporting references. A full list of the documents that make up the generic DSSC, together with details of the flow of information between them, is given in the Overview.

Figure 1 **Structure of the generic DSSC**



1.2 Introduction to the generic Environmental Safety Case

This document is the generic Environmental Safety Case (ESC), which is one of the three safety case documents of the generic DSSC and aims to show how radioactive waste can be disposed of in a GDF in a way that ensures environmental safety at the time of disposal and after the GDF closure. The generic ESC is supported by the generic Operational Environmental Safety Assessment (OESA) [4], which addresses environmental safety during the operational phase of the GDF, and the generic Post-closure Safety Assessment (PCSA) [5], which presents a quantitative analysis that illustrates how radionuclides could be released from waste packages and migrate through an engineered and geological barrier system in the long term after closure of the GDF.

This update of the generic ESC has been produced as part of the update of the generic DSSC. The generic DSSC (including the ESC [6]) was first published in 2010 and the drivers for revising it now include the availability of an updated radioactive waste inventory for disposal (that is, the 2013 Derived Inventory [7]); publication of the Government White Paper on implementing geological disposal [2]; new work on disposal concept design and development; and the publication of new research findings on a range of geological disposal issues both in the UK and overseas. These various drivers for revising the generic DSSC, and consideration of comments on the 2010 generic DSSC from the regulators [8] and the Committee on Radioactive Waste Management (CoRWM) [9] have led to the following developments in the presentation of the generic ESC:

- **Greater emphasis on describing how concepts developed for the disposal of different types of waste in different geological environments ensure long-term environmental safety.**

  The 2016 generic ESC focuses on the environmental safety functions provided by the different components of an engineered barrier system and the geological barrier as conditions in the GDF evolve after closure. Statements about expected barrier performance are underpinned by research findings presented in RWM's knowledge base (see Figure 1), including RWM's suite of research status reports, which reflect learning from overseas waste management organisations and other international work, as well as RWM's own research. Descriptions of how different barrier components are expected to contribute towards environmental safety in different geological environments are supported by illustrative calculations of how a barrier system will contain radionuclides that are released from waste packages, and how the risks arising from any long-lived radionuclides that are transported through a multi-barrier system to the accessible environment will be acceptably low. Details of these calculations are presented in the generic PCSA [5].

- **Consideration of the environmental safety of geological disposal in the context of the 2013 Derived Inventory [7].**

  RWM has identified a range of possible inventory scenarios that depend on factors such as decisions on future reprocessing of spent fuel, changes in operating lifetimes of existing nuclear reactors and changes in plans for the construction of new nuclear reactors [10]. Qualitative judgments are made in the generic ESC about how environmental safety might be affected by the different types and quantities of wastes that would require disposal according to these different inventory scenarios.

- **Reference to the developments that have been made in the Disposal System Specification and design since 2010, as well as in the overall knowledge base (see Figure 1).**

  Advances include developments in waste packaging and disposal concepts, as described in the generic Disposal System Specification (Part B) [11], and progress in understanding nuclear criticality safety following disposal of wastes that contain fissile material [12]. The knowledge base has been developed through research that has focused on key issues identified in RWM's Science and Technology Plan [13] concerning, for example, disposal of HHGW [14], disposal of wastes that contain C-14 [15; 16], disposal of DNLEU [17] and further development of concepts for the disposal of different types of waste in different geological environments.

- **Consideration of non-radiological contaminants in the context of changes in groundwater regulations.**

  Changes in groundwater regulations with regard to non-radiological contaminants are described in the Environmental Permitting (England and Wales) Regulations 2010 (EPR 2010) [18] and the Ground Water Daughter Directive [19]. The generic

ESC includes discussion of RWM’s approach to addressing these requirements for the GDF.

1.3 Objectives

The generic ESC aims to communicate how the geological disposal of radioactive waste can be accomplished in a way that ensures environmental safety, not only at the time of disposal, but also in the long term after wastes have been emplaced and the disposal facility has been closed. This objective of ensuring environmental safety is consistent with the fundamental protection objective contained in the environmental regulators’ Guidance on Requirements for Authorisation (GRA) of geological disposal facilities for radioactive wastes [20, §4.2.1]:

> *“…to ensure that all disposals of solid radioactive waste to facilities on land are made in a way that protects the health and interests of people and the integrity of the environment, at the time of disposal and in the future, inspires public confidence and takes account of costs.”*

The objective of ensuring environmental safety is also consistent with the International Atomic Energy Agency’s (IAEA’s) fundamental safety objective of protecting people and the environment from the harmful effects of ionising radiation [21], which in the context of radioactive waste disposal is to [22, paragraph 2.15]:

> *“… site, design, construct, operate and close a disposal facility so that protection after its closure is optimized, social and economic factors being taken into account...”*

The generic ESC demonstrates how the safety objectives defined by the environmental regulators and the IAEA are met by addressing the regulatory principles and requirements contained in the GRA (encompassing management, radiological and non-radiological hazard, and technical aspects of a safety case) as far as is possible at the present stage of GDF development (that is, while one or more potential disposal sites are being sought). Note that the Government has a strong preference to manage the disposal inventory in a single GDF, on the basis that lower environmental impacts and major costs savings could be realised by developing a facility at a single site. The planning assumption for the generic DSSC is therefore that only one GDF will be necessary for the disposal inventory. The illustrative disposal concepts and designs, which are consistent with RWM’s technical requirements on the disposal system, as set out in the generic Disposal System Specification (Part B) [11], provide the basis for assessments of the associated safety and environmental impacts. Social and economic impacts will also be considered when addressing the GRA’s optimisation requirement as the GDF siting and design processes progress.

This generic ESC has been produced in the context of the GRA requirements (although there is no specific regulatory requirement for an ESC to be produced prior to GDF site investigations). RWM has set out in its Environmental Safety Manual (ESM) [23, §6.1.4.2] the following six objectives for the generic ESC:

- to present the environmental safety arguments and justification for a range of illustrative geological environments and illustrative disposal concept examples
- to demonstrate that a GDF could be developed to meet the principles and requirements of the GRA
- to act as a communication tool within RWM
- to support the provision of packaging advice as part of the Disposability Assessment process [24]
- to provide input to prioritisation of the research programme

- to build capability in demonstrating the environmental safety of geological disposal

Note that this generic ESC does not address each requirement of the GRA systematically, as was done in the first generic ESC published in 2010 [6]. Instead, it focuses on requirements relating to the demonstration of long-term environmental safety in the context of a GDF in different geological environments. However, references are made to the 2010 generic ESC [6] where more detailed information regarding RWM's approach to meeting particular GRA requirements is available, especially in relation to requirements where further developments are likely to be more appropriate at the site-specific stage.

The development of site-specific ESCs will commence when volunteer sites have been identified. However, the generic ESC will be maintained and used to support disposability assessments and feed into research and design programmes until there is sufficient confidence in a site-specific ESC that a generic ESC is no longer required. Eventually, a site-specific ESC will support an application relating to the geological disposal of radioactive wastes made under the Environmental Permitting Regulations (EPR 2010) [18], as amended. Details of the regulatory requirements on the disposal system are presented in the generic Disposal System Specification (Part A) [25, §5].

The primary audience for the 2016 generic DSSC is expected to include regulators and stakeholders such as CoRWM. It is anticipated that the audience will have a scientific and technical background, with some knowledge of the context of geological disposal. The 2016 generic ESC has been written with such an audience in mind.

1.4 Scope

The generic ESC is based on an understanding of the scientific and engineering principles underpinning geological disposal. While disposal sites are being sought, these principles are considered in the context of illustrative disposal concepts for the three types of host geological environment noted in Section 1.1 (that is, higher strength rocks, lower strength sedimentary rocks and evaporites). For each of the three types of host geological environment, illustrative disposal concepts for LHGW and HHGW have been developed, on the assumption that LHGW and HHGW will be disposed of in separate areas of the same GDF.

The radiological hazard potential of the wastes disposed of in the GDF will generally decrease with time as a result of radioactive decay. Also, the materials placed underground will slowly degrade and conditions in the geological environment will evolve. The generic ESC shows how the environmental safety of geological disposal of radioactive waste can be achieved by considering radioactive decay and material degradation processes in the design and implementation of engineered barriers appropriate to particular combinations of waste and geological environment. The generic ESC also shows how the multi-barrier system will protect the environment from any non-radiological hazards posed by the waste. Broadly, the generic ESC is based on a demonstration that the isolation and containment functions provided by a suitable multi-barrier system can ensure that the wastes do not cause any harm to people or the environment, even in the long-term after disposal.

This demonstration of environmental safety is based on an understanding of the environmental safety functions that are expected to be provided by the different barrier components as conditions in the GDF evolve. The understanding of barrier performance and disposal system evolution expressed in the generic ESC draws on the knowledge base presented in RWM's research status reports. Also, calculations of radionuclide behaviour have been undertaken for a number of disposal concepts in order to provide an illustrative evaluation of how the different barriers are expected to contribute to long-term radiological safety. Details of these calculations and the models used are presented in the PCSA [5]. Given the generic stage of RWM's disposal programme, the PCSA is not intended to represent a full performance assessment; instead it explains how understanding of post-closure performance can be evaluated and illustrates aspects of that evaluation in the context of some illustrative examples. For example, the PCSA calculations are limited to an assessment period of a few hundred thousand years, because at this generic stage in GDF development, it is not possible to quantify uncertainties in long-term conditions reliably. A full post-closure performance assessment will be carried out in the future in conjunction with a site-specific ESC when a disposal site has been identified and details of the disposal concept and site characteristics are available.

The PCSA calculations also support the provision of packaging advice to waste producers as part of RWM's process for assessing whether a proposed waste package is suitable for geological disposal (that is, RWM's Disposability Assessment process). The generic ESC discusses how this Disposability Assessment process gives confidence that the acceptance of any waste packaging concept for disposal is based on an assessment of compatibility with the disposability requirements of the future GDF.

1.5 Document structure

The generic ESC is structured as follows:

- Section 2 sets out RWM's environmental safety strategy, focusing on how environmental protection will be achieved throughout the radioactive waste disposal process. In particular, maintenance of the ESC and its integration with the design and siting process is described. Section 2 also discusses the safety assessment strategy at the current stage of the siting process and explains how the ESC supports the Disposability Assessment process. Finally, the approach to ensuring environmental safety during the operational phase of the GDF is discussed, with reference to the generic Operational Safety Case (OSC) [26] and the supporting OESA [4].
- Section 3 presents a qualitative discussion of how the long-term environmental safety of geological disposal is achieved by the environmental safety functions provided by different components of a multi-barrier system.
- Sections 4 to 9 discuss the concepts developed for the disposal of different types of radioactive waste in the illustrative geological environments, focusing on how the barriers are expected to maintain their environmental safety functions as conditions in the GDF evolve.
- Section 10 presents qualitative and quantitative safety arguments based on assessments of the post-closure performance of a GDF in different geological environments. These assessments are supported by a number of illustrative calculations of radionuclide migration in groundwater. Section 10 also includes safety arguments relating to the transport of radionuclides in the gas phase (in particular C-14), the potential effects of nuclear criticality in a GDF, the impacts of human intrusion, and the potential hazards presented by the disposal of non-radiological contaminants.
- The key findings of the generic ESC are brought together in Section 11.

2 ESC Strategy

Developing an ESC is an important part of the programme to implement geological disposal for higher activity wastes. The ESC needs to provide confidence that the GDF will remain safe for hundreds of thousands of years after it has been closed and is no longer actively maintained. Such an ESC, in support of an application for an environmental permit for disposal of radioactive waste at a specific site, will be a substantial submission and will need to demonstrate understanding of:

- the geology, hydrogeology, geochemistry, geotechnical characteristics and surface environment of the chosen site and its setting
- the characteristics of the waste, including its radionuclide and materials content, treatment and packaging
- the design and layout of the disposal facility, including the design of the engineered barriers and how the facility will be constructed, operated and closed
- the environmental safety functions provided by each component of the barrier system
- the evolution of the multi-barrier system after GDF closure
- the basis for, and output from, computer-based models of the performance of the disposal system and its barriers
- semi-quantitative and qualitative supporting evidence that builds confidence in the claims for environmental safety

At the current time the location of the GDF is unknown. As the GDF design will be tailored to the GDF site characteristics, this means that the details of the engineered barriers that will be used to isolate and contain the wastes are also unknown. Thus, it is clearly not possible to produce a site-specific ESC and this ESC is necessarily generic. Once information is known about the potential location of the GDF, it will be possible to start to develop a site-specific GDF design (including an appropriate engineered barrier system) and hence a site-specific ESC.

The generic ESC published in 2010 [6] set out the requirements and structure for an ESC and provided assessment calculations that focused on a ‘reference case’ using a range of assumed hydrogeological parameters based on consideration of a GDF in a higher strength rock. In response to regulatory and other stakeholder feedback on that generic ESC, this generic ESC is taking a somewhat different approach. Instead of defining a reference case, this generic ESC discusses safety in terms of the various barriers of illustrative concepts for disposal facilities in higher strength rock, lower strength sedimentary rock and evaporite rock, explaining how the environmental safety functions provided by the barriers will work together to provide long-term safety. This qualitative discussion of safety is supported by calculations based on the illustrative disposal concept examples [3, §6.1] defined by RWM for different hypothetical geological environments [27, §5].

When appropriate, site-specific ESCs will be developed based on conceptual understanding of actual sites using concepts and designs that have been tailored to the geological environment at each of those sites. Further details on the strategy for developing and maintaining the generic and site-specific ESCs are presented in Section 2.1.

In addition to the high-level strategy for maintaining the ESC, the safety strategy includes a management strategy, a design and siting strategy, and an assessment strategy:

- An overall management strategy is needed to provide confidence that RWM can deliver the Disposal System Specification and the design and assessment strategies in a coherent, integrated way and with appropriate quality and management accountability and a positive safety culture over the long timescales of GDF planning and delivery. RWM's overall management strategy is defined in a Management System Manual (MSM) [28], and includes the Safety and Environmental Management Prospectus [29] that sets out the management strategy and safety procedures for delivering the GDF, and the ESM [23] that provides a framework for the maintenance and updating of the ESC documents throughout the GDF lifecycle. The management strategy is summarised in Section 2.2.
- Section 2.3 discusses the siting and design strategy. It explains how the National Geological Screening Guidance [30] is based on presenting an overview of available information about geology to a depth of about 1000 metres beneath England, Wales and Northern Ireland, especially regarding geological attributes that are important for long-term environmental safety.
- The assessment strategy is presented in Section 2.4. It follows international good practice and the requirements of the environment agencies' GRA [20]. At this generic stage, the assessment strategy is inevitably rather different from that which will be applied at the site-specific stage. Section 2.4 therefore explains the assessment strategy for this generic ESC, as well as summarising the future strategy to be followed as the safety case evolves.

The generic ESC and its supporting PCSA [5] are being maintained to provide an understanding of long-term environmental safety and a demonstration of the viability of constructing a GDF in a range of geological environments. The generic ESC and PCSA also provide the basis for undertaking disposability assessments of waste packaging proposals as part of RWM's Disposability Assessment process (see Section 2.5). Interfaces with the operational safety assessment, which is the subject of the OESA [4], are discussed in Section 2.6.

As noted in Section 1.3, this generic ESC does not address each requirement of the GRA [20] systematically. However, Table 1 indicates where, in the generic ESC, RWM's approach to meeting each requirement of the GRA is discussed and implemented as far as is possible at the generic stage of GDF development. Further discussion of the GRA requirements is provided in Appendix A. In addition, Appendix A includes references to sections of the 2010 generic ESC [6] where more detailed information regarding RWM's approach to meeting particular GRA requirements is available, especially in relation to requirements where further developments are likely to be more appropriate at the site-specific stage; repetition of such information has been avoided in this generic ESC.

Table 1 Sections in this report where the requirements of the GRA [20] are discussed[2]

No.	GRA requirement title	Section of this generic ESC in which the approach to meeting the requirement is discussed
R1	Process by agreement	Section 2.1
R2	Dialogue with potential host communities and others	Section 2.3
R3	Environmental Safety Case	Section 2 (with entire document comprising the generic approach)
R4	Environmental safety culture and management system	Section 2.2
R5	Dose constraint during the period of authorisation	Section 2.6
R6	Risk guidance level after the period of authorisation	Section 2.4.3, 10.3 and 10.4
R7	Human intrusion after the period of authorisation	Section 10.5
R8	Optimisation	Section 2.3
R9	Environmental radioactivity	Section 10.7
R10	Protection against non-radiological hazards	Section 10.8
R11	Site investigation	Section 2.4.6
R12	Use of site and facility design, construction, operation and closure	Section 2.3
R13	Waste acceptance criteria	Section 2.5
R14	Monitoring	Section 2.6

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[2] Note that the “period of authorisation” is the same as the period for which an environmental permit is held.

2.1 Maintaining the ESC

As understanding starts to be obtained about possible sites for the GDF, RWM will begin to develop site-specific ESCs as parallel work-streams. Figure 2 shows how the Environment Agency expects environmental safety cases to be refined as the disposal facility development programme proceeds [20, Figure 6.1]. The objectives of each update of the ESC as the disposal facility is developed are summarised in Table 2 [23, Table 3]. The generic ESC will be maintained throughout the GDF siting process until there is sufficient confidence in the site-specific ESC that the generic ESC is judged no longer to be required. This section describes the high-level strategy for developing the site-specific ESC throughout the GDF implementation programme and for maintaining a generic ESC.

This generic ESC will be submitted for review as part of the regulatory scrutiny programme, although there is no formal regulatory requirement to produce such an ESC. The first formal regulatory submission to the environmental regulator (as indicated in Figure 2) will be an Initial Site Evaluation (ISE) to obtain the necessary permit for the start of intrusive investigations at a specific site, such as drilling boreholes. The ISE will set out how a site-specific ESC will be constructed during subsequent stages of the GDF development programme (see Table 2).

Figure 2 **Refinement of an ESC as increasing amounts of information on possible sites for the GDF become available as set out in the GRA [20, Figure 6.1]**

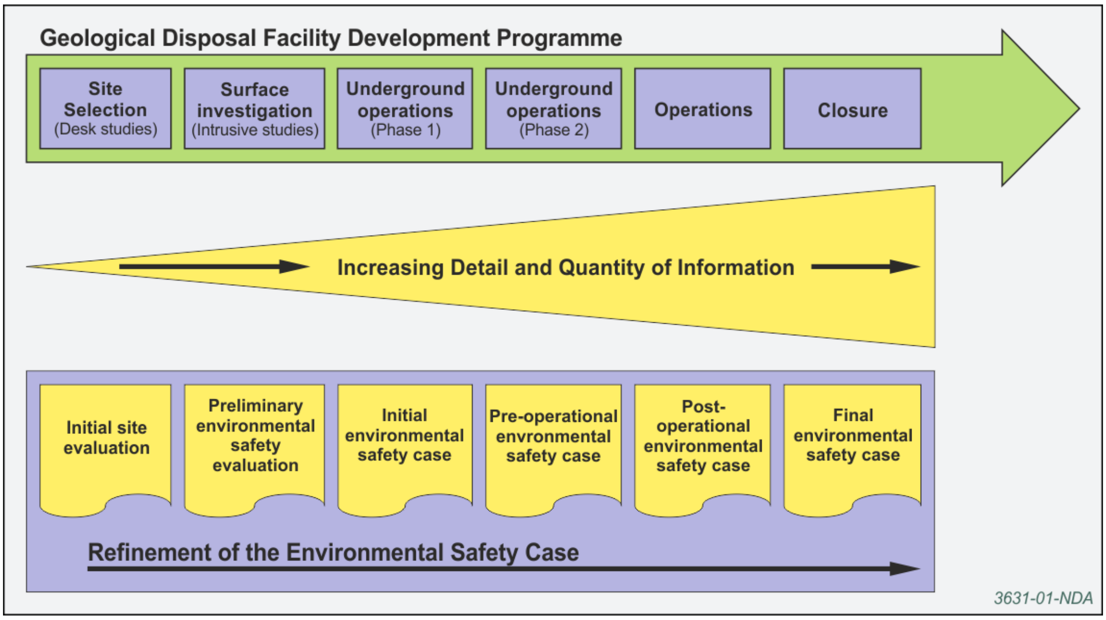


Table 2 Objectives of ESCs produced throughout the GDF development programme [23, Table 3]

Stages of ESC refinement consistent with the GRA	Main objectives of the ESC
Generic ESC	Generic ESCs are not required submissions, but they support the process by agreement (GRA Requirement R1) and the process of dialogue with potential host communities and others (GRA Requirement R2). A generic ESC presents environmental safety arguments and justification for a range of illustrative geological environments and illustrative disposal concept examples, demonstrating that a GDF could be developed to meet the principles and requirements of the GRA.
Initial site evaluation	The ESC produced prior to the start of intrusive site investigations will present mainly qualitative views on the feasibility of constructing a GDF at a candidate site and whether such a facility could meet the principles and requirements of the GRA. It will set out how a site-specific ESC might be constructed and will demonstrate that any proposed intrusive site investigation will not compromise the integrity of a site to the unacceptable detriment of post-closure safety.
Preliminary environmental safety evaluation	The ESC produced prior to the start of underground operations will present qualitative environmental safety arguments supported by quantitative assessment based on available site knowledge and data and specific designs, demonstrating consistency with the principles and requirements of the GRA. The ESC will demonstrate that underground operations would not compromise the integrity of a candidate site to the unacceptable detriment of the ESC.
Initial ESC	The ESC produced during site construction and the first phase of underground operations (pre-waste emplacement) will provide full environmental safety analysis and demonstration through claims, evidence and arguments that the GDF as designed would meet the principles and requirements of the GRA.
Pre-operational ESC	The ESC for waste emplacement, will confirm that the ‘as-built’ GDF meets the criteria defined in the initial ESC, and can be commissioned and operated in accordance with the environmental regulator’s waste disposal permit conditions. ESCs will be produced during GDF operations to demonstrate that the GDF continues to meet the environmental regulator’s permit conditions and that any operational changes do not adversely affect this position. Such an ESC will facilitate issue of variations to disposal permits.
Post-operational ESC	The post-operational ESC will demonstrate that the GDF can be closed in a manner that ensures environmental safety, and meets conditions for the issue of a closure permit by the environmental regulator.
Final ESC	The final ESC (for permit surrender) will provide full justification and confidence that the site will continue to be environmentally safe and that the risks to future populations will be ALARA for as long as required by the regulator.

The key components of RWM's strategy to develop a site-specific ESC that demonstrates sufficient understanding and confidence in the performance of the proposed GDF can be summarised by a number of strategic principles as follows:

- **Building confidence in the safety case**

  Confidence in the environmental safety of geological disposal will be built by applying a multi-barrier concept, which is the internationally accepted approach to geological disposal [25, §1]. A site-specific ESC will document understanding of how the different barriers will perform and ensure that environmental safety requirements are met for the proposed GDF.

- **Parallel generic and site-specific work programmes**

  By developing site-specific ESCs as parallel and separate work-streams to the generic ESC, there will always be an accepted benchmark safety case. In particular, RWM will continue to develop and maintain the generic ESC as a living suite of documents throughout the GDF siting process, until such time as there is sufficient confidence in the site-specific ESC that it is judged that a generic ESC is no longer required. This strategy allows for the possibility of additional, alternative sites being put forward for consideration and allows RWM to continue to undertake disposability assessments (see Section 2.5) that encompass a broad range of potential disposal concepts until such time as a site-specific ESC is sufficiently well-established.

- **Iterative development of the site-specific ESC (closely coupled to needs-driven research, site characterisation, the Disposal System Specification and engineering design programmes)**

  As information is gathered from these programmes and analysed in the ESC (and other parallel safety assessments), the ESC will be able to feed understanding back on site characterisation requirements, definition of research needs, development of site-specific requirements for the Disposal System Specification, and identification of engineering design activities. Thus, the iterative approach will enable there to be focus on those areas where increased understanding will be of most benefit to the evolving safety case. This iterative development of the ESC will be subject to RWM's quality management system, including the change control process as designs and specifications are progressed (see Section 2.2).

- **Presentation of complementary environmental safety arguments**

  In line with regulatory guidance [20, §7.3.5-§7.3.7] and the accepted international approach [22, §4], confidence in geological disposal will be demonstrated in an ESC by making use of multiple lines of reasoning based on a variety of evidence, both qualitative and quantitative. This approach enables the presentation of complementary environmental safety arguments. For example, arguments for environmental safety in the very long term will be supported by evidence for the persistence of uranium ore bodies under conditions similar to those expected to be experienced by wastes in the GDF [31, §4.3.1]. Also, assessments of the rates of radionuclide release from different wasteforms and assessments of radionuclide fluxes through disposal system barriers will provide environmental safety indicators in addition to calculations of radiological risk [20, §7.3.7]. Calculated radiological risk will be compared with the risk associated with the radiological dose that might be received from natural background ionising radiation in order to provide context and understanding of the risks associated with geological disposal.

- **Development and testing of understanding of the GDF system and its evolution over long timescales under a comprehensive range of representative scenarios through computer modelling**

  A rigorous and systematic process to developing and testing understanding of the long-term performance of the GDF will be followed, linked to needs-driven research, site characterisation and engineering design programmes. RWM will develop a hierarchy of computer models to represent understanding and will iteratively test and refine these models in the light of the developing understanding from the needs-driven research, site characterisation and engineering design programmes [32]. This iterative model development process will include:

  - gathering of relevant information
  - interpretation of information by using it to build conceptual models of the GDF components and system, and identifying potential evolution scenarios
  - developing mathematical models that represent the events and processes identified as being of importance to the different scenarios of system evolution
  - use of analytical solutions to simplified forms of the mathematical models to gain insights into the significance of different processes and how they affect the performance of specific barrier components
  - development of computer models to represent understanding of the total system, including any uncertainty in that understanding, at an appropriate level of detail
  - testing understanding of the system and modelling results against observations and other relevant information
  - identifying where the uncertainty in understanding has a significant impact on confidence in the GDF performance
  - commissioning appropriate research/site characterisation/engineering analysis and design work to reduce relevant uncertainties and improve understanding
  - updating the models to reflect improved understanding and testing new modelling results against observations and other information
  - continuing this iterative process of obtaining information, updating and refining models and assessing the significance of outstanding uncertainties until there is sufficient confidence that the quantitative assessment of GDF performance and post-closure environmental safety undertaken in support of the ESC will meet regulatory and stakeholder expectations

- **Demonstration of understanding of the uncertainties relevant to safety assessment**

  Confidence in the ESC will require demonstration that outstanding uncertainties significant to the ESC can be appropriately managed so there is still confidence in overall safety. An appropriate approach to the treatment of uncertainty at each stage of ESC development activities will be adopted, noting that:

  - it is not possible to eliminate all uncertainties; for example, uncertainty relating to the potential for human intrusion into the GDF cannot be eliminated, but practical measures can be taken to reduce the likelihood of intrusion [20, §6.3.42]
  - the types and extent of uncertainty are expected to change as the GDF implementation programme progresses

  - where outstanding uncertainties can be quantified they will be explicitly included in ESC calculations (for example, via appropriate parameter ranges); where significant uncertainties cannot be quantified, they will be acknowledged and treated appropriately (for example, through consideration of potential alternative conceptual models and scenarios)
  - both qualitative and quantitative arguments can be used to address uncertainty

In order to achieve confidence in the strategy and the resulting generic and site-specific ESCs in the future, RWM will continue to:

- ensure that all data used in the ESC are fit for the purpose for which they are being used and maintain traceability of data by developing and maintaining appropriate data records, as set out in the RWM Data Management Procedure [33]
- follow a systematic approach to identify all relevant features, events and processes (FEPs) that have the potential to affect the initial state of the GDF (that is, the state of the GDF immediately following backfilling, sealing and closure) or its evolution over long timescales
- use the FEP understanding to identify possible scenarios of GDF evolution
- develop conceptual models and underpinning mathematical models of system evolution scenarios, verifying that the models are implemented correctly in computer codes and using the computer codes to test the models against site data; to achieve this RWM will develop and maintain a modelling capability throughout the GDF implementation programme in line with RWM's model development procedures and defined roles and responsibilities [34]
- use the computer codes (as well as qualitative arguments) to assess GDF evolution scenarios at the generic and site-specific stages
- use the computer codes to test the models against independent data that have not been used in developing the models, wherever practicable
- develop clear ESC hierarchical documentation that is suitable for all relevant stakeholders at key stages in the GDF decision-making process
- subject ESC-related documents to review throughout their development in accordance with RWM's procedures, including final independent peer review as part of RWM's publication process
- maintain consistency with RWM's Technical Programme [35; 36] and the research and development activities described in RWM's Science and Technology Plan [13]

2.2 Management strategy

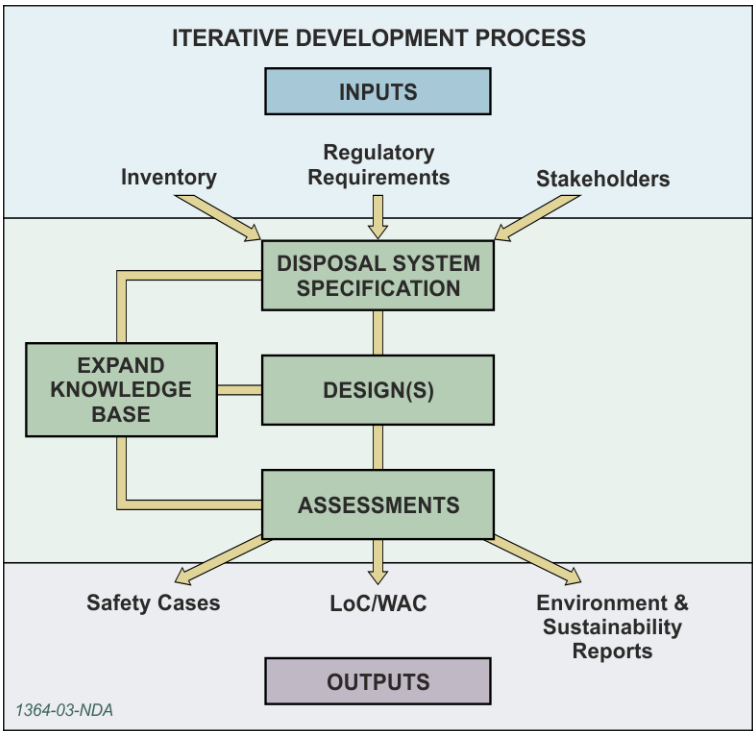
Important aims of the management strategy are to ensure that RWM's activities are co-ordinated and integrated to ensure a sound basis for decision-making that underpins a robust safety case, and to promote a positive environmental safety culture. The management strategy must also ensure that RWM is able to communicate its plans and findings clearly to regulators and to other stakeholders, and take appropriate actions in response to their feedback. RWM's overall management system is described in the MSM [28], which sets out the process for implementing, assessing and continually improving the management system such that safety and environmental protection are properly addressed. The broader aim of continuing to engage with regulators and with appropriate stakeholders in the development of the GDF is set out in RWM's Corporate Strategy [37].

The Overview [1] contains details of RWM's quality management system, including the document review and change control processes that underpin all work undertaken by RWM to deliver the DSSC. In this section the focus is therefore on those aspects of RWM's management strategy that are particularly relevant to supporting the development of the ESC.

The safety arguments and analyses presented in the ESC build on the evidence of the RWM knowledge base and work undertaken to develop the inventory, the Disposal System Specification, disposal concepts and disposal system designs. It is important that all inputs to the ESC are controlled and coordinated in an iterative manner (as illustrated in Figure 3), with the outputs from the ESC used to identify where further work is required to improve the knowledge base.

Figure 3 indicates how development of the Disposal System Specification takes account of the disposal requirements of the inventory, regulatory requirements and stakeholder inputs. The disposal concept designs developed from this specification are assessed and the outputs from these assessments used to identify where the knowledge base requires expanding in order to improve the underpinning of the design and assessments. This iterative approach leads to a needs-driven, prioritised Science and Technology Plan [13] that captures the requirements for future research and development to support the safety case. The science and technology plan is reviewed by the safety case owners to ensure it meets the need of providing the evidence in a timely manner in order to build confidence in the safety case at a particular stage of disposal facility development and environmental permitting. The outputs of a safety case produced at each stage of GDF development support the identification of research requirements to develop the knowledge base for subsequent safety cases.

Figure 3 The iterative approach to developing transport, operational and environmental safety cases at each stage of GDF development; the output of each safety case supports the identification of research requirements to develop the knowledge base for subsequent safety cases[3]



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[3] LoC refers to the Disposability Assessment (or 'letter of compliance') process and WAC refers to waste acceptance criteria.

As the owner of the ESC, it is important that RWM demonstrates itself to be a capable organisation, with suitably qualified and experienced staff, to develop and maintain the ESC [37]. The skills required to develop and maintain the ESC are understood and documented in RWM's competence management system [38]. All those RWM staff involved in the production of the ESC are required to hold and maintain the appropriate competences and RWM's contractors are also selected on the basis of demonstrating the appropriate skills and competences. RWM's post-closure staff maintain an awareness of developments in international safety cases, through active involvement in various OECD NEA (Organisation for Economic Co-operation and Development - Nuclear Energy Agency), IAEA and European Commission (EC) committees and projects and through review of the safety cases of other waste management organisations. In particular, members of the RWM post-closure team recently participated in a study of a selection of international safety cases, with the aim of identifying learning points of relevance to this generic ESC [39]. The development of this ESC has therefore been informed by knowledge gained from studying best international practice and its application in advanced safety cases from other waste management programmes, such as in Sweden, Finland, France and the USA.

In accordance with the application of sound science and engineering, the ESC and supporting assessments are based on a formal development process that conforms to internationally accepted methodologies as set out by the IAEA [22] and the NEA [40]. The formalised assessment methodology ensures that all necessary aspects are covered, and requires a structured treatment of uncertainty (as discussed in the PCSA [5, §3.3]). In house development of the ESC ensures that RWM retains control and understanding of this core component of its work and facilitates interfaces with other areas of the organisation that provide inputs to the ESC. In particular, this approach to developing the ESC helps to ensure that all safety arguments presented in the ESC are underpinned by appropriate evidence, for example from RWM's research and design development work.

In developing the ESC, RWM collaborates with internationally experienced contractors and draws on consideration of GDF designs and environmental safety assessments from many other projects worldwide. Where appropriate, RWM applies standard software for analysis that is in use by many other waste management organisations. For example, at this generic stage, the internationally-accepted GoldSim software [41, 42] is used for post-closure safety assessment calculations (as discussed in the PCSA [5, §3.4]). Software applications are verified and validated (as far as is possible when evaluating processes that operate over long timescales).

RWM's safety case work is exposed to external scrutiny, in particular through peer review by the wider scientific and radioactive waste management communities, which builds confidence in RWM's wider technical and scientific credibility. This includes publication of papers at scientific conferences and in peer-reviewed scientific journals, a recent example of which is the publication of RWM's proposals for the development of the qualitative aspects of the generic ESC in the peer-reviewed Mineralogical Magazine [43].

RWM is certified to ISO 9001:2008 and ISO 14001:2004 by Lloyds Register Quality Assurance (LRQA). RWM's Management Systems Manual [28, Appendices 1 and 2] contains a set of matrices that indicate where the requirements of ISO 9001:2008 and ISO 14001:2004 are addressed within the management system. There are specific quality assurance requirements in a range of areas relevant to development of the generic ESC. For example:

- control of documents
- review and scrutiny of deliverables
- handling of data
- checking of computer calculations

RWM has recently updated the procedures that control the use of numerical data and models [32; 33] to ensure a more robust approach that actively considers and takes account of the potential risks associated with using numerical data and models.

As the GDF development project progresses, additional quality assurance requirements will be defined to cover other key aspects of the GDF implementation programme, such as site characterisation and GDF design, construction and operation.

2.3 Siting and GDF design strategy

UK Government policy for siting the GDF, as set out in the 2014 White Paper [2] and summarised in the Technical Background [3], states that the Government favours an approach based on working with communities that are willing to participate in the GDF siting process. The White Paper sets out a framework for the implementation of geological disposal, beginning with a process of national screening, based on known geological information. National geological screening will present an overview of existing information about the geology to a depth of about 1,000 metres or so beneath England, Wales and Northern Ireland [30]. It will focus on aspects of the geological environment that are relevant to the long-term safety of a GDF. The national geological screening guidance sets out the geological attributes that are relevant to meeting the post-closure safety requirements of the GDF (rock type, rock structure, groundwater, natural processes and resources) and national geological screening will provide information on these geological attributes which will be used to inform discussions with interested communities. Formal discussions between interested communities and RWM will not begin until after the completion of the national geological screening process.

While the geological screening progresses, the strategy for GDF design and assessment is focused on illustrative concepts for radioactive waste disposal in the three generic rock types noted in Section 1.1 (higher strength rock, lower strength sedimentary rock and evaporite rock). Once potential sites for the GDF have been identified, information will be gathered on the specific geological environments that they provide. This information will be used to develop site-specific GDF designs, appropriate to the geological conditions at the site(s) under consideration. These designs may or may not be based on the generic designs considered in this ESC. This is why all calculations presented in this generic ESC can only be considered as illustrative. The site-specific GDF designs will be evaluated in site-specific ESCs. As the GDF implementation programme progresses and further site information is gathered and evaluated, an iterative design optimisation process will be followed using a site-specific ESC to ensure that any radiological exposures from the GDF are ALARA.

At the generic stage, design decisions are being made that relate to waste packaging, and RWM's approach is to provide advice that is robust to a range of future outcomes, thus allowing waste packagers to make decisions as part of their responsibilities for optimisation as duty holders (see Section 2.5). At the current stage of the programme RWM is not seeking to reduce siting or design choices unnecessarily and is therefore maintaining a range of possible options to be considered in future site-specific optimisation decisions.

2.4 Assessment strategy

As stated in the GRA [20, §4.2.1] and discussed in Section 1.2, the fundamental protection objective is:

> *"…to ensure that all disposals of solid radioactive waste to facilities on land are made in a way that protects the health and interests of people and the integrity of the environment, at the time of disposal and in the future, inspires public confidence and takes account of costs."*

Therefore, in the context of the GRA, a safety assessment strategy involves a course of action designed to demonstrate the safety of people and the environment, both at the time of disposal and in the future.

A detailed numerical assessment of safety is not possible prior to identification of a GDF site and the development of detailed GDF designs. Therefore, in this generic ESC the safety assessment strategy focuses on a narrative that presents RWM's understanding of safety in the context of the three identified GDF host rock environments and illustrative disposal concepts for each of those environments.

2.4.1 Illustrative disposal concepts

Illustrative disposal concept designs have been identified for two broad waste categories, namely HHGW and LHGW, and these designs are based on concepts that have been developed in the UK or overseas, examples being selected on the basis that they are well-developed with sufficient information available. The selected examples are shown in Table 3.

Table 3 Illustrative generic GDF concept examples that form the basis of the LHGW and HHGW GDF designs considered in the generic ESC; the developer and country associated with each example are indicated

Host rock	Concept example considered in the generic ESC for LHGW disposal	Concept example considered in the generic ESC for HHGW disposal
Higher strength rock[4]	UK ILW/LLW concept (RWM, UK)	KBS-3V concept (SKB, Sweden)
Lower strength sedimentary rock[5]	Opalinus Clay concept (Nagra, Switzerland)	Opalinus Clay concept (Nagra, Switzerland)
Evaporite[6]	WIPP bedded salt concept (US DOE, United States)	Gorleben salt dome concept (DBE, Germany)

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[4] Higher strength rock – the UK ILW/LLW concept and SKB's KBS-3V disposal concept were selected because of the availability of information on these concepts for the UK context. Supercontainer options (such as assumed in SKB's KBS-3H concept) would also be considered in future work should a potential site be identified in an area of the UK that provides access to suitable higher strength rock at GDF depth.

[5] Lower-strength sedimentary rock – Nagra's concepts for radioactive waste disposal in the Swiss Opalinus Clay were selected because an NEA review regarded the Nagra work as state of the art [44]. However, there is similarly extensive information available for the French (Andra) concepts (for radioactive waste disposal in the Callovo-Oxfordian Clay), which have also been accorded strong endorsement from international peer review. Although the Swiss concepts are used as the basis of the illustrative geological disposal concepts, information from the French programme and from the Belgian HLW/spent fuel supercontainer concept would be drawn upon, should a potential site be identified in an area of the UK that provides access to suitable lower strength sedimentary rock at GDF depth.

[6] Evaporite – the concept developed by the US Department of Energy (US DOE) for disposal of transuranic wastes at the Waste Isolation Pilot Plant (WIPP) facility was selected because of the wealth of information available from a licensed facility that has operated for more than 15 years. The concept developed by the German Company for the Construction and Operation of Waste Repositories (DBE) for disposal of HLW/spent fuel was also selected because of the level of information available.

Each disposal concept is defined by a high-level description of the GDF's multi-barrier system and the safety concept upon which environmental safety is based. The disposal concept will provide the environmental safety functions and meet the requirements defined in the Disposal System Specification for a particular waste group in a particular geological environment [25; 11].

The illustrative generic designs have been used as the basis for illustrative disposal concept examples to support the safety narratives presented in this generic ESC (Sections 4 to 9). The safety claims made in this narrative are underpinned by scientific evidence and are supported by a range of qualitative and quantitative arguments about radionuclide transport and containment for the different illustrative disposal concepts, as discussed in the following sub-sections.

2.4.2 FEPs, scenarios and environmental safety functions

The first stage of any GDF assessment requires building an understanding of what needs to be assessed. In terms of the ESC this means considering all features, events and processes (collectively termed 'FEPs') that have the potential to affect the long-term safety of the GDF. The OECD NEA has developed an international FEP database that is used as a reference checklist for many national geological disposal facility safety cases. The NEA FEP database is kept under review so that any newly identified FEPs can be added. The most recent version available for use in this ESC is that published in June 2014 [45]. For this generic ESC, the NEA FEP database was reviewed to identify all FEPs potentially relevant to a GDF in the UK. This FEP screening, and an explanation of how each relevant FEP has been considered, is provided in an appendix to the post-closure performance modelling report (the Model Report) [46].

The FEPs are used to build a description of the disposal system and the way in which it is expected to evolve. The expected or natural evolution is defined as the 'base scenario'. The base scenario contains all FEPs that are considered more likely than not to occur. These include all features of the disposal system (for example, the wastes, their containers, the buffer or backfill and the features of the geological environment), all natural processes affecting the disposal system (for example, groundwater movement, sorption, solubility, radioactive decay, and corrosion processes) and any events that are expected to occur (for example, resaturation of disposal areas). The FEPs that may or may not occur are termed 'probabilistic FEPs' (for example a large seismic event or nuclear criticality). These FEPs are not included in the base scenario, but their occurrence may define a variant scenario, which may need to be assessed.

In order to identify relevant scenarios for assessment, it is helpful to consider how the GDF provides long-term environmental safety and this is done by understanding the behaviour of the GDF's barrier system through the 'environmental safety functions' that each barrier provides. Environmental safety functions are defined in the GRA as [20, page 111]:

> *"The various ways in which components of the disposal system may contribute towards environmental safety, e.g. the host rock may provide a physical barrier function and may also have chemical properties that help to retard the migration of radionuclides."*

Consideration of environmental safety functions provides a systematic and comprehensive way of understanding and describing the performance of a GDF. Demonstrating safety for all credible environmental evolution scenarios then becomes a matter of considering the environmental safety functions and examining the timescales over which they are effective and the situations in which they may be challenged or compromised.

The GDF is required to isolate and contain the wastes [25, §5.4.4]. Isolation means the removal of the wastes from people and the accessible environment. Containment means retaining the radioactivity from the wastes and any non-radiological contaminants within various parts of the disposal facility such that environmental safety is maintained in the very long term after disposal. Features that contribute positively to providing isolation include the depth of the GDF, the stability of the surrounding geology and the lack of potentially exploitable mineral resources. Features and processes that contribute to containment tend to be those associated with the multiple barriers of the disposal concept; for example, the stability of the wasteform, the container integrity, the retentive properties of the buffer/backfill and the retardation properties of the geological barrier.

It is possible to provide a generic discussion of these high-level environmental safety functions and then to provide more detail for those safety functions associated with specific disposal concept examples. This is because the relative importance of different environmental safety functions will vary between different disposal concepts. Section 3 of this generic ESC discusses environmental safety functions at a general level and Sections 4 to 9 discuss environmental safety functions for the illustrative disposal concept examples listed in Table 3.

The effectiveness of the environmental safety functions can be evaluated within the context of the different scenarios that describe disposal system evolution. A safety case will always need to include evaluation of the base scenario, but relevant variant scenarios will also need to be identified and evaluated. Variant scenarios can be identified by considering those probabilistic FEPs that have the potential to challenge one or more of the barrier system's environmental safety functions for a particular disposal concept. For example, a direct drilling intrusion into the engineered barriers may mean that the containment safety function provided by the geological barrier is negated. Likewise, a major seismic event may damage aspects of the containment safety functions provided by the engineered or geological barriers. Sections 4 to 9 include discussions of base and variant scenarios for the illustrative disposal concept examples.

2.4.3 Evaluation strategy

The main focus of this generic ESC is the qualitative demonstration of the understanding of how long-term environmental safety may be achieved for a GDF through consideration of FEPs and environmental safety functions. Detailed quantification of safety is not appropriate at this generic stage. However, RWM is able to demonstrate its approach to environmental safety evaluation and to illustrate that approach with some example illustrative calculations. This section sets out RWM's safety evaluation strategy for the generic stage and Section 2.4.6 explains how the strategy will change for the site-specific ESC.

At the generic stage, it is possible to gain considerable understanding of the post-closure performance of the GDF, and even to quantify that understanding, by consideration of the basic physics of the disposal system. This is often termed 'insight modelling' and is discussed in Section 2.1 of the PCSA [5]. Insight modelling is particularly helpful at the generic stage because it does not require large amounts of data. At later stages of the GDF programme, when detailed site-specific data are available, insight modelling will support understanding of specific processes associated with the behaviour of radionuclides and non-radiological species under disposal conditions (by, for example, using simplified deterministic representations of potential transport pathways).

Insight modelling complements the more detailed probabilistic modelling of the behaviour of radionuclides and non-radiological species in a disposal system that takes account of uncertainty in system evolution. The detailed total system models have been constructed in order to undertake probabilistic evaluations of post-closure safety. RWM's approach to model development is described in Section 3.1 of the PCSA [5], and details of the total system models and their implementation using the GoldSim software are presented in the Model Report [46].

An appropriate treatment of uncertainties is important to the ESC. Section 3.3 of the PCSA [5] describes how uncertainties are treated in the ESC in terms of uncertainty of future states of the disposal system, data uncertainty, model uncertainty and uncertainty about human behaviour. The probabilistic total system modelling approach enables treatment of data uncertainties. The assessment has also considered specific model uncertainties with regard to 'rock matrix diffusion', which describes how dissolved species can diffuse into and sorb onto rock alongside hydraulically conductive fractures. Uncertainties in biosphere properties have been explored by considering different environments in which human exposure to radioactivity could occur. Also, the ESC has considered inventory uncertainties by undertaking qualitative assessments of the impacts of alternative scenarios for radioactive waste arisings.

For this generic ESC, all numerical evaluation is based on the illustrative examples described in Section 2.4.1. Full details of the parameterisation of the illustrative geological environments, the disposal concepts and system evolution for the total system model applications are presented in the PCSA [5] and the Data Report [47].

As noted in Section 2.1, it is a requirement of the GRA [20] that an environmental safety case presents multiple lines of reasoning to support its evaluation of safety. The use of safety arguments based on the understanding of the environmental safety functions of the GDF and their evolution represents an important line of reasoning, which can be developed at this generic stage for the illustrative disposal concepts and can continue to be applied in the context of a site-specific ESC. Insight modelling and more detailed numerical modelling to understand how radionuclides are contained by each component of the GDF's multi-barrier system constitute further lines of reasoning.

Other lines of reasoning may also be used to support an evaluation of post-closure safety. These include the use of complementary indicators and natural and archaeological analogues. For example, complementary indicators include measurements of groundwater age (by comparisons of oxygen isotope concentrations) that can give confidence in calculated groundwater flow rates. Archaeological analogues include studies of materials proposed for use in the engineered barriers of the GDF to give confidence in calculations of barrier performance. Natural analogues can include comparisons with geological sites that have similarities to one or more components of the GDF. To provide a reference source of safety-relevant examples from natural systems that could be used to support a safety case, RWM has produced a catalogue of natural analogues for radioactive waste disposal [48]. Also, in support of the safety case for spent fuel disposal at Olkiluoto in Finland, Posiva produced a report on 'complementary considerations' with the objective of enhancing confidence in the safety case [49]. Posiva's report includes a compilation of observations from natural and anthropogenic analogues of the disposal facility, its components and the processes that affect safety, and provides a further reference source for consideration in the development of different lines of reasoning to support an evaluation of the safety of a GDF in the UK.

As an example, the uranium ore body known as 'Cigar Lake' in northern Saskatchewan, Canada is often used as a natural analogue for the geological disposal of spent fuel [48; 49]. Cigar Lake was formed some 1,300 million years ago at a depth of about 430 metres; similar to the depth generally considered as suitable for a GDF. At Cigar Lake, the uranium ore is surrounded by a clay-rich halo (analogous to the bentonite buffer proposed for use in many spent fuel disposal concepts). Measurements in the environment above Cigar Lake indicate that there is no significant trace of uranium or its daughters at the ground surface, implying that the rocks surrounding the uranium ore have prevented uranium migrating to the surface for a period that is more than a thousand times longer than that considered in most GDF safety cases. Of course, in making use of archaeological and natural analogue evidence in an ESC, it is important to understand the conditions under which the analogue material was able to persist.

2.4.4 Assessment of environmental safety states

In describing and analysing the performance of a GDF it is helpful to consider three different environmental ‘safety states’:

- containment in the engineered barrier system
- containment in the geological barrier
- return of residual waste materials to the accessible environment at regulated, acceptable levels

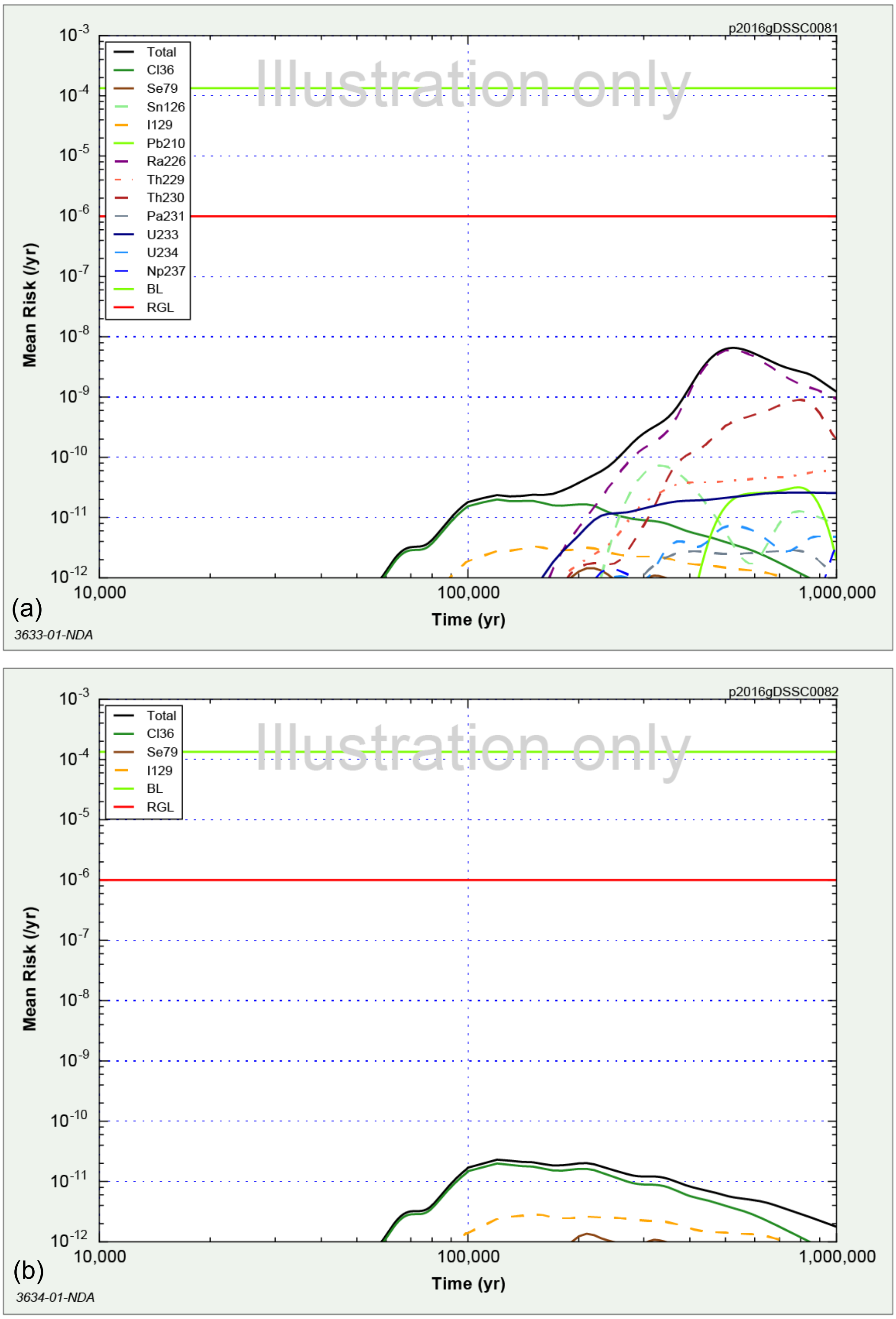
The timescales of these three safety states will vary for different disposal concepts and also for different radionuclides within the same disposal concept. For example, relatively insoluble actinides will be contained in the wasteform and buffer/backfill for a significantly longer period than more soluble and mobile radionuclides such as chlorine and iodine. Also, gaseous releases of radionuclides from waste packages have the potential to occur on much shorter timescales than releases via groundwater. However, the activities of the majority of radionuclides will become insignificant as a result of radioactive decay while the radionuclides are contained within the engineered barrier system or the geological barrier. Section 3.1 of this generic ESC discusses these safety states and the timescales over which they are applicable for different concepts and different radionuclides.

Safety arguments and containment calculations are used to underpin confidence in the first two safety states. Calculations quantifying potential radionuclide releases to the accessible environment are used to compare calculated risks with the regulatory guidelines to support demonstration of the third safety state. For example, Figure 4 provides an illustration of how total system model calculations can be used to explore and understand the environmental safety functions provided by the barrier system of a GDF and how they relate to the different safety states.

These calculations are based on credible assumptions about hydrogeological and geochemical conditions in the vicinity of a GDF at a coastal location. In this illustration, it has been conjectured that a pathway exists along which radionuclides released from degrading LHGW packages are able to migrate slowly until eventually entering a marine environment. The marine environment has been assumed to form part of a biosphere in which humans could become exposed to residual radioactivity associated with the wastes.

Figure 4 shows the calculated mean risk via the marine pathway (based on many probabilistic calculations) for illustrations in which (a) the fractured host rock has been assumed to provide little radionuclide containment and (b) the host rock has been assumed to provide an environment in which strongly sorbing radionuclides are retained. In the first example, migration of Cl-36 (half-life of 3.07×10^5 years [47]) and I-129 (half-life of 1.57×10^7 years [47]) over a distance of some 15 kilometres from the engineered barrier system through the host rock and cover rock and into the marine environment results in a peak in calculated mean radiological risk of 10^{-11}/year on a timescale of 100,000 years. On a timescale of about 800,000 years, there is a peak in calculated mean radiological risk associated with Ra-226. Ra-226 has a relatively short half-life (1.6×10^3 years [47]), but it occurs as a result of the decay of Th-230 (half-life of 7.54×10^4 years [47]), which itself occurs from the decay of U-234 (half-life of 2.46×10^5 years [47]). In the second example, uranium and thorium are strongly sorbed in the host rock, as might be expected in a realistic host rock, but Cl-36 and I-129 are not. Thus, the calculated mean risks associated with Cl-36 and I-129 are little changed, but the calculated risk from Ra-226 and uranium and thorium isotopes on a timescale of 1,000,000 years has diminished substantially.

Figure 4 **Illustration of calculated mean risk associated with LHGW disposal where exposure occurs via a marine pathway and where (a) the host rock provides little radionuclide containment and (b) strongly-sorbing radionuclides are retained in the host rock; the risk guidance level (RGL) and the estimated risk from background level (BL) ionising radiation are shown**



These calculations illustrate how containment provided by the engineered barrier system (in this case, in particular, a cementitious backfill) ensures that the flux of radionuclides entering the geosphere is low and that radiological risk is low irrespective of the properties of the host rock. The results also indicate how understanding geosphere properties and reducing uncertainties through site characterisation can support quantification of the environmental safety functions provided by the multi-barrier system.

Such calculations enable judgments to be made about the environmental safety of a disposal facility in the context of regulatory requirements. The return of residual waste materials to the accessible environment is governed by regulatory discharge authorisations during the operational phase of the GDF, as described in the generic OESA [4]. Beyond the period of authorisation (that is, the period for which an environmental permit is held [18]) it is necessary to demonstrate that the risks associated with the return of any residual materials to the accessible environment are consistent with the regulatory risk guidance level [20, § 6.3.10]. That is, the assessed radiological risk from the disposal facility to a person representative of those at greatest risk should be consistent with a risk guidance level of 10^{-6} per year, which is a cautious standard for environmental safety [20, § 6.3.19]. The calculated mean risks for the example shown in Figure 4 are substantially below the risk guidance level.

The calculated mean risk is also substantially lower than the risk associated with the radiological dose that might be received from natural background ionising radiation. The average annual dose from natural radiation is about 2.23 mSV [50]. Risk factors for low dose rate exposure have been estimated to be about 0.06/Sv for the whole population [47]. Therefore, the risk from natural background radiation is about 1.3×10^{-4}/year. This background level risk is indicated in Figure 4. Thus, by demonstrating that any radiological risks associated with the disposal facility are consistent with the risk guidance level, confidence can be gained in the high level of human protection provided by the disposal facility.

Details of the calculations undertaken using the total system models to generate results such as those shown in Figure 4 are presented in the PCSA [5]. At one level, these calculations illustrate the quantitative analysis that will be undertaken to support a site-specific ESC. However, the calculations also give confidence that a GDF for the UK's higher activity radioactive waste will meet environmental safety requirements and they support the waste package disposability assessment process (see Section 2.5).

As indicated by the example shown in Figure 4, calculations to evaluate the safety state of each disposal concept have been performed by specifying the properties of hypothetical but realistic illustrative geological environments, including possible cover rock sequences. Broad descriptions of the geological environments considered are presented in the Geosphere Status Report [27] and more detailed descriptions of the characteristic of the illustrative geological environments specified for the radionuclide transport calculations are presented in the generic PCSA [5, §5.1 and §5.4]. These calculations have been limited to evaluation of radionuclide transport in groundwater for the illustrative disposal concepts for higher strength rock and lower strength sedimentary rock. Such calculations have not been undertaken for the illustrative disposal concepts for evaporite rock because such host rocks will not exhibit interconnected porosity and there will be no mobile water present [27, §2.1.1].

The calculations of risk to support understanding of the third safety state require assumptions to be made about the biosphere. Descriptions of potential human activities in the accessible environment and pathways for exposure to radioactivity are presented in the Biosphere Status Report [51]. Consistent with international guidance, potentially exposed groups (PEGs) are defined by considering a series of reference biospheres [52], each of which can be considered as an alternative conceptual model for the biosphere. The total system model calculations have assumed that exposure to radioactivity could occur via radionuclide migration from the GDF to terrestrial or marine environments. Potential exposure routes include drinking water, ingestion of crops, ingestion of animal products and fish, inhalation and ingestion of dust and direct external irradiation. Also, calculations of risk have included consideration of a well pathway in which there is exposure to contaminated well-water used for domestic purposes and small-scale irrigation. The hypothetical well is assumed to persist throughout the post-closure period and to extract water from an aquifer at a location that effectively maximises calculated risk from radionuclides that enter the well capture zone.

The results of the illustrative calculations are presented in Section 10 of this generic ESC as part of the assessment of base and variant scenarios of disposal system evolution for the different disposal concepts. The assessment of variant scenarios has generally focused on scenarios relating to more rapid container degradation than expected. A detailed formal analysis of the sensitivity of results to different assumptions about the geosphere and biosphere has not been undertaken at this generic stage of GDF development. Instead, a small number of calculations have been included to explore the robustness of the safety case to key assumptions about geosphere and biosphere characteristics, such as the radionuclide retention properties of the host rock (Figure 4) and the inclusion of a well pathway.

The assessment presented in Section 10 includes a discussion of the potential radiological hazard associated with radionuclide transport in the gas phase, the main concern being exposure to C-14 (half-life of 5.73×10^3 years) in methane. However, illustrative calculations of risk associated with human exposure to such gas have not been undertaken for this generic ESC. RWM's analysis of gas generation and migration in different geological environments is discussed in the generic PCSA [5, §6] based on the more detailed consideration of gas transfer behaviour reported in the Gas Status Report [53, §6]. In many geological environments, conditions will be such that gas generated as a result of waste degradation in the disposal facility will become dissolved in groundwater as the gas migrates and therefore any exposure will occur via the groundwater pathway [5, §6.2; 53, §6]. When a site for the GDF is identified, it will be possible for RWM to develop a quantitative understanding of the different safety states of the disposal facility with regard to radioactive gas generation and migration.

The results of assessment calculations and qualitative arguments can also be used to support demonstrations that non-human species are adequately protected from environmental radioactivity, as required by the GRA [20, § 6.3.64] and discussed in Section 10.7. The analysis of environmental safety states is also important to the consideration of non-radiological hazards that could arise from chemotoxic species in the GDF, as required by the GRA [20, §6.4.1] and discussed in Section 10.8.

2.4.5 Assessment timescales

As discussed in Section 2.4.3, an ESC is required to use multiple lines of reasoning, ranging from reasoned qualitative safety arguments to detailed probabilistic safety analyses. RWM considers that it may be appropriate to use different lines of reasoning when assessing the environmental safety of geological disposal over different timescales after disposal. By considering the hazard presented by the wastes in the GDF and the uncertainties associated with the GDF and its environment, it is possible to determine the types of assessment that are meaningful at different times. Initial uncertainties in disposal system conditions immediately following GDF closure are likely to be associated with transient processes, prior to conditions within the GDF stabilising. Later, uncertainties associated with the evolution of the geological barrier and the biosphere will become significant.

A description of disposal system evolution, supported by safety arguments related to the environmental safety functions provided by the components of the multi-barrier system, is appropriate to all assessment timescales. This narrative of disposal system evolution can be supported with complementary environmental safety arguments and comparisons with appropriate natural and archaeological analogues. Appropriate quantitative assessments include insight models and simple, deterministic calculations. Such safety arguments and assessments are presented in this generic ESC and will be presented in future site-specific ESCs.

The early transient phase may be characterised by factors such as thermal transients in the disposal areas, resaturation of barrier materials, and rock creep, depending on the characteristics of the wastes, the engineered barrier system and the host rock. During this transient phase, the post-closure performance of many types of waste package relies on the containment of the wastes within their waste packages (with the potential exception of any releases in gas or contaminated groundwater from vented containers). That is, assessment of radionuclide releases from many waste packages will not be relevant during the early transient phase.

For the period in which the disposal system is expected to be relatively stable and uncertainties in the behaviour of radionuclides and non-radiological contaminants can be quantified more reliably, it is appropriate to undertake probabilistic calculations of GDF performance. However, if it is not possible to quantify uncertainties reliably, then the results of probabilistic calculations become less meaningful.

In particular, for periods in excess of a few hundred thousand years after GDF closure, the geological environment could be affected by large-scale natural processes, such as tectonism (including earthquakes), subsidence, uplift and erosion, permafrost development and periods of glaciation. The Geosphere Status Report [27, §4] discusses how the geosphere could be affected by such processes over the next one million years and how these processes could affect conditions in the vicinity of the GDF in the UK. For example, climate evolution modelling indicates that a cooling trend could begin to develop in the UK after around 170,000 years, with processes such as glacial loading and unloading, permafrost, glacial erosion and sea-level change all having the potential to affect the long-term environmental safety of a GDF [27, §4.3.2]. The GDF siting process will consider large-scale earth and climate-related processes that could affect the subsurface environment. For example, mapped faults will be avoided in defining the lay out of the GDF, making it unlikely that individual vaults or tunnels could be directly cut by any future movement on existing faults [27, §2.1.4]. Furthermore, GDF structures will be designed to tolerate fault displacements associated with the largest earthquakes expected in Britain [27, §4.4]. However, until specific sites have been identified as potential locations to host a GDF in the UK, RWM considers that it is not appropriate to undertake a detailed assessment of the impacts of large-scale natural processes on GDF performance.

Thus, although calculations of radionuclide behaviour and risk on timescales of 1,000,000 years (such as those shown in Figure 4) for hypothetical and unchanging illustrative geological environments and biospheres can be used to support an understanding of the containment potential of different barriers, the modelled conditions can only be interpreted as representing subsets of the many potential system evolution scenarios that could be conjectured. The probabilistic calculations reported in Section 10 focus on an assessment period of 300,000 years after GDF closure, which is considered to be sufficient to give an indication of the barriers that are likely to be of most importance to GDF performance on the timescales over which some large-scale natural processes could occur.

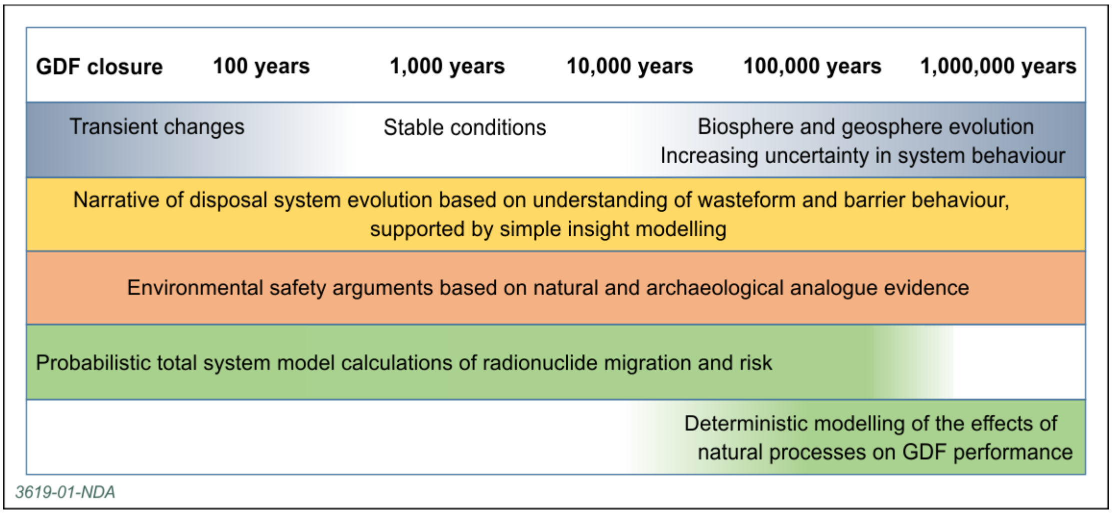
RWM’s research has included consideration of the effects of natural transient processes (such as glaciation and other effects related to climate-change, seismic activity and erosion) on groundwater flow and radionuclide transport [54]. The research concluded that potentially the most significant processes are those associated with glaciation, namely the presence of permafrost and the presence of a warm-based ice sheet. The changes to the biosphere associated with changes to the climate were found to be significant for some climate states.

Other research on the potential implications of natural changes on the performance of a GDF noted that groundwater flow could be influenced by tectonic processes, glacial processes, long-term climate change, erosion and river capture [55]. However, the research concluded that, for the majority of processes considered, the effects on a GDF over the next one million years are likely to be minimal. Glacial erosion and erosion and weathering could affect the near-surface environment, and permafrost (to depths of several hundred metres), seismicity (low probability events) and changes in groundwater flow patterns could affect conditions in a GDF depending on its location, but the consequences are not expected to be significant.

In future site-specific ESCs, the illustrative geological environments will be replaced with information acquired through the site characterisation programme [27, §7], and calculations will be included to evaluate the impacts of natural processes on the safety functions provided by key barriers, based on specific descriptions of possible long-term environmental conditions. That is, assessments of GDF performance over timescales in excess of a few hundred thousand years will be based on stylised deterministic calculations involving different assumptions about how natural processes, such as glaciation, could affect conditions in the biosphere and geological environment [56]. Such an approach has been taken in the assessment of the potential impacts of post-closure criticality on disposal system performance, as discussed in Section 10.6. On these timescales, the majority of the disposal inventory will have decayed and the GDF will have evolved into a system analogous to a large natural uranium deposit [49].

RWM's approach to assessing GDF performance over different timescales through different lines of reasoning is summarised in Figure 5.

Figure 5 Illustration of assessment techniques appropriate to different timescales based on consideration of uncertainties in disposal system conditions



2.4.6 Development of a site-specific ESC

The understanding of safety developed in this generic ESC will provide the basis for developing appropriate disposal concepts and designs for an eventual site-specific ESC, as illustrated in the flowchart in Figure 6.

Figure 6 **Flowchart showing how safety cases are progressed as system understanding develops from a generic to a site-specific level; the preparation of ESCs according to this flowchart at different stages of the GDF development programme is as indicated in Figure 2 and Table 2**

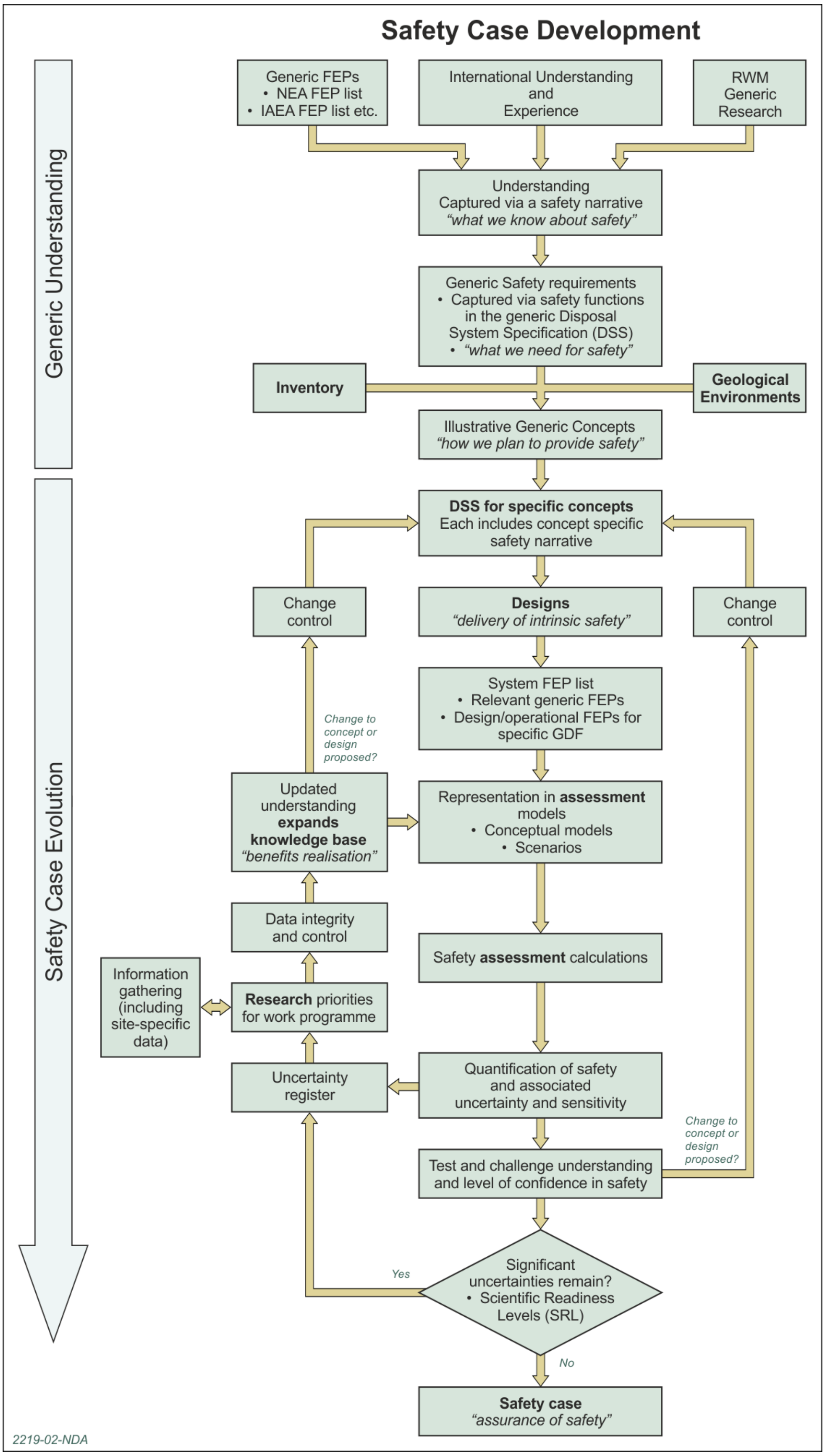


Figure 6 indicates how a site-specific ESC will build on the generic safety narrative presented in this ESC, but the safety assessment calculations will be developed in a new and iterative manner, starting with the development of a site-specific, evidence-based conceptual model. It is in respect of assessment calculations that the ‘twin track’ approach of maintaining generic and site-specific ESCs is applied until the generic ESC is no longer required (as discussed in Section 2.1). The stages of ESC development are not shown on Figure 6, which focuses on the development of system understanding in parallel with the production of progressively refined ESCs (see Figure 2 and Table 2).

Development of conceptual models for the site-specific ESC will be integrated with the research and development and site investigation programmes. In some cases, there will be uncertainty over the most appropriate model representation. For example, particularly in the early stages of site characterisation, there may be significant uncertainty concerning the available geological environment(s) and the routes by which radionuclides released from the engineered barrier system (EBS) could be transported to the accessible environment. Such uncertainty should be progressively reduced as understanding of the site increases. Model uncertainty will be evaluated through implementation and analysis of alternative conceptual models within the performance assessment framework. For example, alternative conceptual models could include different potential transport pathways and mechanisms to take account of uncertainty in the parameters of the geological barrier.

The possible future evolution of the surface environment and the ways in which people living in the far future could be exposed to radioactivity released from the GDF are highly uncertain. For assessments of the present-day situation at a particular site, a critical group can be defined that is representative of those individuals in the population expected to receive the highest dose on the basis of activities that can be currently observed to occur. The critical group is considered throughout the period in which an environmental permit is held, during which time human activities in relation to the GDF can be monitored and controlled if necessary. However, after the environmental permit is surrendered, when active institutional control of the GDF has ceased, developments of the surface environment and new human interactions with it become possible. Some of this uncertainty is dealt with through the development of scenarios, such as those to address inadvertent human intrusion into the GDF. Within the base scenario, as in this generic ESC, uncertainty about biosphere evolution is addressed through consideration of a number of PEGs defined on the basis of reference biospheres [52]. In this way, the behaviour of PEGs and the environment with which they interact is stylised to illustrate the dose and risk that could be received through a particular lifestyle or activity. A stylised approach involves the use of a set of assumptions that are either generally reasonable or clearly conservative, as indicated in Section 2.4.4 for this generic ESC. This approach is accepted by the environmental regulators in the absence of specific information about what would actually happen in the far future.

PEGs have to be chosen conservatively so that the range of potential exposure routes is covered, and the human habits represented are consistent with the geological environment under consideration. It may be appropriate to define more than one PEG for use in an assessment to represent the range of potential exposure routes and their variation with time. As more is learned about the GDF site it will be possible to underpin the definition of the PEGs with more sophisticated analyses, possibly by including catchment-scale modelling.

Figure 6 highlights the important iteration between specification and design of the disposal system, safety assessments and needs-driven research to build understanding, identify and reduce uncertainties and control required changes to the disposal system in order to develop an optimised disposal system with a robust safety case. This is consistent with the iterative development process described in the RWM Environmental Safety Manual [23], which explains how the safety objectives and criteria are met through iterative cycles of assessment, design optimisation and environmental risk reduction in the context of identification, review and specification of the relevant environmental safety functions.

2.5 Strategy for disposability assessment

The Technical Background [3, §2] describes the UK's accumulated legacy of higher activity wastes. Much of this radioactive waste has already arisen and is being stored on an interim basis at nuclear sites across the UK. Some wastes have already been (or are being) conditioned and packaged in anticipation of geological disposal; packaging concepts are being developed for other wastes.

RWM has an important role to support waste producers through assessment of waste packaging proposals and provision of advice on waste package disposability before the waste packages are manufactured. This advice is provided through application of RWM's Disposability Assessment process. The philosophy that underpins RWM's approach to the conduct of disposability assessments is set out in the disposability assessment aims and principles policy [57]. Through the Disposability Assessment process, RWM works with the waste packagers to gain confidence that manufactured waste packages will be compliant with the anticipated needs of an ESC for safe disposal in the GDF. The aim is that any waste package with a Final Stage 'letter of compliance', together with an appropriate package record, will be expected to be acceptable for disposal in the GDF [24].

As discussed in the Technical Background [3, §8.1] waste packages disposed of in the GDF ultimately must be compliant with the waste acceptance criteria (WAC) defined for that facility. In the UK, plans for the geological disposal of higher activity wastes are still at an early stage, so the information necessary to develop final WAC is not available. However, in order that wastes can be converted into a safe and disposable form as soon as possible, RWM has produced and maintains generic specifications for waste packaging (for example, for LHGW [58]). The aim of each generic specification is to define the bounding requirements for all waste packages that might contain a specific type of waste in such a manner that those requirements can be applied to a particular design of waste package. By providing such requirements RWM assists the holders of radioactive waste in the development and implementation of waste conditioning and packaging plans and engenders confidence that waste packages that meet the requirements will be compatible with the anticipated needs for safe transport to and disposal in the GDF. The Disposability Assessment process minimises the risk that the conditioning and packaging of radioactive wastes results in the production of waste packages that are incompatible with geological disposal, as far as this is possible in advance of the availability of WAC for the GDF. Thus, the generic specifications for waste packaging and the Disposability Assessment process enable early hazard reduction on UK nuclear sites.

As part of this safety case update, revisions to the Disposability Assessment process to align with the latest thinking on the approach to undertaking post-closure performance assessments (PCPAs) of waste packages have been discussed (both in this generic ESC and in the supporting generic PCSA [5]). In this revised approach to PCPAs, FEPs associated with the characteristics and post-closure performance of the proposed waste package are considered in order to determine whether the waste package is compliant with post-closure requirements. That is, through a FEP analysis, it is determined whether the wasteform and container provide appropriate environmental safety functions such that the waste package is compatible with the waste isolation and containment requirements of the disposal system. This analysis is undertaken in the context of the environmental safety arguments set out in this generic ESC.

If initial analysis indicates the possibility that one or more FEPs associated with a proposed waste package could have an adverse impact on one or more environmental safety functions of the disposal system, then further more detailed analysis of waste package performance may be undertaken as part of the Disposability Assessment process. For example, where appropriate, the Disposability Assessment process will involve numerical analysis as part of the PCPA for the waste package. The generic PCSA [5, §2.3] provides further information regarding PCPAs undertaken to support disposability assessments.

Undertaking a PCPA as part of the Disposability Assessment process helps to build up an overall picture of the packaged waste for disposal in the GDF; this is also supported by the information in the derived inventory. As discussed in the Technical Background [3, §2], the 2013 Derived Inventory [7] includes packaging descriptions for all waste streams (whether already packaged or not), unlike the UK Radioactive Waste Inventory (UKRWI), which does not include information for waste streams where conditioning processes have not been finalised. Development of the 2013 Derived Inventory included review and revision of the waste containers allocated to waste streams in the UKRWI in order to confirm that assumptions allow for waste to be packaged in a form suitable for its safe management, storage, transport, underground emplacement and potential disposal. Disposability assessments can also inform future updates of the derived inventory by providing the most recent information on waste packaging.

Undertaking disposability assessments provides RWM with confidence that an ESC can be made for the specific wastes present in the UKRWI. A PCPA will determine whether the requirements relating to post-closure safety outlined in the appropriate waste packaging specifications are met at the generic stage in advance of any specific post-closure WAC being developed. The Disposability Assessment process in general gives the waste producers and RWM confidence that the packages will provide the necessary post-closure environmental safety functions in support of a site-specific ESC. Similarly, the parts of the Disposability Assessment process that relate to waste package transport and GDF operational safety aim to give confidence that the transport and operational safety cases can be made [59; 26]. Eventually, the Disposability Assessment process will become a waste acceptance process. WAC will be formalised on the basis of the assumptions in the safety cases, considering, among other things, physical, chemical, thermal, mechanical, and radiological constraints on waste packages to ensure that wastes can be transported, handled and disposed of safely.

2.6 Interface with operational safety

An ESC needs to consider environmental safety both during the period when an environmental permit is held, and in the long term, after the GDF is closed. The generic ESC is supported by the generic OESA [4], which addresses environmental safety during the GDF's operational phase. No further information on operational environmental safety is included in this report, but detailed information can be found in the OESA [4].

Once the GDF has been constructed, but before waste is emplaced, a pre-operational ESC will be submitted to the regulators (see Figure 2 and Table 2). Such a document will be based on the actual site, design and intended inventory, taking account of knowledge and understanding gained during underground investigations and the initial phase of construction. For waste emplacement to proceed, this safety case will need to demonstrate that the GDF meets the requirements of the GRA. The pre-operational environmental safety case will provide a basis for an environmental permit to allow waste disposal to start and will consider the implications of construction and operation of the GDF on the post-closure safety of the facility.

During the construction period, the GDF will be excavated, drained by pumping as required, and the facility will be open to the atmosphere to allow the necessary operational activities associated with waste emplacement. Pumping will affect the hydrogeological regime around the facility. Ventilation will be used to circulate air throughout the facility. Depending on the method of construction, an excavation disturbed zone (EDZ) may form. Depending on the nature of the local geology, the EDZ may persist or begin to partially or completely reseal following construction. The GDF is likely to be constructed, used for waste disposal and closed over a period of several decades. During the operational period, different areas of the GDF may be at different stages of development. For example, at any point in time, new areas of the GDF may be being excavated while elsewhere, in other parts of the GDF, waste may be being emplaced or backfilling and sealing operations may be in progress.

The GDF will be designed and operated to ensure that environmental conditions in the underground facilities during the operational period will be maintained so as to ensure that the waste packages remain in as good a condition as possible prior to GDF closure. However, if there is an extended period when the disposal areas are kept open prior to backfilling, such as in the illustrative concept for LHGW disposal in higher strength rock, some waste package degradation may occur. In this case, appropriate facilities will be maintained for package remediation should it be deemed necessary in order to ensure that operational phase safety requirements are met. Such facilities would include suitable effluent collection and monitoring systems.

The underground facilities will be monitored during the operational period, such that any emissions of radioactive materials will be detected. Any discharges of aqueous radioactive waste will be collected, examined for radioactive material content, and remediated if necessary in the active effluent treatment plant that will form part of the surface facilities [4, §4.2]. Before any aqueous radioactive wastes are discharged (under the appropriate discharge consent) they will be tested to ensure compliance with the requirements of the consent. Discharges of solid radioactive waste from the GDF are discussed at a high level in the OESA [4, §4.1].

Abatement systems, such as high-efficiency particulate air (HEPA) filters, will be in place at discharge points of the ventilation system if required to trap any radioactive particulates detected in the air [4, §4.3]. Note that the ventilation to all radioactive areas underground would be supplied via a drift or shaft and discharged through a dedicated ventilation shaft [60]. Ventilation to construction areas, when construction is taking place in parallel with operational activities, would be supplied via fresh air from a shaft and discharged from a separate shaft and segregated from potentially radioactive gaseous discharges. RWM's operational stage monitoring programmes will be designed to enable informed decision-making about management of discharges and the waste packages in the disposal areas. In addition, radon gas from naturally occurring sources of radioactivity in the host rock may enter the underground facilities. For these reasons, the quantitative assessment of operational environmental safety in the generic OESA [4] focuses on the potential for (and environmental safety implications of) discharges of radioactive gases from the underground facilities.

The Environmental Safety Manual [23] discusses how operational experience and understanding will build confidence in an ESC by confirming whether barriers are initially providing environmental safety functions broadly as expected on the basis of engineering design specifications, and will aid the optimisation process by providing information on possible adjustments that could be made to barrier properties. It is anticipated that such performance confirmation will mostly take place through monitoring of engineered barriers immediately after their emplacement, but prior to facility closure. Alternative performance confirmation methods such as *in situ* experiments to understand barrier behaviour may also be used.

Performance confirmation activities will enable the post-closure 'initial state' to be substantiated. Before the start of operations, the defined post-closure initial state will be the same as the post-closure target state, but it will evolve as operational experience and understanding are incorporated into its definition. This post-closure initial state must be substantiated by evidence and data gathered during operations, and must be shown in the ESC to be consistent with assumptions made in the post-closure assessment, thus ensuring confidence in environmental safety in the post-closure period.

RWM is involved in GEOSAF II, which is an IAEA project that was initiated with the objective of reaching a common understanding of views and expectations regarding operational safety for geological disposal of radioactive waste and the implications of pre-closure activities on post-closure safety [61]. An important objective of GEOSAF II is to ensure that all activities during the pre-closure phase necessary to establish a satisfactorily closed and sealed disposal facility are carried out in a way that delivers the required conditions for the post-closure period. In this vein, the GRA requires that [20, §6.4.16]:

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

The GEOSAF II project [61] defines a 'safety envelope' that represents the boundaries within which, at the start of the post-closure phase, the state of the disposal system (that is, the parameters expressing the safety functions important for post-closure safety) must fall in order to deliver the post-closure safety functions. The safety envelope is usually derived by the operator from the safety case by taking into consideration applicable regulatory requirements. The safety envelope represents an 'outer boundary' that should not be exceeded.

The 'design target' defined by the GEOSAF II project represents the boundaries within which, at the start of the post-closure phase, the state of the disposal system is designed to fall [61]. The design target is derived by taking into consideration appropriate margins with respect to the safety envelope, in order to take into account the principle of optimisation of protection (and safety) and also the uncertainties associated with the anticipated state of the disposal system and its evolution. Depending on events and conditions during the pre-closure phase, the design might be updated and the design target could therefore evolve as the project progresses. The design target is derived by taking into consideration similar existing experience, relevant research and development, and understanding of the site. In practice, the design target will be given in the form of technical specifications to be followed by the operator during construction, operation and closure of the facility.

GEOSAF II [61] defines the 'as-built state' as the real state of the disposal system at a given time during construction, operation and closure. The disposal system at the end of closure represents the as-built state of the disposal system at the start of the post-closure phase. During construction and operation of the GDF, monitoring and inspection activities will be carried out to verify that the characteristics of the host rock correspond to what has been anticipated in the safety assessments. Likewise, monitoring and inspection activities will be carried out to verify that the engineered barriers are constructed according to their specifications so that the as-built state meets the design target.

This generic ESC assumes that the GDF will be constructed and operated as planned so that the barrier systems provide their post-closure environmental safety functions when considering the base scenarios. However, the effects of potential operational phase faults on post-closure behaviour have been considered to some extent when considering variant scenarios. For example, the effects of errors in bentonite buffer emplacement have been considered in the assessment of the concept for HHGW disposal in higher strength rock in terms of how conditions favourable to sulphide attack on copper containers could develop as a result. However, future work will involve assessment of a comprehensive range of potential operational phase faults for different disposal concepts to determine if and how they could impact post-closure performance.

3 Demonstrating Post-closure Safety

3.1 Safety concept

The environmental safety of geological disposal is achieved by isolating the wastes in a facility constructed deep underground and ensuring that the radionuclides and non-radiological contaminants are contained such that long-term safety is provided by passive means. The safety concept is based on ensuring that the long-term safety requirements for the GDF, as defined in RWM's generic Disposal System Specification (Part B) [11, §9] are met. These high-level long-term safety requirements are listed in Table 4; for some safety issues the generic Disposal System Specification (Part B) includes a number of more detailed requirements [11, §9].

The disposal facility's engineered and geological barriers will provide a range of environmental safety functions, consistent with the requirement for multiple safety functions indicated in Table 4. Understanding how the disposal facility's engineered and geological barriers will provide these environmental safety functions, through research, design and site investigation, will enable demonstration of how the long-term safety requirements shown in Table 4 will be met. Having established the environmental safety functions to be provided by a barrier component, requirements on the properties of barrier materials needed to fulfil those environmental safety functions will be provided through engineering design specifications. For example, RWM has developed Generic Specifications and Waste Package Specifications for specific waste types and specific designs of waste packages, respectively, which will ensure that waste packages will be produced such that the necessary environmental safety functions are provided [11, §3.1.3].

Any potential host rock must exist in an appropriate volume to accommodate the GDF and must be expected to remain stable over the timescale relevant to GDF safety such that it provides the necessary long-term safety requirements. As discussed in RWM's national geological screening guidance [30], and consistent with the first seven requirements listed in Table 4, a suitable geological environment will contribute to the following long-term safety requirements:

- the functions of the EBS will be maintained
- radionuclides or toxic substances entering groundwater will not compromise safety
- any gas generated in the GDF will not compromise safety
- natural events and changes will not compromise safety
- the site can be characterised sufficiently to demonstrate safety
- the effect of long-term evolution on safety can be understood
- the likelihood of human intrusion can be assessed[7]

The arrangements and material properties of the engineered barriers will be tailored for disposal of specific types of waste in particular geological environments in order to ensure that the safety requirements are met. Barrier systems typical of geological disposal concepts for ILW and HLW/SF are illustrated in Figure 7.

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[7] This requirement is not intended to apply a need to evaluate the likelihood of human intrusion; rather, it is concerned with assessing the consequences of human intrusion and identifying practical measures that could be implemented to reduce the likelihood of such consequences being realised (see Section 10.5).

Table 4 High-level requirements relating to GDF post-closure safety, as set out in the Disposal System Specification (Part B) [11, §9]

Safety issue	Requirement
Maintenance of the engineered barrier system functions	The disposal system shall be sited in an environment in which the functions of the engineered barrier system will be maintained for a period that will prevent release of radionuclides and toxic materials reaching the surface in quantities that could cause harm
Post-closure safety	The disposal system shall ensure that the quantities of radionuclides or toxic substances entering groundwater will not compromise safety
Gas generation and migration	The disposal system shall ensure that any gas generated in the facility will not compromise safety Design of a geological disposal facility shall ensure that gas pressures cannot develop within a disposal module that result in: • significant damage to the engineered structures or host rock • development of additional pathways for the transport of dissolved radionuclides
Natural events and climate change	The disposal system shall be sited in an environment in which natural events and climate changes will not compromise safety
Site characterisation	The disposal system shall be sited in an environment in which the site can be characterised sufficiently to demonstrate safety
Understanding of long term evolution	The disposal system shall be sited in an environment in which the effect of long-term evolution on safety can be understood
Human intrusion	The disposal system shall be developed such that the consequences of human intrusion can be assessed and any practical measures implemented to reduce the likelihood
Passive safety	Within the disposal system design, safety shall be ensured by passive means to the fullest extent possible
Multiple safety functions	The engineered barriers shall be designed to provide safety by means of multiple safety functions such that the overall performance of the disposal system shall not be dependent on a single safety function

The barrier system shown in Figure 7 for ILW is typical of that being considered more broadly for LHGW disposal and the barrier system shown for HLW/SF is typical of that being considered for HHGW disposal. Generally, the barrier systems comprise the wasteform, the waste container, buffer/backfill material, mass backfill, plugs and seals, and the geological environment. The ensemble of wasteform and waste container is referred to as a ‘waste package’[8] [62]. The buffer/backfill generally refers to material placed adjacent to and around the waste package in a GDF [63]. Mass backfill refers to material used to fill some or all of the empty space remaining in the excavated areas of a GDF once other engineered barriers have been emplaced.

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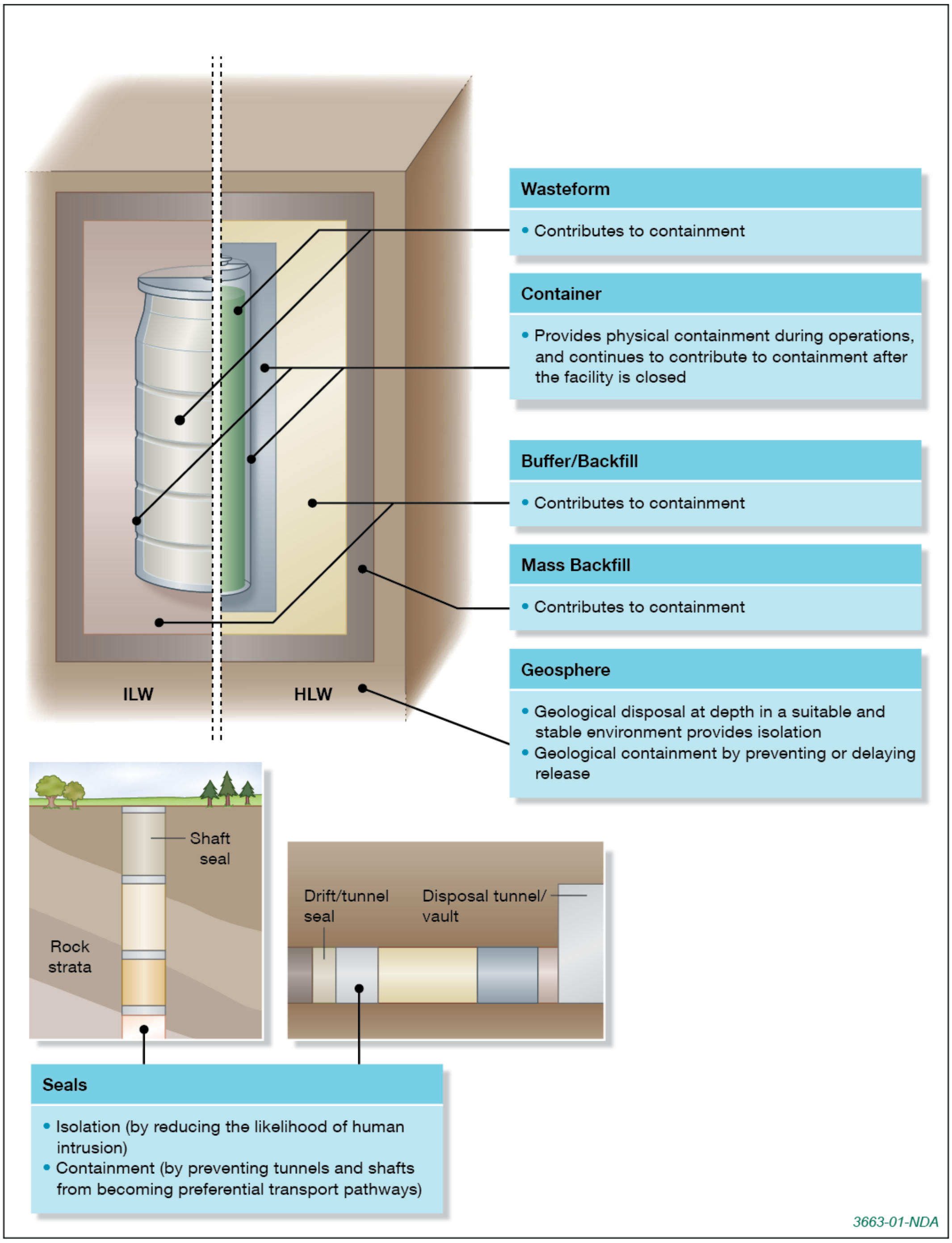
[8] A waste package may include nested containers. For example, wastes that are already packaged may require an additional container or ‘overpack’ for disposal.

Figure 7 Barrier systems for ILW and HLW geological disposal concepts and the isolation and containment functions that they provide; these barrier systems are typical of those being considered more broadly for LHGW and HHGW disposal



Wasteform

- Contributes to containment

Container

- Provides physical containment during operations, and continues to contribute to containment after the facility is closed

Buffer/Backfill

- Contributes to containment

Mass Backfill

- Contributes to containment

Geosphere

- Geological disposal at depth in a suitable and stable environment provides isolation
- Geological containment by preventing or delaying release

Seals

- Isolation (by reducing the likelihood of human intrusion)
- Containment (by preventing tunnels and shafts from becoming preferential transport pathways)

Details of RWM's illustrative packaging and disposal concepts for LHGW and HHGW disposal in different geological environments (see Section 2.4.1) are provided in the Disposal System Specification [25; 11]. The EBS materials that have been identified for these illustrative disposal concepts are summarised in Table 5. EBS concepts are also being developed for other wasteforms, such as thermally treated ILW and polymeric ILW.

Table 5 Example EBS materials identified for the disposal of different waste groups in different geological environments [3, Tables 6 and 7]

Host Rock	Waste Group	Wasteform	Container	Buffer/local backfill	Mass backfill	Seals
Higher strength rock	HHGW	Ceramic	Copper with cast iron insert	Bentonite	Bentonite Crushed rock	Structural concrete and bentonite
		Vitrified				
		Metallic				
	LHGW	Grout encapsulated	Stainless steel (some with concrete annulus/liner), carbon steel, concrete	Cementitious material (Nirex Reference Vault Backfill)	Crushed rock	Structural concrete and bentonite
		Un-encapsulated	Carbon steel, cast iron (some with lead liner)			
Lower strength sedimentary rock	HHGW	Ceramic	Carbon steel	Bentonite	Crushed host rock	Structural concrete and bentonite
		Vitrified				
		Metallic				
	LHGW	Grout encapsulated	Stainless steel (some with concrete annulus/liner), carbon steel, concrete	Cementitious material	Crushed host rock	Structural concrete and bentonite
		Un-encapsulated	Carbon steel, cast iron (some with lead liner)			
Evaporite	HHGW	Ceramic	Carbon steel	Crushed host rock	Crushed host rock	Concrete, clay, asphalt, salt
		Vitrified				
		Metallic				
	LHGW	Grout encapsulated	Stainless steel (some with concrete annulus/liner), carbon steel, concrete	Magnesium oxide (although not a bulk backfill material)	Crushed host rock	Concrete, clay, asphalt, salt
		Un-encapsulated	Carbon steel, cast iron (some with lead liner)			

In the illustrative disposal concepts, LHGW and HHGW will be emplaced in separate areas of the same GDF and will require different emplacement equipment [27, §6.7]. There will be no mixing of LHGW and HHGW packages in a single disposal area. Additionally, ILW/LLW and DNLEU will be disposed of separately within the LHGW area and HLW, spent fuels, HEU and separated plutonium will be disposed of separately in the HHGW area. Where necessary, the distribution and contents of waste packages in a disposal area will be controlled such that there are, for example, no detrimental thermal effects on barrier materials or the potential for post-closure criticality is limited [11; 25].

Also, the layout of the EBS for each co-located waste group in the GDF will need to be designed such that potentially detrimental thermal, hydraulic, mechanical, chemical (including biologically-promoted chemical processes), gas (THMCG) and other interactions between wastes and EBS materials are avoided. This will ensure that the environmental safety functions of the EBS and the geological environment are maintained as required after GDF closure. That is, disposal areas need to be separated by a distance sufficient to ensure that any interactions that do occur between them do not compromise the required performance of the disposal system [64; 27, §6.7]. For example, the performance of some EBS materials may be sensitive to temperature or pH conditions to the extent that minimum separation distances need to be defined between individual waste packages or between disposal areas for different waste groups in order to mitigate thermal or chemical interactions. RWM has determined that a separation distance of 500 metres between LHGW and HHGW disposal areas will ensure that, in most cases, the magnitude of any co-location interaction is likely to be within the uncertainty bounds that would be considered when evaluating the normal evolution of a disposal area independently [11; 64; 27, §6.7]. For the illustrative GDF designs considered in the ESC, co-location interactions between the LHGW and HHGW disposal areas are assumed to be insignificant. This is appropriate at this generic stage. At the site-specific stage, the necessary separation distances will be determined by consideration of the properties of the geological environment and the GDF design [64].

3.2 Environmental safety functions

The safety functions provided by the different barrier system components of a particular disposal concept will operate at different times after disposal, depending on how conditions in the GDF evolve. The radiological hazard potential of the wastes will decrease substantially as a result of radioactive decay while radionuclides are contained in the waste packages. However, eventually, long-lived radionuclides and non-radiological contaminants[9] may gradually migrate from the waste packages as containers and wasteforms degrade under disposal conditions. The migration of these contaminants will be limited by any buffer or backfill components present and the geological barrier. In the long term, if transport pathways exist through the multi-barrier system, small concentrations of contaminants may migrate to the surface environment in groundwater or gas. However, the GDF will be designed to ensure that the risks arising from the transport of residual contaminants to the accessible environment are sufficiently low that there will be no harm to people or the environment and hence that the three environmental safety states described in Section 2.4.4 are achieved.

Disruptive events such as human intrusion into the disposal facility or major seismic events that damage the barrier system could also result in the return of contaminants to the surface environment. Such events are regarded as breaches of the isolation and containment safety functions, and the robustness of the GDF's performance to their occurrence, even if considered highly unlikely due to siting requirements, requires assessment.

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[9] Hereafter, radionuclides and non-radiological contaminants are collectively referred to as contaminants.

By developing an understanding of the environmental safety functions expected to be provided by a particular geological environment and the influences on them, the environmental safety functions required of the EBS in order to fulfil the overall long-term safety requirements (Table 4) for different types of waste can be identified and optimised as part of the disposal system development process. To this end, it is convenient to define a general set of environmental safety functions that could be provided by different barrier system components at different times after disposal, as shown in Table 6. The general environmental safety functions are discussed at a high level in the following sub-sections. Typically, a disposal concept for a particular geological environment will comprise a barrier system that provides a sub-set of the general environmental safety functions shown in Table 6 and discussed below. Sections 4 to 9 discuss in more detail the environmental safety functions provided by the barrier systems of illustrative disposal concepts being considered by RWM for different host rocks [11, §2.2].

Table 6 General environmental safety functions that could be provided by different barrier system components; the barriers of any specific disposal concept may provide only a sub-set of these general environmental safety functions

Barrier component	General environmental safety function
Geological environment	Isolate the wastes Protect the engineered barriers Limit contaminant transport to the surface environment
Wasteform	Limit the release of contaminants Stabilise the structure and geometry of the engineered barriers Protect the internal surface of the waste container Limit the potential for nuclear criticality
Container	Prevent or limit the release of contaminants Prevent disruption by over-pressurisation from gas generation Stabilise the structure and geometry of the engineered barriers Limit the potential for nuclear criticality
Local buffer/backfill	Protect the container Stabilise the surrounding host rock and the structure and geometry of the engineered barriers Limit the release of contaminants Prevent disruption by over-pressurisation from gas generation
Mass backfill	Stabilise the surrounding host rock and the structure and geometry of the engineered barriers Limit the release of contaminants Prevent disruption by over-pressurisation from gas generation
Plugs and seals	Limit the release of contaminants Stabilise the surrounding host rock and the structure and geometry of the engineered barriers Prevent disruption by over-pressurisation from gas generation

3.2.1 Geological environmental safety functions

The manner in which a barrier component achieves its relevant safety functions depends on the FEPs that define the characteristics of the barrier and how the barrier evolves under disposal conditions. The safety functions that would be provided by the geological environment at a particular site can be identified by considering the attributes of the geological environment that are important to the post-closure safety. As noted in Section 2.3 and discussed in more detail in the Geosphere Status Report [27], as part of the consultation process to identify sites for a national geological disposal facility, the geological attributes that are relevant to meeting the long-term safety requirements discussed in Section 3.1 have been defined in terms of [30]:

- rock type
  - distribution of potential host rock types (higher strength rocks, lower strength sedimentary rocks, evaporite rocks) at the depths of a GDF
  - properties of rock formations that surround the host rocks
- rock structure
  - locations of highly folded zones
  - locations of major faults
- groundwater
  - presence of aquifers
  - presence of geological features and rock types which may indicate separation of shallow and deep groundwater systems
  - locations of features likely to permit rapid flow of deep groundwater to near-surface environments
  - groundwater age and chemical composition
- natural processes
  - distribution and patterns of seismicity
  - extent of past glaciations
- resources
  - locations of existing deep mines
  - locations of intensely deep-drilled areas
  - potential for future exploration or exploitation of resources.

Understanding of the geological attributes at the GDF site will be obtained through a site characterisation process, as described in RWM's Site Characterisation Status Report [65], and this will support an understanding of the environmental safety functions provided by the geological environment in relation to safety requirements.

The depth and extent of the host rock are key factors with regard to achieving **waste isolation**, and knowledge of the natural processes that could affect the geological environment (such as erosion and uplift) builds an understanding of how isolation of the waste will continue in the long term after disposal. RWM currently assumes that the disposal facility is likely to be constructed between 200 and 1000 metres below the ground surface. For planning purposes for this generic safety case, the following assumptions have been made [11, §3.14.2]:

- in a higher strength rock environment, the depth of the disposal horizon is assumed to be 650 metres below ground level

- in a lower strength sedimentary rock environment, the depth of the disposal horizon is assumed to be 500 metres below ground level
- in an evaporite rock environment, the depth of the disposal horizon is assumed to be 650 metres below ground level

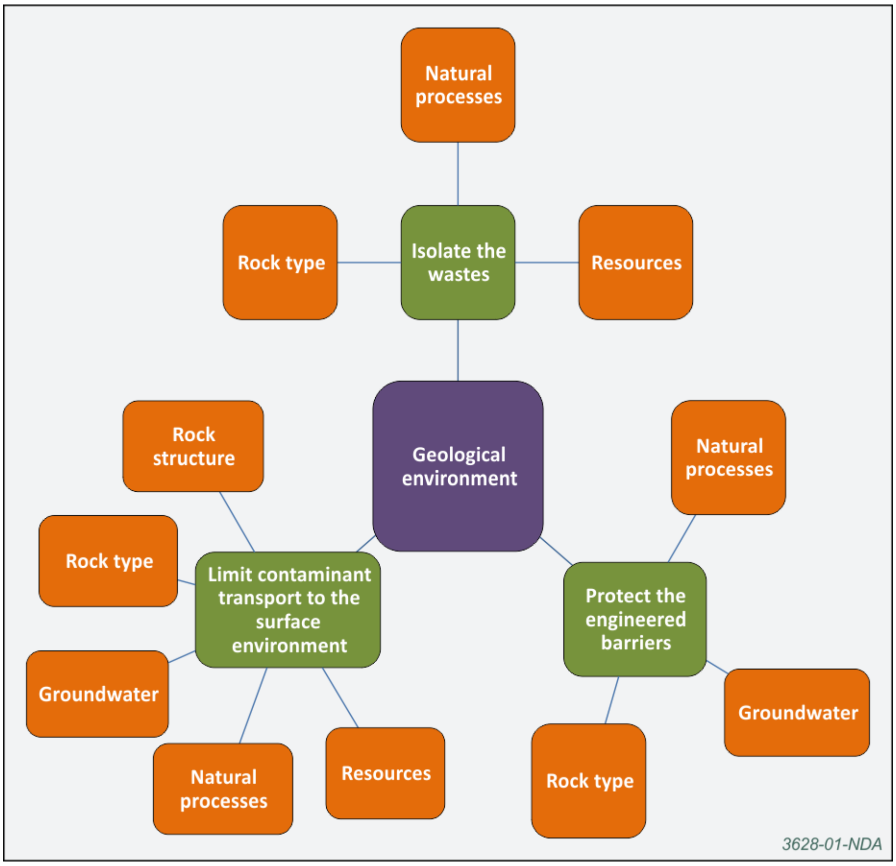
Information about resources at a site contributes to an understanding of the potential for future human activities, such as drilling for resource exploitation, to result in intrusion into a GDF at the site. Such an intrusion could expose humans to wastes, effectively disrupting the isolation and containment functions of the GDF, although various controls will be put in place to reduce the likelihood of intrusion.

The extent to which the host rock **protects the EBS** from mechanical damage will depend on the rock type and its stability (for example, whether it deforms plastically under stress changes). Knowledge of groundwater attributes (that is, hydrological and geochemical conditions) is important in terms of understanding how conditions in engineered barriers will evolve. For example, factors such as groundwater flow rates and redox conditions will influence the extent to which the barriers are protected from degradation processes and the rate at which gas generation reactions occur.

Knowledge of hydrological and geochemical conditions, rock type and structure, natural processes and resources at the disposal site will also support an understanding of the extent to which the geological environment provides a barrier that **limits the transport of contaminants to the surface environment** in groundwater or gas in the long term. For example, knowledge of the location of major faults (which could be hydraulically conductive) with respect to potential GDF locations will support understanding of the ability of the host rock to limit the transport of contaminants released from the EBS in the long term. The rocks that surround the host rock may also contribute towards safety. For example, if the surrounding rocks are of low permeability they may hydraulically isolate the host rock, preventing contaminants from reaching the surface environment. Also, specific rock-forming minerals may influence long-term safety. Some minerals (such as clay minerals and iron oxides) are particularly effective at removing radionuclides from groundwater by sorption or precipitation. In the long term, natural processes such as sea level change, erosion, earthquakes, regional uplift and the growth and retreat of ice sheets and glaciers could influence conditions in the geological environment and affect contaminant transport.

The geological environment will contribute to the long-term safety requirements, but the actual safety functions provided by the geological environment and the ways in which the geological safety functions are complemented by those of the engineered barriers, will be site-specific. Sufficient characterisation of the site in order to understand the effect of long-term evolution of the GDF on safety is therefore essential in order to produce a site-specific ESC that demonstrates that each of the long-term safety requirements can be met. An illustrative example of the relationship between geological attributes and the generic environmental safety functions provided by the geological environment is provided in Figure 8. The geological attributes shown in Figure 8 represent the high-level attributes listed above and have associated sub-attributes.

Figure 8 **Indication of the types of geological attributes (orange boxes) that determine the different environmental safety functions (green boxes) provided by a geological environment; each attribute shown has sub-attributes as listed in the main text**



3.2.2 Wasteform environmental safety functions

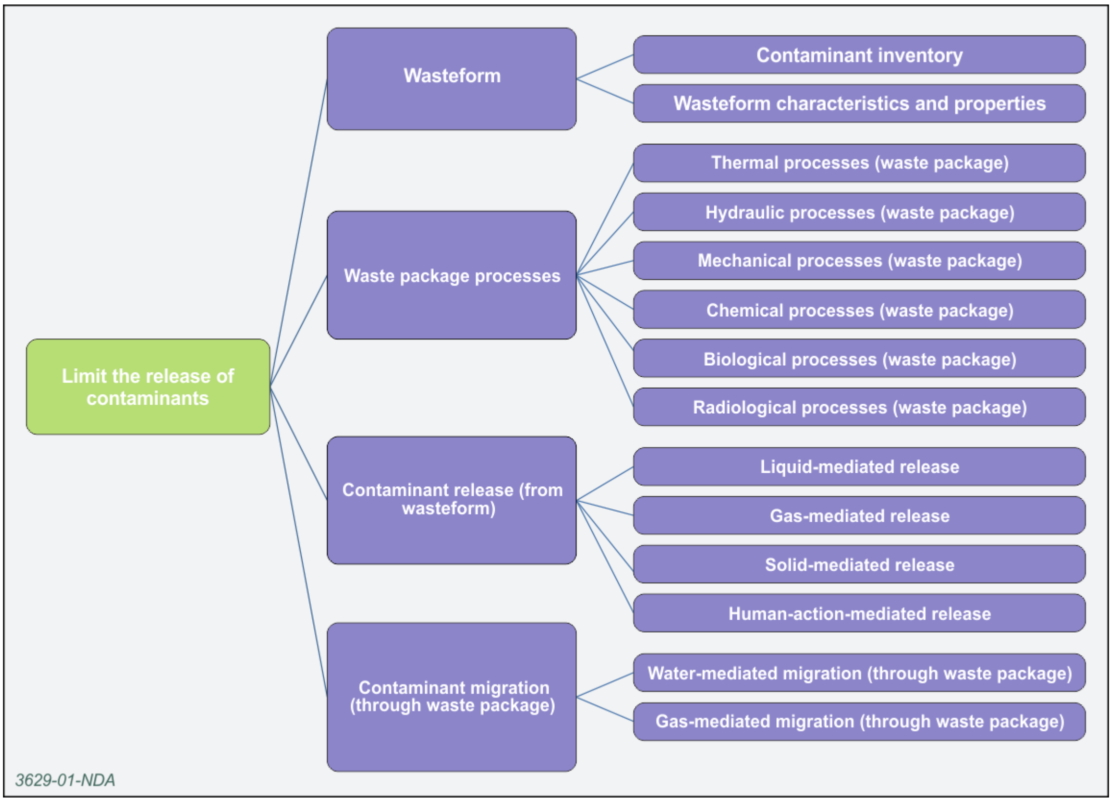
If, as required, a wasteform is a durable solid that immobilises the radioactive content of the waste (as well as any potential non-radioactive species), it will contribute to the overall containment function and will **limit the release of contaminants** in groundwater or gas. In particular, when a container is eventually breached (for example, as a result of corrosion), the wasteform will continue to support the containment requirement if the rate of any leaching of radionuclides or non-radioactive species into groundwater is low. Some wastes arise as solids that provide significant immobilisation and containment without additional treatment (for example spent fuels, irradiated graphite blocks and large items of metallic ILW) [62, §3.2]. Some other wastes may be treated with encapsulation or embedding processes to ensure their effective immobilisation [62, §3.1]. Encapsulation or embedding may achieve immobilisation by creating a durable material (that is, a material with a microstructure that has a low leaching rate), by promoting the development and retention of chemical conditions that limit the solubility of radionuclides and other species in groundwater, or by limiting water's access to the waste.

A stable and strong wasteform will provide resistance to mechanical stresses imposed by a backfill or host rock, thus helping to **stabilise the structure and geometry of the engineered barriers**, and factors such as the dryness of a wasteform and the provision of a barrier such as a grout annulus around the waste will help to **protect the internal surface of a waste container**. However, these may not be primary safety functions of a wasteform, but may be additional features that support the long-term environmental safety of the GDF.

Radioactive wastes include fissile radionuclides (most significantly U-235 and Pu-239) that, under certain conditions, can fission and result in nuclear criticality. Controls on waste packaging, such as fissile material limits, and the presence of the diluent and neutron absorber U-238 in the waste, will help to **limit the potential for criticality** after disposal. Also, wasteform durability will influence the potential for criticality after water ingress into a waste package. In particular, containment for sufficient time (about 100,000 years) to ensure substantial decay of any Pu-239 (half-life of 24,100 years) will limit the potential for post-closure criticality involving accumulation of Pu-239 after disposal. Rapid transient criticality (in which positive feedback mechanisms lead to rapid increases in temperature and pressure) generally requires accumulation of Pu-239 under disposal conditions and is considered not to be credible after about 100,000 years (as discussed further in Section 10.6). Features such as a grout annulus or controls on the emplacement locations of waste packages that contain fissile material (including with respect to non-fissile waste packages) will also limit the potential for post-closure criticality.

Each of these wasteform environmental safety functions will be influenced by various FEPs after disposal. For example, Figure 9 shows the waste package FEPs listed in the OECD NEA international FEP database [45] that could influence how a wasteform limits the release of contaminants from a waste package. Such FEP lists capture how thermal, hydraulic, mechanical, chemical (including biologically-promoted) processes and gas (THMCG) affect wasteform performance, and include coupled THMCG processes. Note that the international FEP list includes more detailed FEPs at a lower level in the hierarchy than are shown in Figure 9. Some environmental safety functions are interrelated and are influenced by similar FEPs. For example, FEPs related to wasteform characteristics that act to limit the release of contaminants will also influence the potential for criticality after disposal. RWM is developing influence diagrams for each environmental safety function of each barrier component and is incorporating the diagrams and associated technical discussions into computer software that will enable automated interrogation of the environmental safety functions provided by GDF barriers. The software application will support future communication of the safety case and the waste package Disposability Assessment process (see Section 10.10.7).

Figure 9 **Illustration of the waste package FEPs listed in the OECD NEA international FEP database [45] that could influence how a wasteform limits the release of contaminants from a waste package; the lowest level, most detailed FEPs in the OECD NEA FEP list are not shown**



3.2.3 Container environmental safety functions

Container materials with a corrosion resistance (such as stainless steel and copper) or where there is provision of a corrosion allowance (such as carbon steel) will ensure that **contaminants are contained** to the extent that their release does not occur until after substantial decay of short-lived radionuclides.

If substantial gas generation is expected to occur in a waste package, then the inclusion of gas vents in the container will **prevent disruption through over-pressurisation** and, although the container does not provide complete containment because of the presence of the vents, **release of contaminants in groundwater will be limited**.

The container may be designed to have sufficient mechanical strength to resist the mechanical stresses and strains imposed by any surrounding backfill material or the host rock, thus supporting the **stabilisation of the structure and geometry of the engineered barriers**.

Long-term containment of wastes that include fissile radionuclides will **limit the potential for criticality** after disposal. In particular, the potential for post-closure criticality involving accumulation of Pu-239 after disposal will be limited if there is a long containment period (100,000 years or more). Also, container features that provide geometric controls and minimise voidage will provide criticality control after container breach and potential water ingress.

3.2.4 Local buffer/backfill environmental safety functions

The buffer or backfill materials that surround the waste packages may **protect the containers** from degradation processes. For example, a cementitious or bentonite backfill will buffer groundwater to alkaline conditions under which metal corrosion rates are low and a low-permeability barrier will limit the movement of aggressive species to the surface of a container.

The local buffer/backfill may also protect waste packages from rock movements (including rock falls) thus helping to **stabilise the surrounding host rock and the structure and geometry of the engineered barriers**.

Properties of a local buffer/backfill that will **limit the release of contaminants** into the geological environment include low permeability, the potential to filter colloids that could otherwise facilitate radionuclide transport, the generation of alkaline conditions (which will ensure that the solubility of many radionuclides is low) and a high capacity for sorption. Also, carbon dioxide generated in the disposal facility and any C-14 that it contains may react with a cementitious backfill such that it is not released into the host rock as a free gas.

If the buffer/backfill is gas permeable, it will serve to **prevent disruption by over-pressurisation**.

3.2.5 Mass backfill environmental safety functions

A mass backfill may provide mechanical support, resisting rock movements and the movement of other engineered barrier components (such as swelling bentonite), thus **stabilising the surrounding host rock and the structure and geometry of the engineered barriers**.

Mass backfill may also **limit the release of contaminants,** for example by supporting alkaline conditions and providing a surface for sorption, a low-permeability environment and a barrier to human intrusion.

If the mass backfill is gas permeable, it will also help to **prevent disruption by over-pressurisation**.

3.2.6 Plugs and seals environmental safety functions

Plugs and seals may provide low permeability barriers that **limit the release of contaminants** from the disposal facility. They may also serve to resist the mechanical movements of other barriers (such as swelling bentonite), thus **stabilising the surrounding host rock and the structure and geometry of the engineered barriers**. Seals may also be designed to be gas permeable, thereby **preventing disruption by over-pressurisation**.

3.3 Environmental safety functions of the illustrative disposal concepts

The illustrative disposal concepts provide different sub-sets of the general environmental safety functions discussed above, according to the particular wasteform and geological environment considered and the appropriate engineered barrier system. For each disposal concept, the barrier system components will provide relevant combinations of environmental safety functions that will work together to provide safety throughout the post-closure period. The relative importance of different environmental safety functions will change over time. Sections 4 to 9 discuss the environmental safety functions provided by the barrier systems of the illustrative disposal concepts for each host rock environment. The environmental safety functions are discussed at a high level, with reference to RWM's knowledge base, including the research status reports, for supporting arguments and evidence relating to how FEPs could influence barrier performance.

Sections 4 to 9 also include discussions of how conditions might evolve in a GDF for HHGW and LHGW in the three host rocks with different types of cover rock sequences. GDF evolution is discussed in terms of three timeframes that relate broadly to certain events and processes that are expected to occur in those timeframes [63, §3.2]. The durations of these timeframes will depend on the waste types and geological environment of the GDF. These timeframes are notionally referred to, for each concept, as the construction and operational period, the early post-closure period and the late post-closure period.

For each illustrative disposal concept, a base scenario has been defined that represents understanding of expected GDF evolution in each timeframe, with reference to the environmental safety functions to be provided by each barrier component. In addition, variant scenarios for GDF evolution have been identified for each disposal concept.

Descriptions of the base scenarios presented in Sections 4 to 9 refer to the descriptions of barrier system evolution presented in the Engineered Barrier System Status Report [63] and descriptions of geological barrier evolution presented in the Geosphere Status Report [27]. While there is some overlap in parts of the generic ESC and these status reports, the status reports describe the scientific understanding that underpins expectations of the evolution of the disposal system, whereas the ESC explains how the multiple barriers provide the required environmental safety functions throughout disposal system evolution.

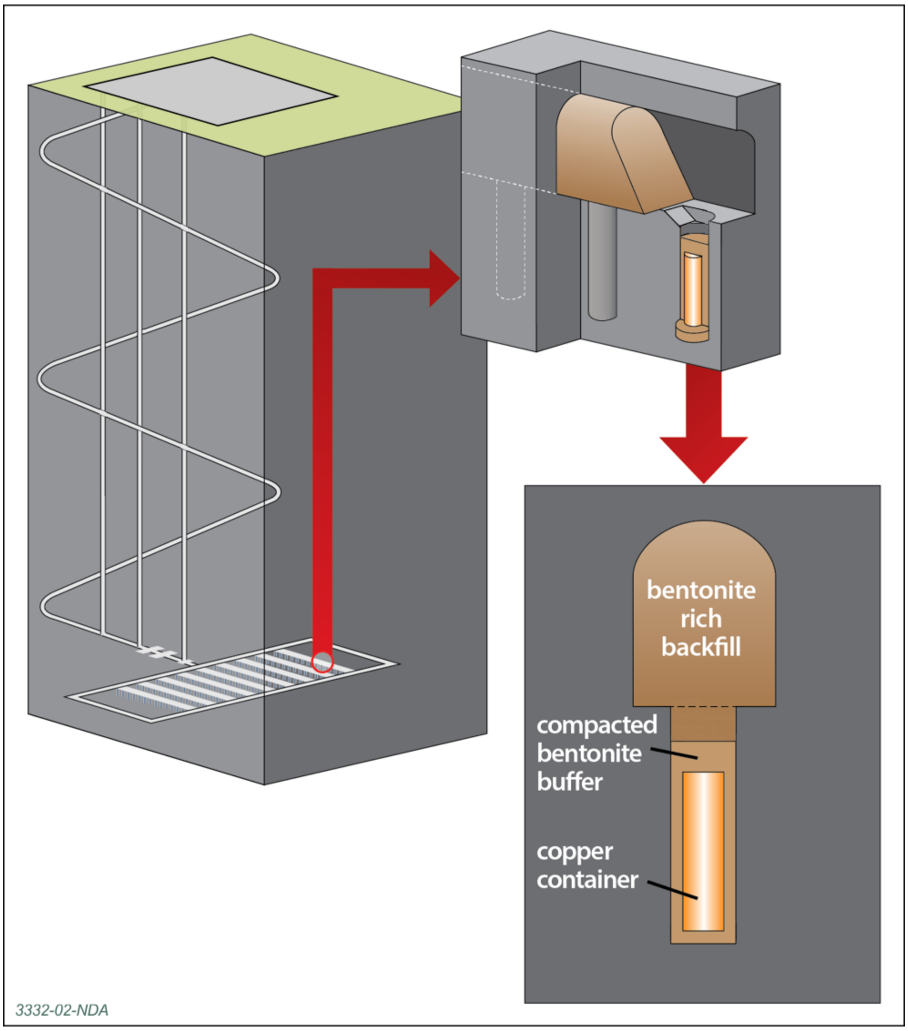
4 HHGW Disposal in Higher Strength Rock

The higher strength rock category refers to igneous, metamorphic or older sedimentary rocks [27, §2.1.1]. Such rocks have low permeabilities and matrix porosities, with the majority of any groundwater movement being confined to fractures within the rock mass. The transport of any mobile species through the rock would be dominated by advection through the fractures.

The illustrative concept defined for the disposal of HHGW in higher strength rock involves packaging the wastes within cast iron inserts inside copper containers [3, §6.1]. The waste packages will be placed in vertical boreholes drilled from the floor of deposition tunnels. Each borehole will accommodate one waste package surrounded by compacted bentonite blocks. The disposal tunnels will be backfilled with bentonite and the access tunnels will be backfilled with bentonite and crushed rock. The disposal concept is illustrated in Figure 10.

The environmental safety functions provided by the barrier components (geological environment and EBS) are discussed in the following sub-sections. In addition, descriptions are provided of the base scenario for which the barriers are expected to provide their planned environmental safety functions and of variant scenarios involving FEPs that, although unlikely to occur, could disrupt barriers and their environmental safety functions.

Figure 10 **Illustrative concept for the disposal of HHGW in a higher strength rock [3, Figure 6]**



4.1 Geological environmental safety functions

4.1.1 Isolation of the wastes

The geological environment will isolate the waste from people and the surface environment by providing a substantial radiation shield [27]. The host rock (and any cover rock) above the disposal facility will be sufficiently thick that the isolation function will be expected to be robust to erosion associated with natural processes, such as uplift of the Earth's crust and glaciation [27, §4]. Also, the disposal facility is likely to be at sufficient depth below the ground surface that the wastes will not be intercepted by near-surface resource exploration and recovery activities, such as shallow drilling and mining, although the depth of the disposal horizon will be determined on the basis of results from geological and hydrogeological investigations and safety cases.

4.1.2 Protection of the engineered barriers

A higher strength rock provides a stable mechanical environment in which relatively large excavations (with a span of 16 metres or more) will remain open for long periods with minimal rock support [63, §4.1.1]. The EBS will not be subject to large mechanical stresses and strains from the host rock.

The rate of degradation of the EBS will depend on the groundwater flow and chemical conditions to which it is exposed. Potential hydrogeological and geochemical conditions in a higher strength rock are discussed in the Geosphere Status Report [27, §5.3.1-§5.3.3]. The extent to which the host rock protects the EBS will be a function of the hydraulic conductivity of the connected fracture network and the hydraulic head gradient in the vicinity of the disposal facility. Groundwater chemistry is expected to be stable, with reducing, mildly alkaline and low to moderate salinity conditions likely to prevail. These conditions will not be affected significantly by groundwater recharge or chemical reactions in the rock in the long term. Under such conditions (particularly mildly alkaline and reducing conditions), the corrosion rates of metals in the EBS will be low.

The host rock will provide a medium for the conduction of heat generated by radioactive decay and other exothermic reactions in the near field (that is, in waste packages and other EBS components) away from the disposal facility [27, §6.1]. Thus, heat transfer through the host rock will ensure that any potentially detrimental temperature-dependent effects on EBS materials and the host rock, and the environmental safety functions that they provide, are avoided given appropriate constraints on the distribution of heat generating materials in the disposal facility [11, §9.9.6].

The inter-connected fracture network in the host rock will allow gases generated in the disposal facility to be dispersed, limiting the potential for high gas pressures to be sustained and allowing any pressure-induced micro-fissures in the bentonite buffer to close [53, §6.2.2].

The protection of the EBS provided by the geological environment will help to ensure that fissile radionuclides are contained in the disposal facility for a long period of time. A containment period in waste packages of the order of hundreds of thousands of years will ensure that nuclear criticality involving accumulations of Pu-239 will not be possible because of its radioactive decay over this time (the half-life of Pu-239 is 24,100 years) [12, §5.3.1]. Furthermore, the disposal facility will be located away from any large, hydraulically-conductive faults that could act to channel and accumulate any mobile uranium, which will also help to ensure that nuclear criticality and any associated disruption of the barrier system does not occur in the long term after GDF closure [60, §2.7.2].

4.1.3 Limitation of contaminant transport to the surface environment

Any radionuclides and non-radiological species that are eventually released from the disposal facility may migrate through the EDZ into any connected fractures in the host rock. Potentially, such contaminants could migrate to the surface environment through the host rock and any overlying rock sequences present. The rate of contaminant transfer and the concentrations of any contaminants that reach the surface environment will be controlled by the characteristics of the groundwater and gas transport pathways and groundwater and gas flow rates. In this respect, rocks overlying the host rock could have an important influence on the containment safety function [27, §5.3.1-§5.3.3; 53, §6.3]. In particular, the presence of a laterally extensive low-permeability layer above the host rock would provide a barrier to groundwater flow and gas transfer. Contaminant transport through such sedimentary rocks would be limited to diffusion. Groundwater flow and gas transfer pathways laterally through the host rock to the biosphere may be long. Generally, the presence of an extensive low-permeability layer above the host rock would be expected to result in a long containment period (providing for further radionuclide decay).

Key geological, hydrological and geochemical characteristics that will determine the extent of the containment function provided by the geological environment are [27, §7.2.5; 31, §4.3.6]: the length of mass transport pathways; hydraulic and gas conductivities; the hydraulic head gradient; hydrodynamic dispersion; the sorption potential of the rock and fracture surfaces along potential transport pathways; the availability of connected porosity for matrix diffusion alongside fractures; and conditions for precipitation, co-precipitation or incorporation of contaminants into rock minerals.

4.2 Wasteform environmental safety functions

4.2.1 Limitation of the release of contaminants

Oxide fuels are in the form of ceramic uranium dioxide pellets that provide a stable matrix, but the spent fuel will be substantially cracked after irradiation in a reactor [62, §6.2.1] and, potentially, over very long timescales, as a result of internal pressurisation from helium production by alpha-decay [62, §6.1.2]. However, the fuel will display high chemical stability when contacted by groundwater and, apart from the rapid release of radionuclides at the grain boundaries and in accessible parts of the fuel (the instant release fraction), the rate of release of radionuclides after container failure will be low [62, §6.3]. Oxide fuel cladding and other fuel assembly components are mostly made of corrosion-resistant metals (Zircaloy, which is a zirconium alloy, stainless steel or nickel alloys). Cladding that is intact at the time of container failure will provide an additional barrier to the release of radionuclides contained within the fuel and fuel assembly components [62, §6.5], although the safety function provided by the cladding is not expected to be significant in terms of post-closure environmental safety.

The disposal routes for metallic fuels, such as Magnox spent fuel, and some of the various spent fuels and nuclear materials termed exotic fuels, are yet to be determined [62, §2.3.3-§2.3.4]. Magnox fuel (uranium metal) and cladding (magnesium alloy) will corrode relatively quickly when accessed by groundwater under disposal conditions [62, §6.4-§6.5]. The feasibility of options for the disposal of un-dismantled Magnox fuel (that is the fuel and its cladding), without encapsulation and immobilisation in an encapsulation or embedding medium, is being considered.

Highly active liquor (a by-product of spent fuel reprocessing) is immobilised as a solid, vitrified product (HLW) within a stainless steel canister [62, §2.2]. Although expected to crack during cooling as the vitrified product is formed [62, §5.2.1], the HLW glass will be highly durable under disposal conditions. The vitrification canister that holds the HLW may be perforated by localised corrosion processes relatively quickly on exposure to groundwater and is not expected to provide a significant containment safety function.

However, after canister breach, the release of radionuclides from the HLW glass is expected to occur slowly, congruently with the dissolution of the glass matrix [62, §5.1.2]. A layer of silica-rich gel is expected to gradually form on the surface of the HLW as the more soluble components are dissolved. This silica-rich gel preferentially incorporates radionuclides such as plutonium and americium and acts as a protective barrier, limiting the dissolution rate for the underlying unaltered glass [31, §3.1.1]. Precipitation of secondary phases during glass dissolution may remove radionuclides from solution, although they could result in the formation of colloids that could transport radionuclides [31, §3.1.1].

Plutonium residues would require immobilisation prior to disposal; incorporation into a ceramic or glass-ceramic wasteform are potential options [62, §3.1.3]. Such wasteforms would be extremely durable under disposal conditions [62, §7.4]. HEU could be immobilised in a similar way.

4.2.2 Stabilisation of the structure and geometry of the engineered barriers

Spent fuel, HLW and ceramic or glass-ceramic wasteforms (for example for plutonium residues) are strong materials [62, §5-§7], but mechanical strength is not a key safety function in terms of supporting other engineered barrier materials.

4.2.3 Protection of the internal surface of the waste container

Advanced Gas-cooled Reactor (AGR), Pressurised Water Reactor (PWR) and most Magnox fuel that has been stored under water will be dried before packaging for disposal [62, §3.2.1], so that there will be only residual water carry-over to the waste packages. HLW and ceramic or glass-ceramic wasteforms for plutonium residues or HEU will be dry [62, §11.1.3]. Thus, there is little potential for significant corrosion of the internal surfaces of metal containers holding these wastes prior to container breach.

4.2.4 Limitation of the potential for nuclear criticality

HHGW packages are expected to be sub-critical after disposal, even after breach of the container and ingress of groundwater (a neutron moderating medium, the presence of which could lead to an increase in nuclear reactivity, which is a measure of how close a system is to criticality). The composition of nuclear fuel following its irradiation in a reactor, as well as limits on the fissile material content of waste packages, will contribute towards the sub-critical condition of spent fuel waste packages. In particular, changes in the actinide composition of the fuel (for example, reduction in the fissile content), and the generation of fission products in the fuel during irradiation in a reactor, will lead to a reduction in the nuclear reactivity of the fuel [12, §2.3.1]. Waste packages containing HLW will include substantially less fissile material than required for criticality to be possible [12, §5.5].

Plutonium residues and HEU may be immobilised in robust ceramic wasteforms that are demonstrably sub-critical for a long time after disposal, even after container breach. Neutron absorbing materials are included in the ceramic matrix to ensure that nuclear reactivity is low, even in the presence of groundwater [12, §3.6].

4.3 Container environmental safety functions

4.3.1 Prevention or limitation of the release of radionuclides

The hydrogeological conditions in a higher strength rock may be such that the rock provides only limited protection against the migration of any contaminants released from the disposal region. In this case, the EBS will be required to provide the containment safety function for a long time after disposal (hundreds of thousands of years). Copper containers would provide such a containment function. Copper is resistant to corrosion under expected disposal conditions (a reducing environment with limited transport of water and corrosive species) and a copper container a few tens of millimetres thick would provide a very long period of containment [62, §9.2.1, §11.2.1]. A corrosion allowance (generally of the order of a few millimetres) will be incorporated into the container design to account for any corrosion generated by the limited transport of corrosive species (sulphide) in the buffer [62, §10.6, §11.2.1]. If a container is breached and the cast iron insert and other ferrous metals in the waste package begin to corrode in groundwater, then many of the actinides released from the wasteform may sorb strongly onto the iron corrosion products [31, §3.2].

4.3.2 Prevention of disruption through over-pressurisation

Even after drying following pond storage, residual water may be carried over with spent fuel when placed in a disposal container. However, the water content of the waste package (complemented by the presence of sufficient void space within the container) will be insufficient to generate high gas pressures as a result of corrosion of the cast iron insert (and other metals in the container) or as a result of water radiolysis [62, §11.1.3]. Helium generation is also expected to be slow, occurring over very long periods of time [62, §6.6, §11.1.3]. HLW, plutonium residues and HEU wasteforms will be dry. Therefore, a copper container of HHGW will not fail as a result of over-pressurisation.

4.3.3 Stabilisation of the structure and geometry of the engineered barriers

The cast iron insert in the copper container will provide mechanical strength sufficient to resist bentonite swelling pressures, stresses induced by shear displacements along rock fractures that could occur in association with the highest magnitude seismic events expected to occur in the UK, and copper creep, ensuring that the fuel is protected from mechanical loads [62, §9.2, §10.3].

The container will provide radiation shielding, thereby protecting the bentonite buffer from radiation damage.

4.3.4 Limitation of the potential for nuclear criticality

The exclusion of water by the container (apart from the residual water content of the spent fuel waste packages) will minimise neutron moderation, which will provide criticality control [12]. Also, spent fuel assemblies will be placed in fuel channels in the cast iron insert, which will provide criticality control by limiting neutron interaction between assemblies. The longevity of the copper container will ensure that substantial decay of Pu-239 to U-235 will have occurred in the waste packages prior to container breach and the potential for water infiltration into the waste package (and its associated increase in nuclear reactivity). Therefore, there is little potential for criticality following accumulation of Pu-239 (for example, from spent fuel or separated plutonium residues) in the disposal facility.

4.4 Local buffer/backfill environmental safety functions

4.4.1 Protection of the container

The copper container will be surrounded by bentonite in a deposition hole. As the bentonite saturates it will swell and provide a low permeability barrier, which will minimise fluid flow and ensure that any mass transfer is predominantly by diffusion [63, §3.7.1]. This limitation on mass transfer will limit the rate of transfer of aggressive species, such as sulphide ions to the container surface. Also, the high pore pressure, low porosity and low permeability of the bentonite will limit the biological activity and mobility of microbes, such as sulphate-reducing bacteria [63, §3.13]. Thus, the rate of sulphide production in the vicinity of the containers and the potential for sulphide attack will be limited.

Chemical reactions between the bentonite materials and the resaturating waters will condition the bentonite porewater environment (neutral to mildly alkaline conditions), which will also promote container longevity [63, §3.9.4, §3.14]. The bentonite will not be subject to significant alteration because the temperature in the buffer will be limited by controls on waste package contents and distribution in the GDF [11, §9.9.6], and groundwater pH will not be sufficiently alkaline for such reactions to occur [63, §3.9.4]. Sufficient erosion of the buffer that it fails to achieve its post-closure environmental safety functions will be avoided by excluding the use of deposition holes that are found to intersect fractures where the groundwater flow rate is deemed to be too high [63, §3.9.5].

4.4.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The hydration and swelling of the bentonite causes the buffer to develop mechanical properties that protect the container from minor rock movements by absorbing the effects of rock displacements (earthquakes) [63, §3.7.1, §3.9.1], although this safety function requires the bentonite to have saturated and achieved its swelling pressure prior to any such displacement. Large fractures that could be susceptible to substantial shear movement will be avoided when locating container deposition holes [63, §3.15].

4.4.3 Limitation of the release of contaminants

If a container is breached, then, provided the bentonite is intact at the time of breach, its low permeability will ensure that the transport of any contaminants released from the container is diffusion-dominated rather than driven by advection [63, §4.1.3]. Intact bentonite will also act to filter any mobile radionuclides in colloidal form, thus preventing any colloid facilitated radionuclide transport [31, §3.3.1].

The conditioning of the groundwater to a near-neutral to mildly alkaline pH will ensure that the solubility of many radionuclides is low and the large surface area and high cation-exchange capacity of the bentonite will provide a strongly sorbing medium, limiting radionuclide transport [63, §4.1.3].

4.4.4 Prevention of disruption through over-pressurisation

The buffer does not have a significant role with regard to prevention of disruption through over-pressurisation. If the gas pressure becomes sufficiently large that dilatant pathways occur, then gas will migrate along these pathways. These pathways will close when the gas pressure falls [53, §6.2.2].

4.5 Mass backfill environmental safety functions

4.5.1 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The mass backfill in the tunnels will provide a confining pressure that resists the swelling of the bentonite in the deposition holes. This mechanical resistance will ensure that the required bentonite swelling pressure is achieved without the bentonite escaping into the tunnel [63, §4.1.3]. The mass backfill will also provide mechanical stability, resisting host rock movement (such as rock falls and likely fracture displacements).

4.5.2 Limitation of the release of contaminants

The low permeability of the saturated backfill will ensure that advective mass transport through the backfill is limited [63, §4.1.3].

4.5.3 Prevention of disruption through over-pressurisation

The mass backfill does not have a significant role with regard to prevention of disruption through over-pressurisation.

4.6 Plugs and seals environmental safety functions

4.6.1 Limitation of the release of contaminants

Seals in access tunnels and shafts will isolate the waste by preventing access of people into the GDF. The seals throughout the GDF will help to ensure that no preferential pathways develop for the migration of radionuclides through the bentonite buffer and backfill as a result of piping of the bentonite [63, §3.11].

4.6.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

Plugs in the deposition tunnels will provide resistance to swelling bentonite, which will help to ensure that the swelling is uniform and that appropriate swelling pressures are achieved in the backfill [63, §4.1.3]. The seals will provide mechanical support and will serve to limit rockfalls.

4.6.3 Prevention of disruption through over-pressurisation

The plugs and seals do not have a significant role with regard to prevention of disruption through over-pressurisation.

4.7 Base scenario

The following sub-sections discuss the key processes that influence how conditions in the GDF are expected to evolve with respect to the three timeframes described in Section 3.3 (that is, the GDF construction and operation and early and late post-closure periods). The discussions draw on the descriptions of barrier environmental safety functions for the illustrative disposal concept and the descriptions of system evolution presented in the Engineered Barrier System Status Report [63, §4.1.4] and the Geosphere Status Report [27, §6.8.1], unless otherwise stated.

4.7.1 Evolution during GDF construction and operation

The period of construction and operation of the GDF encompasses the excavation of the shafts, tunnels and deposition holes, waste package emplacement, deposition tunnel backfilling, and final closure engineering (such as backfilling of the various access tunnels and shafts and emplacement of the low-permeability seals). Final closure completes the isolation of the wastes and the closure engineering acts as an impediment to intrusion by people in the future. The waste packages, protected by the bentonite buffer, will provide complete containment of the wastes during the operational period.

In this period, conditions are expected to evolve as follows:

- Activities to excavate the tunnels and deposition holes of the GDF, and the resultant redistribution of stresses, will alter the characteristics of the rock in a region around the openings. This region – the EDZ – could extend several tens of centimetres from the excavated region, depending on the excavation method used and the response of the rock to stress field changes. Where stress levels are high, spalling may occur (that is, pieces of rock may break off the walls of tunnels or deposition holes). The permeability of the EDZ will be greater than that of the host rock. Any significant fractures may be sealed during construction, for example by grouting.

- The construction of the GDF, ventilation and groundwater management controls (for example drainage and pumping to remove inflowing water) will cause the rock around the GDF openings to desaturate and fluid pressure to decrease in the vicinity of the GDF. After waste package emplacement the surrounding rock and buffer will begin to resaturate, with the time until complete saturation taking between a few years and several decades, depending on the characteristics and spatial variability of the fracture network which control inflows to individual deposition holes. Some deposition holes and tunnels could be fully resaturated by the time the GDF is closed, but other deposition holes may not resaturate for thousands of years.
- As the buffer and tunnel backfill resaturate they will begin to swell and form low permeability barriers. The bentonite buffer will protect the container by limiting the transport of water and aggressive species (such as sulphides and microbes that might promote corrosion) to the container surface and by limiting transport of any corrosion products away from the container. The buffer will also protect the container from minor movements in the rock discontinuities that intersect the deposition hole.
- After waste package emplacement, the temperature in the waste packages, surrounding buffer and rock will increase as a result of radiogenic heat generation. The disposal facility will be designed such that the temperature on the surface of the bentonite does not exceed 100°C at any time following emplacement in order to prevent thermal processes from affecting the buffer’s ability to fulfil its environmental safety functions [11, §9.9.6; 63, §3.5.2].
- Groundwater at GDF depth will be reducing prior to construction, but during GDF operations oxygen present in the air will diffuse into the groundwater, altering redox conditions near to the GDF openings. Oxygen may also react with the partially desaturated rock around the openings, causing changes in rock mineralogy and porewater composition. The extent of this oxidised disturbed zone will depend on the rock properties and the duration of GDF operations. Groundwater chemistry could also be affected by infiltration of near-surface waters and/or upwelling of more saline waters from depth as a result of perturbations to the hydrological system caused by excavation and operation of the GDF.

4.7.2 Early post-closure evolution

The early post-closure phase refers to the thermal period in which temperatures are elevated above ambient. The copper containers are expected to remain intact and provide containment in the thermal period. In this period:

- Redox conditions in the disposal facility will evolve quickly after closure. Oxygen will be depleted as a result of redox reactions with dissolved reducing species and reducing mineral impurities in the bentonite (such as pyrite), and as a result of aerobic corrosion of the copper disposal containers. Radiolysis reactions are not expected to produce significant amounts of oxidised species in the buffer. Once anaerobic conditions have been established, corrosion of the copper container will be very slow. Dissolution, precipitation and ion-exchange reactions will buffer the bentonite pore water to near-neutral to slightly alkaline pH. The chemical conditions in the host rock will slowly return to values close to undisturbed conditions over tens to hundreds of years.

- Elevated temperatures may affect the solubility of minerals in the bentonite, and hence porewater pH and mineralogy, leading to spatial variation in porewater characteristics. However, the temperature will decrease towards ambient values over a period of around 10,000 years and more uniform conditions will persist. The disposal concept will be designed such that the temperature on the surface of the bentonite is less than 100°C at any time following emplacement in order to avoid significant thermal alteration that might affect the potential for the bentonite to achieve its desirable swelling pressure and hydraulic properties [11, §9.9.6].
- Hydraulic conditions in the host rock will slowly return to equilibrium with the surrounding environment once the GDF is fully saturated and natural hydraulic gradients have been re-established.
- The EDZ may gradually seal as a result of mineralisation processes in fractures, but such sealing is likely to be slow.
- Isostatic or distributed loads on the outer surface of the copper containers as a result of hydrostatic and lithostatic loads and swelling of the bentonite buffer could cause slow creep of the copper as it is compressed onto the cast iron insert, closing up small void spaces [63, §3.15]. However, the buffer will protect the container from any minor rock movements [63, §3.7.1].

4.7.3 Late post-closure evolution

The copper containers are expected to provide complete containment for many hundreds of thousands of years, by which time a high proportion of the radionuclide inventory will have decayed. Over longer periods (millions of years) there is more uncertainty as to whether the copper containers will remain intact and, over these timescales, complete containment in all waste packages is not expected. Conditions will evolve as follows:

- When a container fails, water will access the cast iron insert, which will corrode and generate hydrogen gas. The gas will diffuse away from the container in solution, or a free gas phase could form (although as the gas pressure in the container increases the inflow of water will slow and the rate of corrosion and gas generation will be restricted).
- By the time of container failure, the majority of the initial HLW radionuclide inventory is likely to have decayed. Slow dissolution of the glass matrix will limit the release rate of the remaining radionuclide inventory.
- When a spent fuel container fails, the majority of its inventory is also likely to have decayed, but long-lived radionuclides that have segregated to the grain boundaries of the fuel or are present in gas (fission and neutron activation products) will be released if and when the cladding has failed (this is the ‘instant release fraction’). The spent fuel matrix will then dissolve slowly, gradually releasing the remaining radionuclides.
- The gradual dissolution of plutonium and HEU ceramic wasteforms after container failure will result in the slow release of radionuclides that have not yet decayed.
- The bentonite buffer will retard the transport of radionuclides including those in colloidal form, depending on the extent of any buffer degradation. Sorption and rock matrix diffusion in the geological barrier will substantially retard radionuclide transfer to the biosphere. Any rock sequences overlying the host rock will affect how radionuclides may be transported to the surface environment. For example, radionuclide travel times to the biosphere may be longer if the host rock is overlain by a low-permeability sedimentary layer than if the host rock extends to the ground surface.

Over timescales of a few hundred thousand years or more, natural disturbances or transients that can arise from the effects of global climatic events (for example glaciation) may affect conditions in the disposal system. It is anticipated that the GDF will be located such that its performance is robust to expected natural changes. In particular, on these timescales the vast majority of the disposal inventory will have decayed and the GDF will have evolved into a system analogous to a large natural uranium deposit [49]. However, as discussed in Section 2.4.5, until specific GDF sites have been identified, it is not appropriate to undertake a detailed assessment of the impacts of large-scale natural processes on GDF performance.

4.8 Variant scenarios

EBS environmental safety functions could be disrupted if conditions in the GDF do not evolve as expected. By considering the range of events and processes that could affect how the different barrier components perform, variant scenarios of system evolution can be identified and assessed as a means of developing an understanding of the robustness of the EBS to potential challenges. The long-term containment provided by the copper container is an important environmental safety function of the disposal concept. Thus, the identification of variant scenarios is focused on the consideration of events and processes that could lead to failure of the container. Various factors could lead to container failure, such as:

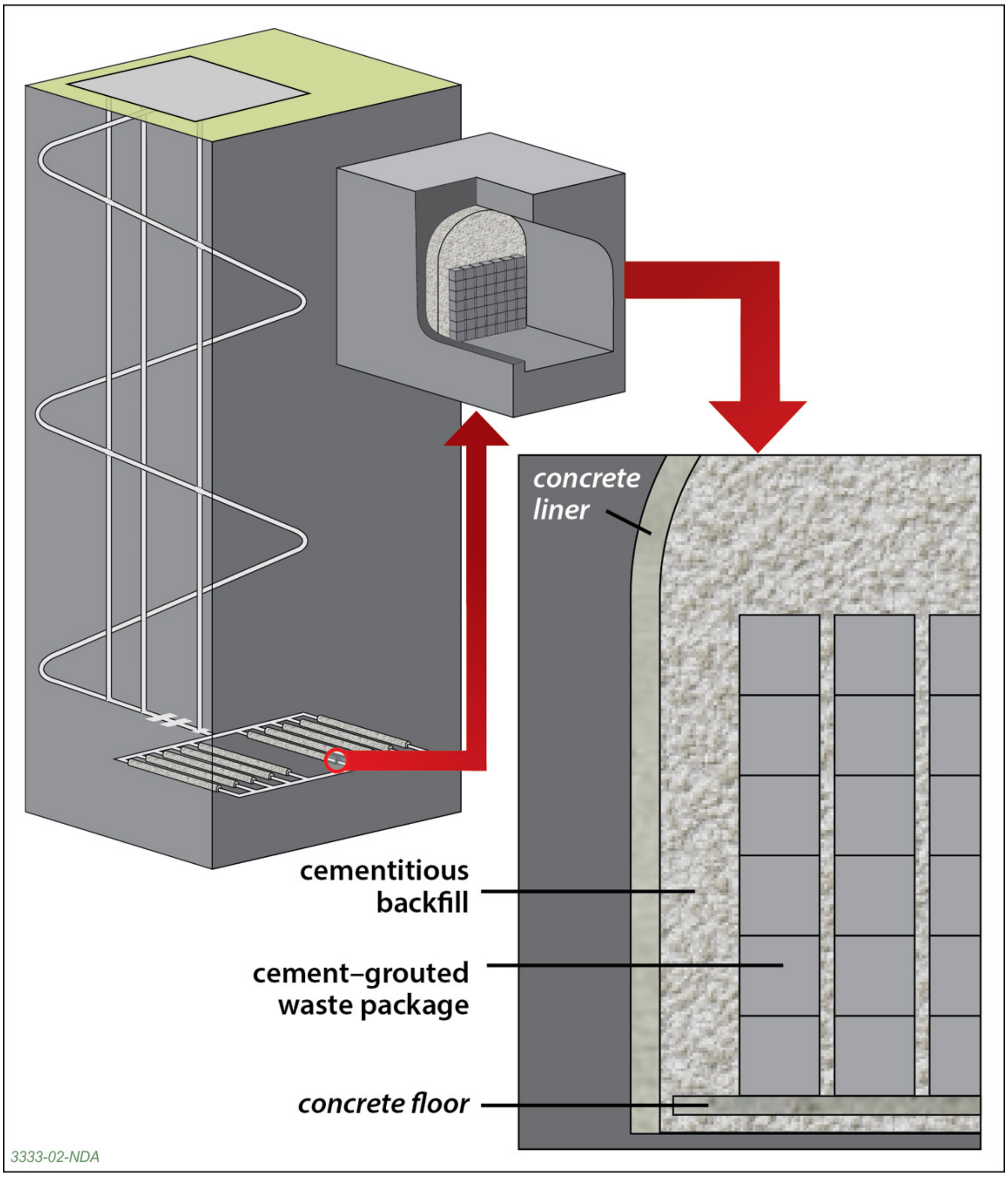
- Failures in the quality control of container, buffer or backfill materials (such that they do not meet design specifications at the time of emplacement) could mean that EBS components do not perform their intended environmental safety functions. As a result, conditions could develop under which copper corrosion is accelerated. For example, if the buffer density is too low, conditions may be favourable for the growth of sulphate-reducing bacteria populations, which could increase the rate of sulphide production and the potential for sulphide attack at the container surface.
- Uneven creep of the copper under stress might result in container failure if the ductility of the material is insufficient to accommodate the deformation [63, §3.15].
- Earthquakes of magnitude greater than considered in the barrier system design could result in shear displacement along large fractures that intersect deposition holes (that were either undetected or formed after GDF closure) sufficient to cause container failure [63, §3.15].
- If, during a glacial cycle, dilute groundwater reaches deposition hole depth, buffer erosion and colloid generation could occur because of the reduction in cation concentrations in the groundwater [63, §3.9.5]. The rate of corrosion of the container could then be increased as a result of the transport of corrosive species (sulphide) to the container through the degraded buffer [62, §11.2.1]. Also, mobile bentonite colloids could affect the transport of radionuclides from breached containers [31, §3.3.1].

It is considered highly unlikely that these variant scenarios could occur because of the controls that will be imposed through the GDF design, construction, waste management and disposal processes in the context of the understanding of site characteristics and system evolution that will be acquired. However, a variant scenario involving early container failure (as a result of corrosion associated with enhanced sulphide attack due to insufficient swelling of the bentonite) has been assessed in order to demonstrate the robustness of the multi-barrier concept to such scenarios for an illustrative higher strength rock environment. The results of this illustrative assessment are presented in Section 10.3.

5 LHGW Disposal in Higher Strength Rock

The illustrative concept for the disposal of LHGW in higher strength rock involves stacking waste packages in large vaults [3, §6.1]. The vaults will be backfilled with Nirex Reference Vault Backfill (NRVB), which is a cementitious material. The disposal concept is illustrated in Figure 11. In developing this concept, the vault dimensions have been maximised to meet the stacking requirements of the different types of waste package in the context of the stability of openings in higher strength rocks. The actual profiles and dimensions of the vaults will be determined based on the prevailing host rock geotechnical characteristics and the *in situ* stress regime at disposal depth.

Figure 11 Illustrative concept for the disposal of LHGW in a higher strength rock [3, Figure 5]



5.1 Geological environmental safety functions

The isolation and containment environmental safety functions provided by higher strength rock are as described in Section 4.1 for the illustrative disposal concept for HHGW. These environmental safety functions are broadly applicable to the concept for LHGW disposal in higher strength rock, although heat transfer in the host rock is less important for the LHGW disposal concept.

5.2 Wasteform environmental safety functions

5.2.1 Limitation of the release of contaminants

A conditioned wasteform (cement-based, polymer, glass or ceramic) will provide a chemically stable matrix that limits the release of radionuclides by dissolving only slowly in any groundwater that comes into contact with it [62, §3.1]. Encapsulation in cement has been used for the majority of ILW/LLW packaging that has been undertaken to date. Cement encapsulation is particularly suitable for sludges, fine particulate and, in general, materials that do not undergo detrimental chemical reactions in contact with the cement porewater [62, §3.1.1]. If groundwater comes into contact with a cement encapsulated wasteform after GDF closure, the release of radionuclides and other potential contaminants from the waste packages will be slow because of the low permeability of the wasteform and because of the effects of cement conditioning on the solubility and sorption behaviour of many radionuclides. Conditioning of the groundwater is expected to persist for hundreds of thousands of years or more based on the mass of NRVB expected to be present in the vaults [63, §3.5.2]. Also, corrosion of steel in the wastes will promote reducing conditions, which will support the containment of many radionuclides by limiting their solubilities [31, §3.1.4]. Where used, cement encapsulants will be expected to be tolerant to the chemical constituents of the waste and the radiation doses and temperatures to which they will be subjected, and will, therefore, provide a containment function for a long time after GDF closure.

However, for some wastes, potentially detrimental reactions could occur in the waste or between the waste and the encapsulant in the wet alkaline environment provided by a cement encapsulant. For example, the corrosion of reactive waste metals, such as aluminium, magnesium and uranium, may affect the physical and dimensional stability of cement-based wasteforms [62, §3.1.2]. Such reactions can be avoided by encapsulating the waste using an organic thermosetting polymer, which provides a dry, lower-permeability wasteform, although organic polymers may be susceptible to degradation in the presence of ionising radiation and high temperatures [62, §3.1.2]. Alternatively, through thermal treatment such wastes could be immobilised in glass or glass-ceramic materials, which are less susceptible to degradation than cements or organic polymers under most conditions, so are likely to result in particularly durable wasteforms [62, §3.1.3]. The thermal treatment process would remove organic components from the waste, which could otherwise degrade under alkaline conditions to form water-soluble radionuclide complexants, non-aqueous phase liquids (organic liquids, such as oils and solvents, which have limited miscibility with water) and gases, which may have detrimental effects on post-closure safety. For example, if radionuclides and other species partition into non-aqueous phases, this may provide an additional carrier for their migration. However, it has been demonstrated that it is unlikely that significant quantities of non-aqueous phase liquids (NAPLs) would escape from the waste packages and be transported into the host rock. Further, the Disposability Assessment process will ensure that the amount of NAPLs in a waste package is limited [31, §2.9].

Wastes packaged in robust shielded waste containers may not be encapsulated or immobilised, in which case the wasteforms are unlikely to provide a significant containment function after container breach (however as these containers are expected to remain intact for more than 1,000 years much of the inventory will have decayed before the containers are breached).

Graphite generally arises in large blocks and is a stable and durable wasteform. Further immobilisation processing before disposal may not be required [62, §3.2.2].

Most DNLEU destined for disposal is likely to arise as a stable solid powder (uranium oxide) or will require processing to be transformed into a stable solid. DNLEU that contains less than 1 weight percent U-235 will be disposed of in the form of oxide powders (UO_3 and U_3O_8) and will not be removed from its storage containers prior to disposal [7, §4.4; 66]. That is, the uranium will not be immobilised in grout. However, multiple storage containers will be placed in large stainless steel transport and disposal containers, which will be infilled with grout. DNLEU at higher enrichments will be immobilised with grout and disposed of in smaller stainless steel containers according to RWM's current plans.

5.2.2 Stabilisation of the structure and geometry of the engineered barriers

A conditioned stable and strong wasteform in a container with limited voidage will provide resistance to mechanical stresses imposed by the backfill or host rock as a result of creep or rock-fall, thus limiting mechanical disruption (for example, backfill or host rock fracturing) associated with any redistribution of voidage. Cement, thermoset polymeric, glass and ceramic wasteforms all have such characteristics [62, §3.1.1-§3.1.3].

5.2.3 Protection of the internal surface of the waste container

LHGW is generally dry, which minimises the potential for internal corrosion [62, §12.1.4]. In the case of wastes encapsulated in cement, corrosion is inhibited by the alkalinity of the porewater [62, §3.1.1, §12.1.4].

Polymeric, glass and glass-ceramic wasteforms are also dry, which will result in limited potential for corrosion of the internal surfaces of metal containers prior to their perforation by other degradation processes [62, §7.1.2-§7.1.3].

ILW packages that contain plutonium-contaminated materials (PCM) may release acidic species in the wasteform, including hydrochloric acid from the degradation of polyvinyl chloride (PVC), which could affect the rate of corrosion of stainless steel containers. The use of a thick cement annulus will limit the contact of such acids with the container [62, §8.3.1]. Also, corrosion of metals in the waste package may lead to wasteform expansion, which could affect waste package integrity. However, PCM waste packages typically have sufficient free volume to accommodate such wasteform expansion [62, §8.3.1]. Also, the protection of the internal surface of the container is a more significant environmental safety function for these wastes in the period prior to GDF closure than after closure, when calculated risk is likely to be less sensitive to the containment period in the waste package.

5.2.4 Limitation of the potential for nuclear criticality

Waste package fissile material limits and other controls, such as ensuring that the fissile material is distributed uniformly in a waste package and the provision of a grout annulus, will prevent criticality in a waste package at the time of disposal and will ensure that the likelihood of criticality will remain low as conditions in the disposal facility evolve [12, §8.2].

5.3 Container environmental safety functions

5.3.1 Prevention or limitation of the release of contaminants

Thin-walled stainless steel containers are typically used to package suitably immobilised or encapsulated LHGW [62, §9.3]. Stainless steel will corrode only very slowly under disposal conditions, especially where conditions are reducing and alkaline; waste containers with a wall thickness of few millimetres may be able to retain their functionality for some 100,000 years if general corrosion is the only active corrosion mechanism [62, §10.9.2, §12.2.1]. Pitting, crevice corrosion and stress corrosion cracking (SCC) could develop if chloride-rich groundwater comes into contact with the container whilst oxygen is still present in the GDF (especially if the temperature of the package is high), or if any thiosulfate (that may be produced by redox transformation of sulphur species) is present. However, the potential for chloride-induced corrosion becomes significantly reduced once oxygen is consumed and anaerobic conditions are established, although there is some uncertainty about whether thiosulfate corrosion occurs in anoxic conditions [62, §10.9.2]. In summary, the longevity of stainless steel depends on the geochemical conditions encountered and, in particular, on whether localised corrosion mechanisms occur.

Carbon steel and cast iron are less corrosion resistant than stainless steel, but the containers are typically thick-walled in order to accommodate a suitable corrosion allowance. For example, thick-walled robust shielded waste containers manufactured from ductile cast iron, possibly with a lead liner, may be used where the waste is not immobilised [62, §9.3]. In this case, the containment function of the container may be important. For example, a container with a wall thickness of about 10 millimetres would be expected to provide a containment function for 1,000 to 10,000 years, and potentially much longer where conditions are highly alkaline (up to 100,000 years) [62, §10.7.2, §12.2.2]. Ductile cast iron containers will be considerably thicker than 10 millimetres and hence will be highly durable. Carbon steel has been used to manufacture some ILW containers, although in relatively thin-walled designs (for example Miscellaneous Beta Gamma Waste Store Boxes at Sellafield) [62, §9.3.2].

The container corrosion process will support the maintenance of reducing conditions, which will lead to low solubility and strong sorption of some radionuclides; the corrosion products will also provide a high sorption capacity for radionuclides [63, §4.1.5; 31, §3.2].

Concrete containers have been used to package some ILW and may be used for packaging ILW/LLW generated by the operations of new nuclear power plants [62, §9.3]. These containers are generally thick-walled and include carbon steel re-bars within the cement structure and, in the case of containers used so far, external metallic components made with carbon steel treated with a zinc-based coating to enhance their corrosion resistance [62, §10.11]. Concrete containers do not provide an impermeable barrier to radionuclide release, but they may contribute to the chemical conditioning of the pore water, limiting radionuclide solubility and ensuring that the release of radionuclides is slow [62, §9.3.3, §12.2.3].

Although most LHGW containers include gas vents [62, §9.1.1] through which groundwater could enter and saturate the wasteform, it is unlikely that a flow path will be established through the waste package until the container is breached (for example, by corrosion). Any radionuclide transport from the containers through the vents of un-breached containers will be limited to a low diffusion-driven flux.

5.3.2 Prevention of disruption through over-pressurisation

Containers are vented to allow gas release, thus preventing waste package over-pressurisation and damage [62, §9.3; 63, §4.1.5].

Depending on the chemistry of the EBS, and the presence of steel reinforcement, degrading concrete containers may generate less gas than corroding carbon steel or cast iron containers [62, §9.3.3].

5.3.3 Stabilisation of the structure and geometry of the engineered barriers

Stainless steel waste packages (and the stillages that hold 500 litre drums) and stacks of robust shielded waste containers, such as thick-walled carbon steel and cast iron containers, will provide mechanical stability in the vaults for a period after disposal [62, §9.3.1-§9.3.2], but eventually will be weakened by corrosion processes. Large concrete containers can be manufactured with relatively good mechanical properties (particularly under compression) and good durability [62, §9.3.3].

5.3.4 Limitation of the potential for nuclear criticality

While the containers retain their integrity, the container walls will shield and separate fissile wasteforms from each other in a vault (limiting neutron transport between packages) and the exclusion of water will limit neutron moderation and fissile material relocation processes, thus supporting the prevention of criticality after GDF closure [12, §3.3].

5.4 Local buffer/backfill environmental safety functions

5.4.1 Protection of the container

The cementitious backfill will buffer groundwater to a high pH and will limit the aerobic period after disposal by limiting the volume of oxygen present after backfilling [27, §6.4.2]. It is expected that sufficient backfill will be used to ensure that alkaline conditions are maintained for at least a hundred thousand years [63, §4.1.6], although leaching of cementitious materials by groundwater will gradually reduce the pH of the pore water [63, §3.10.1]. Microbial activity is suppressed under alkaline conditions, limiting the potential for microbiologically-influenced corrosion while the pH is high. Generally, metal corrosion rates are low under alkaline and reducing conditions, thus supporting the longevity of the containers [63, §3.7.2].

5.4.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The cementitious backfill is not designed to provide mechanical stability, but it will provide some protection of the containers from rock-fall.

5.4.3 Limitation of the release of contaminants

The solubility of many radionuclides is low under the high pH conditions induced by the backfill and under the reducing conditions that will eventually persist in the disposal vaults [63, §4.1.5]. The backfill will also have a high capacity for radionuclide sorption and co-precipitation will act to incorporate some radionuclides into the structure of backfill minerals [31, §3.3.2]. Thus, the migration of radionuclides through the backfill will be inhibited [63, §4.1.5].

The suppression of microbial activity under high pH conditions will limit microbial gas generation reactions and the release of radioactive gases (such as C-14) [31, §2.8]. Also, depending on the conditions at the time of release, C-14 may be immobilised by carbonation in the backfill [31, §3.3.2; 63, §3.10.1].

The formation of precipitates due to reactions between the cementitious materials and groundwater solutes may change the performance of the cement by forming layers on the backfill surfaces. As a result, cracks in the backfill may be partially or completely closed [63, §3.10.1]. Also, if dissolved cement minerals come into contact with the host rock, the precipitation of new minerals may occur, leading to re-sealing of fractures and effective self-sealing of the vaults [27, §6.4.3; 31, §4.2.2]. These processes may reduce groundwater flow and contaminant transport through the vaults, although armouring of fractures in the backfill could modify the backfill's pH conditioning capacity [63, §3.10.1].

Cementitious colloids may affect concentrations of radionuclides in near-field porewaters. However, cementitious colloids are not expected to be chemically stable in the undisturbed host rock beyond the chemically disturbed zone; instead, they are expected to dissolve and release any radionuclides that they had been transporting to the aqueous phase [31, §3.3.2].

5.4.4 Prevention of disruption by over-pressurisation

The backfill will be gas permeable, thus allowing the transfer of gas into the fractured host rock and preventing the generation of high gas pressures [63, §4.1.6].

Carbon dioxide generated from the microbial degradation of organic wastes will react with cement materials (carbonation) [63, §3.10.1].

5.5 Mass backfill environmental safety functions

5.5.1 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The mass backfill will provide mechanical support, resisting rockfalls and the extension of the EDZ into the surrounding rock [63, §4.1.5].

5.5.2 Limitation of the release of contaminants

A cementitious mass backfill will condition the groundwater (ensuring it is alkaline), thus supporting the environmental safety functions provided by the vault backfill. The mass backfill will prevent the access tunnels from acting as preferential pathways for groundwater flow and radionuclide migration, although the EDZ around the tunnels may provide a migration pathway, and will provide a barrier to human intrusion. The backfill will also provide a large surface area for sorption of any dissolved radionuclides that do enter the tunnels [63, §4.1.5].

5.5.3 Prevention of disruption through over-pressurisation

The mass backfill does not have a significant role with regard to prevention of disruption through over-pressurisation.

5.6 Plugs and seals environmental safety functions

5.6.1 Limitation of the release of contaminants

The seals throughout the GDF will act to prevent the release of contaminants by closing potential groundwater flow pathways through the GDF [63, §4.1.5]. The seals will also isolate the waste by providing a barrier to the access of people into the GDF.

5.6.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The seals will provide mechanical support to the backfill and will serve to prevent rockfalls.

5.6.3 Prevention of disruption through over-pressurisation

The seals do not have a significant role with regard to prevention of disruption through over-pressurisation.

5.7 Base scenario

The following sub-sections discuss the key processes that influence how conditions in the GDF are expected to evolve with respect to the three timeframes described in Section 3.3. The discussions draw on the descriptions of barrier environmental safety functions for the illustrative disposal concept and the descriptions of system evolution presented in the Engineered Barrier System Status Report [63, §4.1.6] and the Geosphere Status Report [27, §6.8.2].

5.7.1 Evolution during GDF construction and operation

During the period of GDF construction and operation:

- An EDZ will be induced by activities to excavate the vaults and other openings. Any significant EDZ fractures are likely to be sealed using a cement-based grout. Concretes may also be used to provide structural support to the excavations.
- The vaults and access tunnels will be maintained in a dry and ventilated state, which will result in some desaturation of the host rock.
- Waste package degradation during the operational period (atmospheric conditions) will be kept to a minimum by ensuring that groundwater does not come into contact with the packages and that temperature and humidity, and/or the amount of corrosive contaminants (for example chloride), are controlled.
- Waste packages will be vented so that any gas generated within the waste packages will be released through the vents and removed by the ventilation system.
- After all waste emplacement has been completed, the disposal vaults will be backfilled with NRVB and the vaults and any surrounding desaturated rock will start to resaturate.
- Backfilling will bring water into contact with the waste packages, resulting in the onset of corrosion processes and, in the case of carbon steel and cast iron containers, an increase in the gas generation rate.
- The probability and rate of corrosion of waste packages will be increased during the transient period of temperature increase associated with cement curing, but the corrosion rate will be low in the presence of water conditioned by cement. It may be possible for temperatures of up to 80°C to be accommodated for some waste packages (although probably not stainless steel containers) for a period of up to five years during cement curing, but the disposal facility will be designed such that waste package temperatures do not exceed 50°C following closure [11, §9.9.6].

5.7.2 Early post-closure evolution

In the early post-closure period (tens of thousands of years) the engineered barriers will degrade slowly as a result of interactions with the groundwater and with each other. However, the containers and other barriers will remain sufficiently intact that they are able to perform their intended environmental safety functions fully. In this period, it is expected that:

- The disposal vaults will resaturate at a rate that depends on the properties of the host rock. Typically, in higher strength rock full resaturation will take a few decades to a few centuries.
- The groundwater will rapidly equilibrate with the NRVB, resulting in the development of alkaline conditions that are expected to be maintained for at least a hundred thousand years.

- Corrosion of (non-stainless) steel components and many metals present in the waste will result in the establishment of reducing conditions.
- Gas (predominantly hydrogen, but also some carbon dioxide and methane) will be generated, mostly by the corrosion of Magnox and aluminium present in the waste, but also from the corrosion of the various (non-stainless) steel components and the degradation of organic materials. However, under alkaline and reducing conditions the rate of corrosion and the activity of microbes that degrade the organic components of the waste will be limited. Hence, the gas generation rate, including the generation of radionuclides in the gas phase, will be limited.
- Any carbon dioxide generated (which may include C-14) will react with the cementitious backfill and some of the gas will dissolve in the groundwater. It is likely that a free gas phase will form, including C-14 in methane. However, the gas will be able to escape relatively easily into the host rock, although its presence may slightly reduce the rate of resaturation. Depending on the gas transport properties of the geological environment at the site (that is, the connectivity of the fracture network in the host rock and the gas permeability of the cover rocks), this free gas might reach the ground surface.
- Once the disposal vaults resaturate, small concentrations of dissolved radionuclides will begin to be released by diffusion from vented containers. More substantial advection and diffusion of radionuclides from the waste packages will occur as the containers are breached by corrosion. The high pH will limit the solubility of many radionuclides, and the minerals in the cement of waste package grout and the backfill will promote the sorption of radionuclides.
- The backfill and wasteforms are likely to become cracked as a result of stress changes (for example from temperature changes and swelling from the generation of corrosion products), but this is not expected to impact the performance of the cementitious barriers significantly. The cracks may become partially or completely closed by the formation of precipitates, which will reduce groundwater flow, although the armouring of cracks could affect the capacity of the backfill to condition the pH and to immobilise carbon dioxide by carbonation.
- Organic complexing agents derived from the wastes could increase radionuclide mobility, but their impact will become progressively less significant as their concentrations are reduced by chemical, radiolytic or microbial degradation. NAPLs may be present in some waste packages, which could facilitate contaminant transport, but NAPLs will not migrate from the waste packages to the host rock in significant quantities.
- Reactions between porewater that has been chemically conditioned by the cementitious backfill and the host rock will result in the development of an alkaline disturbed zone around the vaults. In this zone, mineral dissolution and precipitation of new minerals will alter the hydrogeological properties of the host rock. It is expected that there will be a net decrease in porosity and permeability as fractures, especially those in the EDZ, become filled with new, relatively high volume minerals. Cementitious colloids (which could transport radionuclides) will not be stable beyond the alkaline disturbed zone.

5.7.3 Late post-closure evolution

After hundreds of thousands of years, degradation of the engineered barriers will be such that the barriers will no longer be able fully to perform their original environmental safety functions:

- The wasteforms and the NRVB will be altered through reaction with the groundwater. Eventually the pH will fall to a level where the chemical barrier provided by the NRVB backfill loses some of its effectiveness. However, it is expected that a pH of more than 10 will be maintained for at least one million years [63, §3.5.2], continuing to provide an effective chemical barrier to the migration of many radionuclides and non-radiological species. The alkaline disturbed zone may evolve in the presence of lower pH and low calcium groundwater, with migration of the disturbed zone downstream, unless alteration has been sufficient to divert flow away from these areas.
- Radionuclides that have not decayed in the waste packages and within the EBS may be released to the host rock.
- Gas will continue to be produced from the corrosion of metals, but at a low rate.

In the very long term (many hundreds of thousands to millions of years) there is greater uncertainty as to whether the containers will remain intact but, over these timescales, the EBS will not be expected to provide complete containment. However, the degraded barriers will continue to retard the release of contaminants to some degree by chemical containment and, by this time, the vast majority of the inventory will have decayed. On these timescales, the behaviour of the disposal system could be affected by natural disturbances or transients arising from the effects of global climate events (such as glaciation).

5.8 Variant scenarios

The establishment of alkaline and reducing conditions is key to ensuring that the corrosion rates of metal containers are low and that the rate of release of contaminants from the waste packages and their mobility within the EBS is limited. Therefore, the identification of variant scenarios has focused on the environmental safety functions provided by the backfill:

- Substantial localised corrosion of stainless steel containers could occur if niches of low pH groundwater are present in the backfill, especially if the groundwater is rich in chloride and conditions remain oxic for a long period after waste emplacement [62, §12.2.1]. Low pH conditions could occur as a result of not emplacing the backfill completely or correctly, as a result of carbonation of the backfill [62, §7.2.3], or if backfill cracking (through plastic settlement, thermal contraction, waste package expansion, the collapse of degrading packages with high voidage [67], or collapse of the vault roof) leads to a more rapid rate of groundwater flow through a disposal vault [63, §3.10.2]. Microbiologically-influenced corrosion may also be significant and could affect stainless steel, carbon steel and cast iron containers where the pH of the water in the vaults is low.
- The solubility of many radionuclides will be greater where the pH of the water in the vaults is lower than expected (for example, for the reasons noted above), which could result in more rapid wasteform dissolution and radionuclide transport through the backfill. Radionuclide sorption in the backfill will also be reduced if the pH is lower.
- Radionuclide transport through cracked backfill in a vault may be rapid if highly-permeable preferential pathways develop.

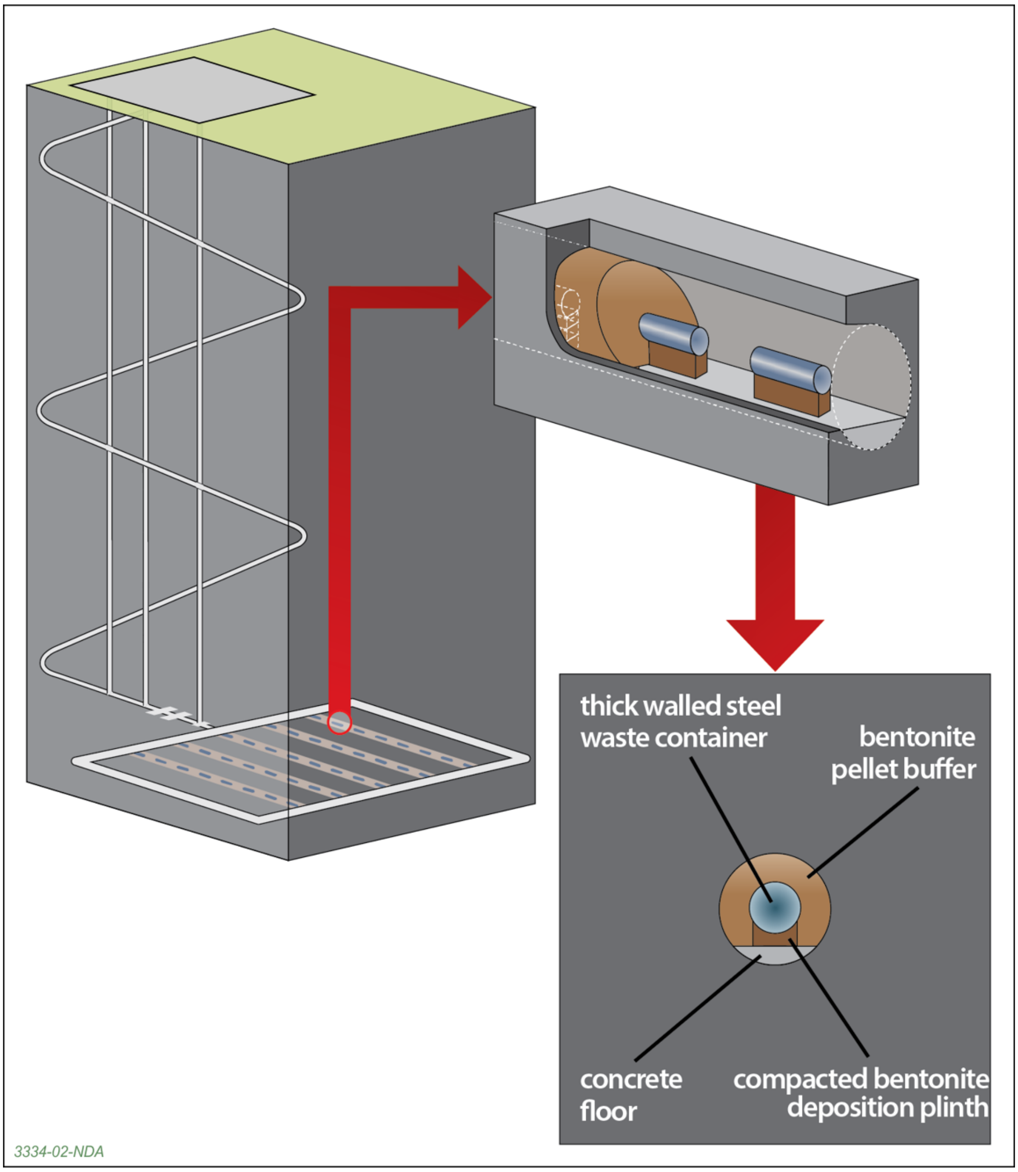
The occurrence of many of these conditions depends on factors such as controls on backfill emplacement and factors specific to the GDF location. One variant scenario involving early failure of stainless steel containers as a result of corrosion, leading to advection of radionuclides from the waste packages, has been assessed in order to demonstrate the robustness of the multi-barrier concept to such scenarios for an illustrative higher strength rock environment. The results of this assessment are presented in Section 10.3.

6 HHGW Disposal in Lower Strength Sedimentary Rock

The lower strength sedimentary rock category refers to fine-grained, sedimentary rocks with a high content of clay minerals and, thereby, a low permeability. Such rocks are mechanically weak, so that open fractures cannot be sustained. The transport of any mobile species through such sedimentary rocks would be dominated by diffusion [27, §2.1.1].

The illustrative concept defined for the disposal of HHGW in lower strength sedimentary rock involves packaging the wastes within thick-walled carbon steel containers [3, §6.1]. The waste packages will be placed on bentonite plinths in tunnels (unlined, but with concrete floors). The tunnels will be backfilled with pelleted bentonite. The disposal concept is illustrated in Figure 12.

Figure 12 Concept for the disposal of HHGW in a lower strength sedimentary rock [3, Figure 6]



6.1 Geological environmental safety functions

6.1.1 Isolation of the wastes

A lower strength sedimentary rock and its geological environment will provide an isolation function similar to that of other types of host rock (see Section 4.1.1).

6.1.2 Protection of the engineered barriers

A lower strength sedimentary rock provides an environment in which small excavations will remain open, but some form of engineered support is likely to be required to ensure long-term stability in rocks that might otherwise deform plastically or be subject to rock fall [63, §4.2.3; 27, §3.1.2 and §6.3.4-§6.3.5].

The integrity of the EBS will depend on the hydrological and geochemical conditions in the vicinity of the disposal facility [27, §5.3.4-§5.3.5]. Groundwater movement in the host rock will be slow, taking place predominantly through the rock matrix; sedimentary rocks that are more indurated (hardened) may contain fractures, but such fractures are likely to be sealed [27, §3.1.2]. Therefore, the supply of water needed to drive engineered barrier degradation processes (such as corrosion) will be slow. The groundwater is likely to be mildly reducing, although saline, and changes in groundwater chemistry in the host rock in response to natural events such as glaciation will be slow [27, §5.2.1, §5.3.4-§5.3.5]. Thus, in general, barrier system degradation rates will be low and are expected to remain low in the long term.

As for higher strength rock, heat transfer through the rock will ensure that any potentially detrimental temperature-dependent effects on EBS materials and the host rock are avoided, given appropriate controls on the distribution of heat generating materials in the disposal facility [27, §6.1].

The rate of gas generation by metal corrosion will be limited by the rate of supply of water from the host rock, which will limit the potential for the formation of a free gas phase, and the generation of high gas pressures and possible disruption of the barrier system [27, §6.3.7; 53, §6.1.4].

Where groundwater movement is slow and mass transfer is diffusion-dominated, there is limited potential for fissile material released from degrading waste packages to accumulate at a single location in the EBS or geological environment [12, §5.3.2]. Thus, post-closure nuclear criticality and any associated disruption of the barrier system resulting from such accumulations is not expected to occur.

6.1.3 Limitation of contaminant transport to the surface environment

Any radionuclides and non-radiological species released from the disposal facility will slowly diffuse through the host rock; groundwater movement is expected to be too slow for advection of contaminants to be significant [27, §2.1.2, §3.3.4]. Although an EDZ will be induced in the host rock by the excavation activities, the fractures in the EDZ will gradually heal as a result of rock creep, thus reducing the capacity for groundwater movement and contaminant transfer in the EDZ [27, §6.3.2-§6.3.4]. Similarly, should high volumes of gas be generated, by for example the corrosion of reactive metals, many lower strength sedimentary rocks exhibit sufficient creep that they would self-heal following any short-term crack formation [27, §6.3.7; 53, §6.3.3]. Stress changes (for example associated with glacial loading and unloading) could result in fracturing in the host rock, but the fractures would be expected to self-heal by creep [27, §6.3.4], limiting their potential to act as preferential pathways for radionuclide migration.

Many radionuclides, including actinides, will sorb strongly to the clay minerals in the host rock [27, §3.1.2]. Therefore, the host rock will contain all but the most mobile and long-lived radionuclides.

The sequences of rocks overlying the host rock will also provide a containment function [27, §5.3.4-§5.3.5]. A laterally extensive higher-permeability layer above the host rock and beneath a lower-permeability clay layer would provide a conduit for the advection and dispersion of contaminants before they diffuse back into the host rock or into the cover rock, which may result in a long containment period in the geological barrier.

6.2 Wasteform environmental safety functions

The environmental safety functions provided by the HHGW wasteforms are as described in Section 4.2 for the higher strength rock disposal concept.

6.3 Container environmental safety functions

6.3.1 Prevention or limitation of the release of contaminants

Under oxic conditions, the rate of corrosion of carbon steel containers may be relatively high, but the corrosion depth is expected to be limited to of the order 100s of μm before the oxygen inventory in the disposal facility is consumed after closure [62, §10.7.2]. The rate of corrosion will reduce once anaerobic conditions have become established [62, §10.7.2]. A carbon steel container with a corrosion allowance of the order of 10 mm is expected to provide containment for at least 10,000 years [62, §11.2.2]. Container corrosion will provide redox buffering within the EBS, which will limit the solubility of some radionuclides [63, §4.2.3] and container corrosion products will provide favourable surfaces for radionuclide sorption [63, §4.2.4].

6.3.2 Prevention of disruption through over-pressurisation

As noted in Section 4.3.2, the water content of HHGW packages at the time of disposal will be limited to residual water associated with spent fuel. The small mass of water present and the void space within the container will be such that any gas generation by internal container corrosion or water radiolysis will not generate high pressures [62, §11.1.3]. Therefore, a carbon steel HHGW container will not fail as a result of over-pressurisation.

6.3.3 Stabilisation of the structure and geometry of the engineered barriers

The carbon steel containers will have sufficient strength to withstand the mechanical loading caused by host rock creep (lithostatic pressure) until degradation processes (for example corrosion) have substantially weakened them [62, §11.2.2; 63, §4.2.3-§4.2.4]. The container will also provide radiation shielding, thereby protecting the buffer from radiation damage [63, §4.2.3].

6.3.4 Limitation of the potential for nuclear criticality

The spent fuel assemblies will be placed in channels in the carbon steel containers, which will provide criticality control by limiting neutron interaction between assemblies. The exclusion of water by the container (apart from the residual water content of the spent fuel waste packages) will minimise neutron moderation, which will provide criticality control [12]. The longevity of the container will ensure that Pu-239 decays to U-235 to some extent in the waste packages prior to container breach and the potential for water infiltration into the waste package. Also, the slow dissolution of oxide spent fuels and ceramic or glass-ceramic plutonium residue wasteforms will ensure that the potential for criticality following accumulation of Pu-239 in the disposal facility is small [12, §5.3.2].

6.4 Local buffer/backfill environmental safety functions

6.4.1 Protection of the container

As noted for the HHGW disposal concept in higher strength rock, saturated bentonite provides a low permeability barrier through which any mass transfer will be predominantly by diffusion (Section 4.4.1). The rate of transfer of aggressive species, such as chlorides or sulphides, to the container surface, and corrosion products away from the container surface, will be limited. Also, the high pore pressure and reducing conditions will limit bacterial activity and the container will be protected from corrosive attack [63, §3.13, §4.2.3].

6.4.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The bentonite will provide mechanical support for the containers and will protect them from maximum expected shear displacements along rock fractures, although this safety function requires the bentonite to have saturated and achieved its swelling pressure prior to any such displacement occurring [63, §3.7.1, §3.9.1, §4.2.3].

6.4.3 Limitation of the release of contaminants

The bentonite will help to condition the groundwater to a near-neutral to mildly alkaline pH, which, coupled with the prevailing reducing conditions, will ensure that, after container breach, wasteform dissolution rates and radionuclide solubilities are low [63, §3.9.4, §4.2.3]. The low-permeability buffer will ensure that any radionuclide transport from the container is by diffusion and will act to filter any mobile radionuclides in colloidal form [31, §3.3.1]. The large surface area and high cation-exchange capacity of the bentonite will provide a strongly sorbing medium for many radionuclides low [63, §3.9.2, §4.2.3].

6.4.4 Prevention of disruption through over-pressurisation

The bentonite does not have a significant role with regard to the prevention of over-pressurisation as a result of gas generation. If the gas pressure becomes sufficiently large that dilatant pathways occur, then gas will migrate along these pathways, but the pathways will close when the gas pressure falls [53, §6.2.2].

6.5 Mass backfill environmental safety functions

6.5.1 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The crushed rock mass backfill in the access tunnels will fill the void space and stabilise the host rock [63, §4.2.3].

6.5.2 Limitation of the release of contaminants

The mass backfill in access tunnels will provide a barrier to human intrusion [63, §4.2.3]. The low permeability of the mass backfill will ensure that any mass transport through it is by diffusion.

6.5.3 Prevention of disruption through over-pressurisation

The mass backfill does not have a significant role with regard to the prevention of over-pressurisation as a result of gas generation.

6.6 Plugs and seals environmental safety functions

6.6.1 Limitation of the release of contaminants

Seals in access tunnels and shafts will isolate the waste by providing a barrier to access of people into the GDF. Seals throughout the GDF will act to prevent the release of contaminants by closing potential groundwater flow pathways through the GDF [63, §4.2.3; 27, §6.8.3].

6.6.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The disposal tunnel seals will resist the swelling (and prevent loss of density) of the bentonite buffer in the tunnels [63, §4.2.3] and will serve to prevent rockfalls.

6.6.3 Prevention of disruption by over-pressurisation

The seals may be designed to be gas permeable, while preventing the flow of water, thereby mitigating the potential for over-pressurisation [27, §6.8.4; 53, §5, §6.2].

6.7 Base scenario

The following sub-sections discuss the key processes that influence how conditions in the GDF are expected to evolve with respect to the three timeframes described in Section 3.3. The discussions draw on the descriptions of barrier environmental safety functions for the illustrative disposal concept and the descriptions of system evolution presented in the Engineered Barrier System Status Report [63, §4.2.4] and the Geosphere Status Report [27, §6.8.3].

6.7.1 Evolution during GDF construction and operation

During the period of GDF construction and operation, conditions are expected to evolve as follows:

- An EDZ will be induced in the GDF host rock by the excavation activities. The characteristics of the EDZ will depend on the geotechnical characteristics of the host rock, the *in situ* stress, the excavation technique and any engineering support installed. Typically, the EDZ around a tunnel in an indurated mudrock could extend into the rock for a distance equivalent to the radius of the tunnel.
- Waste package degradation during the operational period (atmospheric conditions) will be kept to a minimum, by ensuring that groundwater does not come into contact with the packages and that temperature and humidity and/or the amount of corrosive contaminants (for example chloride) are controlled.
- The rock around the excavations will dry out during the operational phase and the presence of the EDZ will result in localised changes to hydrogeological properties. Given that the waste emplacement and backfilling in each disposal tunnel are expected to take only a few months, some tunnels will be sealed early in the operational phase. However, the degree to which the disposal areas will resaturate during the operational phase will be limited by the low permeability of the host rock and the coupling of gas generation to groundwater inflow.
- Creep is likely to result in the eventual self-sealing of the EDZ. For a poorly-indurated rock, this self-sealing could be rapid, with EDZ fractures closing in a few years or less (that is, during the GDF operational period), although the rate and extent of self-sealing will depend on the degree to which the rock has become dehydrated. After the tunnels are backfilled and sealed, the inward convergence of

the host rock will be opposed by the backfill and seals, especially as they begin to resaturate and the bentonite exerts a swelling pressure. By limiting creep of the host rock, the EBS will limit macroscopic deformation, including fracturing. Gaps between the buffer and the waste packages and host rock will also become sealed as the bentonite swells.

6.7.2 Early post-closure evolution

During the early post-closure period, the engineered barriers will degrade slowly as a result of interactions with the groundwater and with each other. However, the barriers are expected to remain sufficiently intact that they are able to perform their intended environmental safety functions. In this period, it is expected that:

- The resaturation process described above will continue and the bentonite buffer will become established as a low-permeability barrier.
- Creep closure of the EDZ and the backfilled and sealed GDF will continue at a rate that depends on the physical properties of the host rock and the stress regime. For indurated rocks, self-sealing could take many centuries to thousands of years and in some cases, the host rock may never completely return to its undisturbed state.
- Porewater redox conditions will tend to be reducing, controlled by the presence of iron in engineered materials, together with a neutral to mildly-alkaline pH provided by the weak buffering capacity of the bentonite and minerals contained in the host rock.
- The carbon steel disposal containers will corrode at a rate that depends *inter alia* on water availability and the rate of transfer of corrosive agents to the container surface. The containers are expected to provide full containment during the resaturation period and for long times after resaturation.
- Corrosion of the waste containers will result in the generation of hydrogen gas. Given the low permeability of the bentonite and host rock, two-phase flow of gas (dissolved and free gas) is expected to occur at elevated pressures. However, the gas will be able to escape through the bentonite without compromising its properties as a hydraulic barrier because the bentonite will reseal after gas breakthrough.
- The rate of heat generation in the wastes will be high until the short-lived components of the inventory have decayed. As a result, the temperature of the buffer and the surrounding rock may rise by several tens of degrees, remaining elevated for at least 1000 years, before slowly decreasing. The disposal concept will be designed such that the temperature in the outer half of the bentonite is limited to 125°C at any time following emplacement in order to preclude significant thermal alteration that might affect the potential for the bentonite to achieve its desirable swelling pressure and hydraulic properties [11, §9.9.6]. Temperatures will be expected to return to ambient values before the containment provided by the container is lost.

6.7.3 Late post-closure evolution

Eventually, the containers are expected to fail as a result of weakening by corrosion. Based on the current understanding of likely container corrosion rates under *in situ* conditions and their material thicknesses, and taking into consideration the chemical and physical protection of the container by the bentonite buffer following resaturation, a carbon steel disposal container is expected to have a lifetime of at least ten thousand years.

Once water penetrates the disposal container, the wasteform will start to dissolve and release radionuclides. Most of the HLW inventory is likely to have decayed by the time container failure occurs and, following an initial enhanced release rate, the slow dissolution of the glass matrix will limit the release rate of any remaining radionuclides. Similarly, most of the spent fuel inventory is likely to have decayed by the time of container failure. However, when a spent fuel container fails, a portion of the remaining inventory that has segregated to the grain boundaries of the fuel will be released rapidly upon exposure to groundwater (the instant release fraction). The remaining radionuclides will be released slowly from the fuel as it dissolves.

Iron corrosion products and the bentonite buffer will provide good substrates for sorption and will retard radionuclide migration. The bentonite will filter any mobile radionuclides in colloidal form. Also, because groundwater movement is expected to be extremely slow in the low-permeability rock, solute transport will be predominantly diffusive. Many radionuclides will decay to negligible activities as they diffuse through the EBS and into the host rock and will not reach the biosphere.

On very long timescales (hundreds of thousands of years or more) the behaviour of the disposal system could be affected by natural disturbances or transients arising from the effects of global climate events (such as glaciation). It is anticipated that the GDF will be located such that its performance is robust to expected natural changes. In particular, on these timescales the vast majority of the disposal inventory will have decayed and the GDF will have evolved into a system analogous to a large natural uranium deposit. However, as discussed in Section 2.4.5, detailed assessments of the impacts of large-scale natural processes on GDF performance will not be undertaken until specific GDF sites have been identified.

6.8 Variant scenarios

The environmental safety functions provided by the host rock in limiting contaminant migration are important to the environmental safety of the disposal concept. Therefore, variant scenarios relating to the environmental safety functions provided by the host rock are likely to be of greatest significance to GDF performance, although variant scenarios associated with disruptions to container and backfill performance also require consideration:

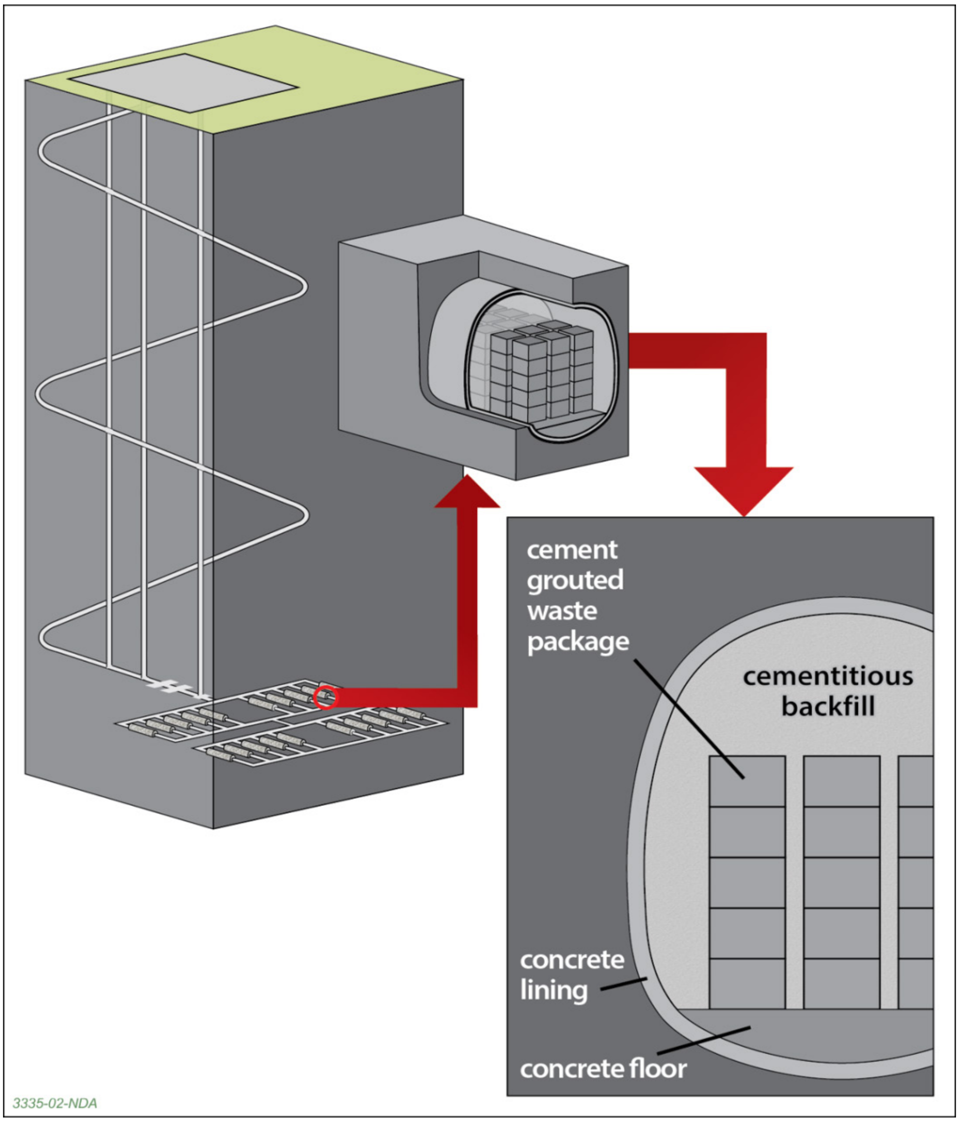
- The barrier function of the host rock could be by-passed if shaft seals do not fulfil their environmental safety functions, for example, as a result of quality control failures of shaft-sealing materials. Such failures could result in the presence of preferential groundwater flow and contaminant transport pathways through seals between the GDF and overlying formations.
- Failures in the quality control of container or buffer materials such that they do not meet design specifications at the time of emplacement could mean that EBS components do not perform their intended environmental safety functions. For example, defects in the container lid welds could result in early failure of carbon steel containers under the mechanical stresses imposed by swelling bentonite.
- Gas pressurisation due to waste package corrosion could result in the generation of fractures in the host rock that could provide pathways for contaminant migration whilst they remain open [27, §6.3.7].
- As the waste packages corrode, collapse could lead to redistribution of voidage [67]. As a result, the integrity of the backfill and host rock could be disrupted, which could introduce groundwater flow and transport pathways through the host rock before the pathways close by creep [27, §6.3.6].

The occurrence of these conditions depends on factors such as controls on container lid welding, seal emplacement and factors specific to the GDF location. Variant scenarios involving factors such as shaft seal failure would be assessed in detail at a site-specific stage if a lower strength sedimentary rock is investigated as a potential host rock, when suitable data on facility design and site characteristics are available. In this generic ESC, an illustrative variant scenario, involving early breach of the carbon steel containers as a result of weld failure due to large, undetected defects has been assessed in order to demonstrate the robustness of the multi-barrier concept to such scenarios for an illustrative lower strength rock environment. The results of this assessment are presented in Section 10.3.

7 LHGW Disposal in Lower Strength Sedimentary Rock

The illustrative concept for the disposal of LHGW in lower strength sedimentary rock involves stacking waste packages in vaults [3, §6.1]. The vaults may be lined with concrete and will be backfilled with a cementitious material. The disposal concept is illustrated in Figure 13. In developing this concept, the vault dimensions have been maximised based on consideration of the stacking requirements of the different types of waste package in the context of the stability of openings in lower strength sedimentary rocks. The actual profiles and dimensions of the vaults at the GDF site will be determined based on the prevailing host rock geotechnical characteristics and the *in situ* stress regime at disposal depth.

Figure 13 Illustrative concept for the disposal of LHGW in a lower strength sedimentary rock [3, Figure 5]



7.1 Geological environmental safety functions

The isolation and containment environmental safety functions provided by lower strength sedimentary rock are described in Section 6.1 for the illustrative disposal concept for HHGW. These environmental safety functions are broadly applicable to the concept for LHGW disposal in lower strength sedimentary rock, although heat transfer in the host rock is less important for the LHGW disposal concept.

7.2 Wasteform environmental safety functions

The environmental safety functions provided by the LHGW wasteforms are as described in Section 5.2 for the higher strength rock disposal concept.

7.3 Container environmental safety functions

7.3.1 Prevention or limitation of the release of contaminants

The containers will provide similar containment functions to those they provide in the higher strength rock disposal concept (see Section 5.3.1). The thin-walled stainless steel containers will corrode slowly under expected post-closure conditions, which will ensure a long period of containment [62, §10.9.2, §12.2.1]. Thicker-walled robust shielded waste containers, constructed from ductile cast iron or carbon steel, will also provide long containment periods [62, §10.7.2, §12.2.2]. The potential for chloride-induced corrosion, particularly for stainless steel containers, will be reduced once oxygen is consumed and anaerobic conditions are established [62, §10.9.2].

Container corrosion (particularly corrosion of the carbon steel and cast iron containers) will support maintenance of reducing conditions and, thus, the low solubility and strong sorption of many radionuclides; the corrosion products will provide a high sorption capacity for radionuclides [63, §4.2.5; 31, §3.2].

As noted in Section 5.3.1, concrete containers are generally thick-walled and include carbon steel re-bars and external carbon steel components treated with a zinc-based coating to enhance their corrosion resistance [62, §10.11]. Concrete containers do not provide an impermeable barrier to radionuclide release, but they may contribute to the chemical conditioning of the pore water within the EBS, limiting radionuclide solubility and ensuring that the release of radionuclides is slow [62, §9.3.3, §12.2.3].

Groundwater could enter through the gas vents that will be present in most containers and will saturate the wasteform, but any contaminant transport from the containers will be limited to diffusion through the vents until the containers are breached (for example, by corrosion) [63, §4.2.5].

7.3.2 Prevention of disruption through over-pressurisation

Most LHGW containers have vents for gas release, thus preventing waste package over-pressurisation and damage [62, §9.3; 63, §4.2.5]. Degrading concrete containers may generate less gas than corroding carbon steel or cast iron containers [62, §9.3.3].

7.3.3 Stabilisation of the structure and geometry of the engineered barriers

Stainless steel waste packages (and the stillages that hold 500 litre drums) and stacks of robust shielded waste containers will provide mechanical stability and will have sufficient strength to withstand the mechanical loading caused by host rock creep in the vaults until the packages are weakened by corrosion [62, §9.3.1-§9.3.2]. The concrete containers will have good mechanical properties and durability [62, §9.3.3].

7.3.4 Limitation of the potential for nuclear criticality

The container walls will help shield and separate fissile wasteforms from each other in a vault (limiting neutron transport between packages), thus supporting the prevention of criticality after GDF closure [12, §3.3].

7.4 Local buffer/backfill environmental safety functions

7.4.1 Protection of the container

As the cementitious backfill resaturates, it will generate a high-pH environment and the presence of the backfill will limit the aerobic period after disposal by limiting the volume of oxygen present [27, §6.4.2; 63, §4.2.5]. Under alkaline and reducing conditions, metal corrosion rates will be low, thus supporting the longevity of the containers [63, §3.7.2, §4.2.5].

Saturated backfill provides a thermally conductive medium for heat transfer from the waste packages, thus limiting the rates of potentially detrimental temperature-dependent chemical reactions, such as container corrosion.

The concrete liner and backfill will provide mechanical stability, which will protect the containers from rockfalls and the effects of creep [63, §4.2.5]. The crown space will be backfilled in this concept.

7.4.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The concrete liner and backfill, which will be emplaced immediately after vault filling, will provide mechanical resistance to creep closure [63, §4.2.5]. By limiting creep of the host rock, the liner and backfill will prevent macroscopic deformation of the host rock, including fracturing, and will enable a homogeneous stress state to be re-established.

7.4.3 Limitation of the release of contaminants

In the long term, the waste packages may become saturated. However, the solubility of many radionuclides will be limited under the high pH conditions induced by the cementitious backfill [63, §4.2.5]. Thus, the dissolved concentration and the rates of release of these radionuclides from the waste packages will be low. The low permeability of the backfill will ensure that any contaminant transport from the containers is by diffusion [63, §4.2.5].

Also, the cement-based backfill has a high capacity for sorbing radionuclides, thus inhibiting the migration of radionuclides through the backfill. Co-precipitation will act to incorporate some radionuclides into the structure of backfill minerals [63, §3.10].

Cementitious colloids may affect concentrations of radionuclides in near-field porewaters. However, cementitious colloids are not expected to be chemically stable in the undisturbed host rock beyond the chemically disturbed zone; instead, they are expected to dissolve and release any radionuclides that they had been transporting to the aqueous phase [31, §3.3.2].

The high pH conditions will suppress microbial activity, thus limiting microbial gas generation reactions and the release of some radioactive gases (for example gases containing C-14) [31, §2.8; 63, §4.2.5].

If dissolved cement minerals come into contact with the host rock, the precipitation of new minerals may occur, leading to re-sealing of fractures and effective self-sealing of the vaults [27, §6.4.3, §6.8.4; 31, §4.2.2]. However, the extent of the alkaline disturbed zone will be limited owing to the low permeability of the rock [27, §6.8.4]. Low pH cements could be used (pH of about 10) for example in the concrete liner in order to limit the potential for hyperalkaline leachates to form and, thereby, to minimise impacts of the cement on host rock properties [27, §6.4.3].

7.4.4 Prevention of disruption by over-pressurisation

The backfill will be gas permeable, and its high porosity will accommodate considerable volumes of gas, thus limiting the potential for the generation of high pressures [63, §4.2.5].

Carbon dioxide generated from the microbial degradation of organic wastes will generally react with cement materials, thus limiting gas pressurisation [63, §3.10.1, §4.2.6].

7.5 Mass backfill environmental safety functions

7.5.1 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The mass backfill will provide mechanical support, resisting rockfalls and the extension of the EDZ in the surrounding rock [63, §4.2.5].

7.5.2 Limitation of the release of contaminants

The mass backfill will prevent the access tunnels from acting as preferential pathways for groundwater flow and contaminant migration [63, §4.2.5] and will provide a large surface area for sorption of any dissolved contaminants that enter the tunnels.

7.5.3 Prevention of disruption by over-pressurisation

The porous mass backfill will accommodate gas generated in the disposal vaults, thereby limiting the potential for over-pressurisation [63, §4.2.5].

7.6 Plugs and seals environmental safety functions

7.6.1 Limitation of the release of contaminants

The plugs and seals will prevent the release of contaminants by closing potential groundwater flow pathways through the GDF [63, §4.2.5]. The seals in access tunnels and shafts will isolate the waste by providing a barrier to the access of people into the GDF.

7.6.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The seals will provide mechanical support to the backfill and will also serve to resist creep and rockfalls.

7.6.3 Prevention of disruption by over-pressurisation

The seals are designed to be gas permeable, but to prevent the flow of water, thereby mitigating the potential for over-pressurisation [63, §4.2.5].

7.7 Base scenario

The following sub-sections discuss the key processes that influence how conditions in the GDF are expected to evolve with respect to the three timeframes described in Section 3.3. The discussions draw on the descriptions of barrier environmental safety functions for the illustrative disposal concept and the descriptions of system evolution presented in the

Engineered Barrier System Status Report [63, §4.2.6] and the Geosphere Status Report [27, §6.8.4].

7.7.1 Evolution during GDF construction and operation

During the period of GDF construction and operation, conditions are expected to evolve as follows:

- An EDZ will be induced around the vaults and tunnels. In lower strength sedimentary rocks such as indurated mudrock the EDZ could extend into the rock for a distance equivalent to the radius of a tunnel.
- The rock around the excavations will dry out during the operational phase and damage associated with the EDZ will result in localised changes to hydrogeological properties.
- Waste package degradation during the operational period (atmospheric conditions) will be kept to a minimum, by ensuring that groundwater does not come into contact with the packages and that temperature and humidity and/or the amount of corrosive contaminants (for example, chloride) are controlled.
- Creep of the host rock in response to stress and strain changes may be sufficient to cause the EDZ fractures, and to some extent the excavations, to self-seal. For a poorly-indurated rock this self-sealing could be rapid, with EDZ fractures closing in a few years or less. The concrete liner will provide structural stability, preventing macroscopic deformation of the host rock.
- Backfilling of the disposal vault will take place immediately after the vault has been filled. This will bring water into contact with the waste packages. Also, some water may have been introduced with the waste and/or an encapsulant. Metal corrosion and, as a result, gas generation rates may be highest under such conditions.
- Cement curing in the backfill will increase temperatures, which could increase corrosion rates. Waste package temperatures of up to 80°C can be accommodated for a period of up to five years for some containers (not stainless steel) during cement curing, but the disposal facility will be designed such that waste package temperatures do not exceed 50°C following closure [11, §9.9.6].
- As the cement cures, groundwater will gradually seep into the EBS from the host rock and will saturate the pore space in the backfill and in waste packages (through the waste package vents). However, the rate of saturation will be slow for lower strength sedimentary rocks because of their low permeability.
- Alkaline conditions will develop as the groundwater interacts with the backfill, which will favour slow corrosion.
- Initially conditions in the disposal vaults will be oxidising, but corrosion and other reactions will consume oxygen and conditions will become reducing.

7.7.2 Early post-closure evolution

In the early post-closure period the engineered barriers will degrade slowly as a result of interactions with the groundwater and with each other. However, the barriers will remain sufficiently intact that they are able to perform their intended environmental safety functions fully. In this period, it is expected that:

- The resaturation process will continue and will eventually complete on a timescale that depends on the hydraulic conductivity of the host rock, but may be in excess of thousands of years.

- The backfill and concrete liner will provide structural support, thereby maintaining the stability of the host rock.
- The corrosion reactions and the degradation of organic materials in the waste could generate significant volumes of gas (mostly hydrogen, but also some methane and carbon dioxide). The pressure increase in the EBS will oppose the saturation process, which might limit the availability of water for the gas generation reactions, including the generation of radionuclides in the gas phase.
- Any carbon dioxide produced (which may include C-14) will dissolve or react with the cementitious backfill. Other gases are likely to accumulate in the EBS within pore spaces in the backfill (including C-14-bearing methane) – initially dissolved in porewater, then as a free gas phase as the concentration increases above the gas solubility limit. Gas will diffuse slowly through the host rock and some pressurisation will occur in the EBS as the free gas phase develops. If the gas pressure exceeds the rock-entry pressure, free gas could enter the host rock as a result of pore dilation and microfissuring. However, if the vault backfill has sufficiently high porosity and the vault seals allow the passage of gas whilst restricting the flow of water, the generation of excessive gas pressures in the vaults will be avoided.
- The waste package will provide an important barrier to the release of contaminants in groundwater during the resaturation period while the chemical barrier provided by the cementitious backfill is becoming established. Eventually, contaminants will be released as dissolved species from the LHGW containers, initially in small quantities by diffusion through vents until the containers are breached by corrosion and more substantial diffusion occurs. The high pH conditions will limit the solubility and will promote the precipitation of key radionuclides.
- Organic complexing agents derived from the wastes could increase radionuclide mobility, but their impact will become progressively less significant as their concentrations are reduced by chemical, radiolytic or microbial degradation. NAPLs may be present in some waste packages, which could facilitate contaminant transport, but NAPLs will not migrate from the waste packages to the host rock in significant quantities.
- Reactions between cementitious water and the clay minerals of the host rock will result in the development of an alkaline disturbed zone around the vaults in which precipitation of new minerals will reduce host rock porosity, resulting in a decrease in permeability and sealing of any EDZ fractures that have not self-sealed as a result of creep. Cementitious colloids (which could transport radionuclides) will not be stable beyond the alkaline disturbed zone.

7.7.3 Late post-closure evolution

After tens to hundreds of thousands of years, degradation of the engineered barriers will be such that the barriers will no longer be able to perform their original environmental safety functions fully:

- The wasteforms, cementitious backfill and concrete liner will alter through reaction with the groundwater and may be disrupted as a result of rock creep and compaction, but will resist any significant deformation of the host rock.
- The pH in the disposal area will eventually fall to a level where the chemical barrier provided by the backfill is less effective.
- Radionuclides that have not decayed in the waste packages and EBS, and mobile non-radiological contaminants, may be released to the host rock.

- Gas will continue to be produced from the corrosion of metals, but at a low generation rate.

In the very long term (many hundreds of thousands to millions of years) the EBS is not expected to provide containment, although by this time the vast majority of the radionuclide inventory will have decayed. On these timescales, the behaviour of the disposal system could be affected by natural disturbances or transients arising from the effects of global climate events (such as glaciation). It is anticipated that the GDF will be located such that its performance is robust to expected natural changes, but, as discussed in Section 2.4.5, detailed assessments of the impacts of large-scale natural processes on GDF performance will not be undertaken until specific GDF sites have been identified.

7.8 Variant scenarios

The role of the host rock in limiting contaminant migration and, therefore, host rock stability are important for this disposal concept. Also, the establishment of alkaline and reducing conditions will ensure that the corrosion rates of metal containers are low and that the rate of release of contaminants from the waste packages is limited. Therefore, the identification of variant scenarios has focused on the environmental safety functions provided by the host rock, concrete liner and backfill:

- As the waste packages corrode, those with high voidage (for example robust shielded waste containers for un-encapsulated wastes) could collapse, leading to redistribution of the voidage [67]. If the concrete liner and backfill fail to maintain their structural stability, the integrity of the host rock could be disrupted, which could introduce groundwater flow and transport pathways through the host rock before the pathways close by creep [27, §6.3.6].
- As noted for the higher strength rock disposal concept (Section 5.8), localised corrosion of stainless steel containers could occur under low pH conditions, especially if the groundwater is rich in chloride and conditions are oxic. Low pH conditions could occur as a result of not emplacing the backfill completely or correctly or as a result of carbonation of the backfill. Microbiologically-influenced corrosion may also affect stainless steel, carbon steel and cast iron containers when the porewater pH is low.
- The solubility of many radionuclides will be greater where the groundwater pH is lower than expected, which could result in more rapid leaching of radionuclides from the wasteform. Radionuclide sorption in the backfill will also be reduced where the pH is lower.
- Gas pressurisation due to waste package degradation could result in the generation of fractures in the host rock that could provide pathways for contaminant migration whilst they remain open [27, §6.3.7].
- The barrier function of the host rock could be by-passed if shaft seals do not fulfil their environmental safety functions, for example, as a result of quality control failures of shaft sealing materials. Such failures could result in the presence of preferential groundwater flow and contaminant transport pathways through seals between the GDF and overlying formations.

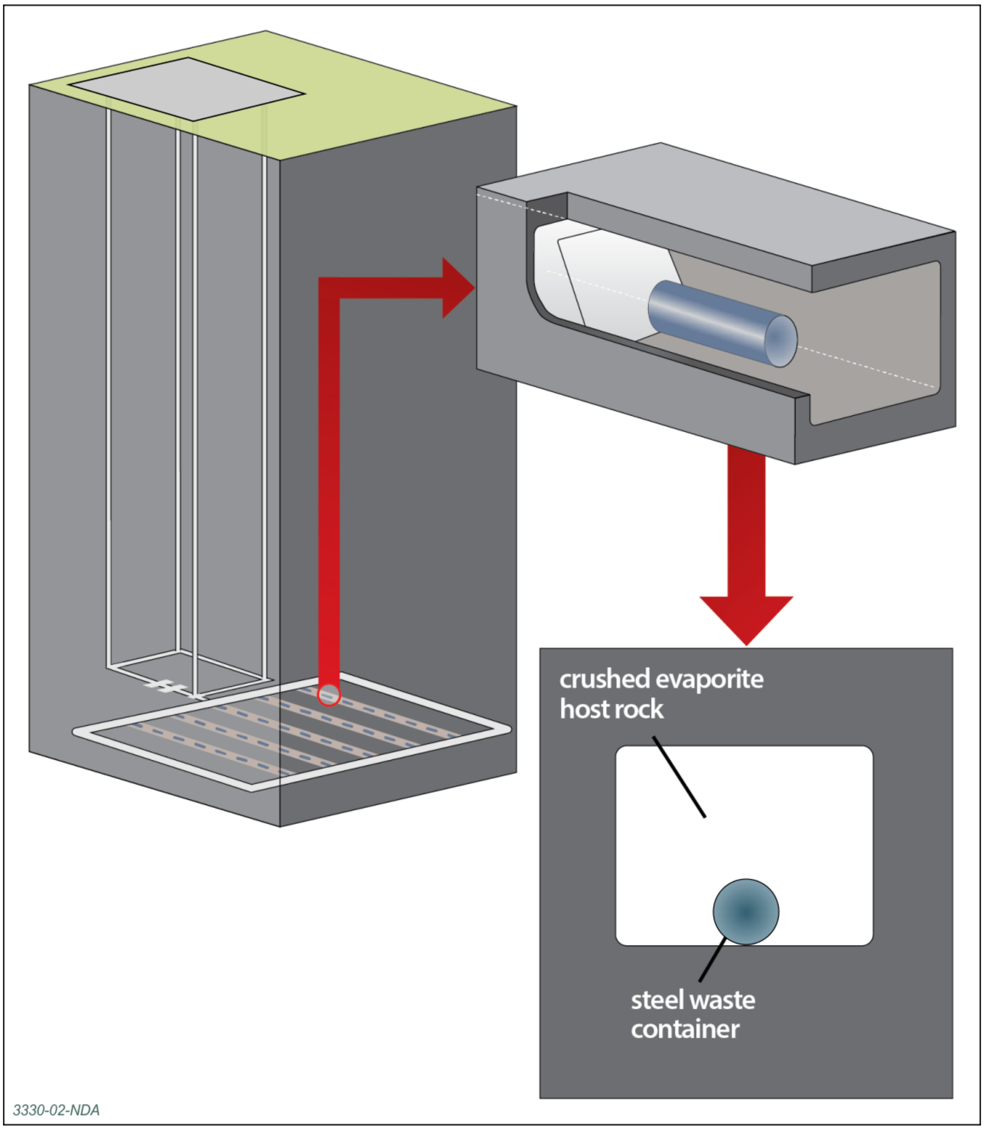
The occurrence of these conditions depends on factors such as controls on concrete liner, backfill and seal emplacement and factors specific to the host rock and the GDF location. Variant scenarios involving events such as shaft seal failure or voidage redistribution would be assessed in detail at a site-specific stage if a lower strength sedimentary rock is investigated as a potential host rock, when suitable data on facility design and site characteristics are available. In this generic ESC, a variant scenario involving early failure of metallic containers as a result of corrosion, leading to early, more rapid diffusion of radionuclides from the waste packages than occurs through vents, has been assessed in order to demonstrate the robustness of the multi-barrier concept to such scenarios for an illustrative lower strength rock environment. The results of this assessment are presented in Section 10.3.

8 HHGW Disposal in Evaporite

The evaporite rock category refers to rocks formed following the evaporation of ancient seas and lakes, which often contain bodies of halite. Halite provides a dry environment; it is weak and creeps such that open fractures cannot be sustained. Transport of mobile species through the rock would be by diffusion through any brine that might be present in regions of interconnected pore space, although such connectivity is unlikely to exist over significant distance in halite.

The illustrative concept defined for the disposal of HHGW in evaporite rock involves packaging the wastes within thick-walled carbon steel containers [3, §6.1]. The waste packages will be placed on the floor of tunnels (unlined). The tunnels will be backfilled with crushed host rock. This concept relies on the property of evaporite rock masses to mechanically creep to close any void spaces, typically over a period of decades; this is known as 'creep closure'. The disposal concept is illustrated in Figure 14.

Figure 14 Illustrative concept for the disposal of HHGW in an evaporite rock [3, Figure 6]



8.1 Geological environmental safety functions

8.1.1 Isolation of the wastes

An evaporite rock provides an isolation function similar to that of other types of host rock (see Section 4.1.1). Low-permeability sedimentary cover rocks will be present and will continue to protect the evaporite rock from near-surface hydrological systems and any dissolution [27, §3.1.1, §5.3.6].

8.1.2 Protection of the engineered barriers

Evaporites have sufficient strength to support large openings with minimal engineering support [63, §4.3.1]. However, as discussed above, an important characteristic of evaporites is that they flow plastically under pressure (that is they will creep at likely GDF depth). Thus, the openings are expected to close gradually over time.

Halites have extremely low permeability and do not contain mobile groundwater [27, §3.1.1]; any groundwater will be present in isolated pores. Therefore, there will be little water available to drive engineered barrier degradation processes. Natural events, such as glaciation, are expected to have little effect on groundwater availability or flow conditions in the host rock; salt bodies have typically experienced many glacial and interglacial periods without significant disturbance [27, §4.3-§4.4]. Thermal gradients could drive the migration of brine pockets towards the GDF, although the evidence for such a process is unclear and its occurrence is likely to depend on the site-specific properties of the rock [27, §6.8.5].

The rate of gas generation by metal corrosion will be limited by the rate of supply of water from the host rock, which will limit the potential for the formation of a free gas phase, and the generation of high gas pressures and resultant disruption of the barrier system [27, §6.8.5].

Nuclear criticality in the disposal facility would require substantial waste package degradation, leading to fissile material relocation and accumulation. Water would be needed in order for the degradation reactions and mass transfer processes to progress. Furthermore, criticality would be more likely to occur under conditions in which neutrons are moderated; water is the most efficient neutron moderator likely to be present in a disposal facility. With limited availability of mobile groundwater, the potential for conditions to develop under which post-closure criticality could occur would be extremely limited [12, §5.2.3]. Also, chlorine is a strong neutron absorber and its presence in any groundwater (brine) and in the evaporite rock would mean that criticality in the disposal system or in the host rock (should fissile radionuclides enter the rock) and associated disruption of the barrier system is not credible [12, §6.3.1].

8.1.3 Limitation of contaminant transport to the surface environment

Openings in the GDF will gradually close over time as a result of rock creep (the backfilled disposal tunnels will close over a period of hundreds of years) [27, §6.8.5], creating a low-permeability barrier around the waste. Stress changes (such as those associated with glacial loading and unloading) could result in fracturing in the host rock, but the fractures would most likely be short-lived, because they would be expected to self-seal by creep. Thus, any contaminant transport through evaporite rock will be negligible, being limited to diffusion through brine in small regions of connected pore space that might be present. The host rock will contain even the most long-lived radionuclides. Any radionuclide-bearing colloids in brine would be filtered in the rock [31, §3.3.3].

8.2 Wasteform environmental safety functions

The environmental safety functions provided by the HHGW wasteforms are as described in Section 4.2 for the higher strength rock disposal concept.

8.3 Container environmental safety functions

8.3.1 Prevention or limitation of the release of contaminants

In the dry environment of a halite host rock, container corrosion will not occur [62, §10.7] and, under such conditions, the thick-walled carbon steel containers are likely to provide containment even under the stresses imposed by creep closure.

8.3.2 Prevention of disruption through over-pressurisation

The water content of the waste package will be limited to residual water in spent fuel assemblies that will be insufficient to generate high pressures as a result of internal container corrosion or as a result of radiolysis [62, §6.1.2, §11.1.3].

8.3.3 Stabilisation of the structure and geometry of the engineered barriers

The carbon steel containers are likely have sufficient strength to withstand the mechanical loading caused by host rock creep unless degradation processes (such as corrosion) have substantially weakened them. However, such degradation processes could not be sustained without water ingress to the facility, which is unlikely for a GDF located in halite [62, §10.7.2].

8.3.4 Limitation of the potential for nuclear criticality

The spent fuel assemblies will be placed in channels in the carbon steel containers, which will provide criticality control by limiting neutron interactions between assemblies. The exclusion of water by the container (apart from the residual water content of the spent fuel waste packages) will minimise neutron moderation, which will provide criticality control [12].

8.4 Local buffer/backfill environmental safety functions

8.4.1 Protection of the container

The backfill does not have a significant role with regard to protection of the container.

8.4.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The crushed salt backfill will compact as the disposal tunnel walls converge owing to the plasticity of the salt host rock under stress. This compaction will support rapid sealing of the GDF, with the properties of the backfill becoming like those of the surrounding rock [63, §4.3.3-§4.3.4]. The creep rate will be greater in the vicinity of the waste packages while they are hot.

8.4.3 Limitation of the release of contaminants

As the porosity of the backfill is reduced by creep, the permeability will reduce, which will limit the potential for migration of radionuclides, although there is little potential for the backfill to become saturated in an evaporite.

8.4.4 Prevention of disruption through over-pressurisation

The backfill does not have a significant role with regard to prevention of disruption through over-pressurisation.

8.5 Mass backfill environmental safety functions

8.5.1 The ability to stabilise the structure and geometry of the engineered barriers

The crushed salt mass backfill in the access tunnels will be compressed by rock creep but will eventually provide some stability.

8.5.2 Limitation of the release of contaminants

As the porosity of the mass backfill is reduced by creep, the permeability will reduce, which will limit the potential for migration of radionuclides, although there is little potential for the mass backfill to become saturated.

8.5.3 Prevention of disruption through over-pressurisation

The mass backfill does not have a significant role with regard to prevention of disruption through over-pressurisation.

8.6 Plugs and seals environmental safety functions

8.6.1 Limitation of the release of contaminants

Seals in access tunnels and shafts will isolate the waste by providing a barrier to the access of people into the GDF. Low permeability seals in shafts and access tunnels will prevent groundwater ingress to the disposal areas from the ground surface and overlying aquifers, thus ensuring that dry conditions are maintained in the disposal facility and contaminant migration is prevented [63, §4.3.3-§4.3.4].

8.6.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The seals will provide mechanical stability in resistance to rock creep [63, §4.3.3-§4.3.4].

8.6.3 Prevention of disruption through over-pressurisation

The seals do not have a significant role with regard to prevention of disruption through over-pressurisation.

8.7 Base scenario

The following sub-sections discuss the key processes that influence how conditions in the GDF are expected to evolve with respect to the three timeframes described in Section 3.3. The discussions draw on the descriptions of barrier environmental safety functions for the illustrative disposal concept and the descriptions of system evolution presented in the Engineered Barrier System Status Report [63, §4.3.4] and the Geosphere Status Report [27, §6.8.5].

8.7.1 Evolution during GDF construction and operation

During the period of GDF construction and operation, conditions will evolve as follows:

- An EDZ will be induced around the excavations extending up to a few metres into the host rock. The EDZ will be more permeable and will exhibit lower pore pressure than the host rock. However, the rock will begin to creep immediately following excavation, driven by the stress field perturbation caused by the excavation, and will close the EDZ fractures.
- Waste package degradation during the operational period (atmospheric conditions) will be kept to a minimum by ensuring that brine does not come into contact with the packages and that temperature and humidity are controlled.
- Resaturation of the backfill is unlikely because of the lack of free water and connected porosity in the host rock and the low permeability of the compressed backfill.
- Oxidising conditions will predominate in the EBS during GDF construction and operation, but conditions will quickly become reducing once the GDF is closed.

8.7.2 Early post-closure evolution

During the early post-closure phase:

- The low-permeability components of the shaft seals (such as concrete, clay and asphalt) will prevent the inflow of water to the GDF from the surface.
- Compaction of the crushed salt components of the tunnel and shaft seals by rock creep will render their permeability similar to that of the host rock within hundreds of years.
- Recovery of the EDZ by creep around the shafts will be aided by the resistance of the rigid components of the shaft sealing system.
- The seals will prevent any circulation of groundwater in the disposal region and flow to the accessible environment.
- Temperatures in the waste package, surrounding backfill and rock will increase as a result of radiogenic heat generation. The disposal facility will be designed such that the temperature in the backfill does not exceed 200°C at any time following emplacement. The high temperature limit has been set to accommodate the low thermal conductivity of the high porosity crushed salt and the resultant high temperatures at the interface between the waste container and backfill [11, §9.9.6].
- Rock creep around the disposal tunnels will compact the crushed salt backfill and will quickly seal the EDZ fractures. Creep will be accelerated in the vicinity of heat-generating wastes and the thermal conductivity of the backfill will increase as its porosity decreases, thus reducing the container temperature [11, §9.9.6]. Eventually, the backfill will provide a continuous barrier of low-permeability salt.
- As the heat output from the waste falls and the EBS cools, thermal contraction may reduce compressive stresses, or even introduce tensile stresses in the surrounding host rock, which may cause cracking.
- If the rock permeability is sufficient to allow brine movement the disposal area will slowly saturate until natural hydraulic gradients are restored, but this is highly unlikely in a halite considered suitable to host the GDF.
- Gas pressurisation due to waste package degradation (for example, from corrosion) may cause fracturing of more brittle host-rock layers and may provide pathways for fluid flow from the excavated region. However, gas generation is likely to be limited by the lack of availability of water for gas-generating reactions in a halite host rock.

8.7.3 Late post-closure evolution

After several thousand years, the process of compaction of the backfill and seals is likely to be complete. Even if containers are breached as a result of compaction, complete containment of the waste in the GDF will be provided by the host rock and no contaminant releases to the accessible environment are expected to occur from an undisturbed GDF.

8.8 Variant scenarios

The dryness of the disposal tunnels and encapsulation of the waste packages by creep closure are important features of the disposal concept that ensure long-term environmental safety. Therefore, the identification of variant scenarios has focused on the environmental safety functions provided by the host rock:

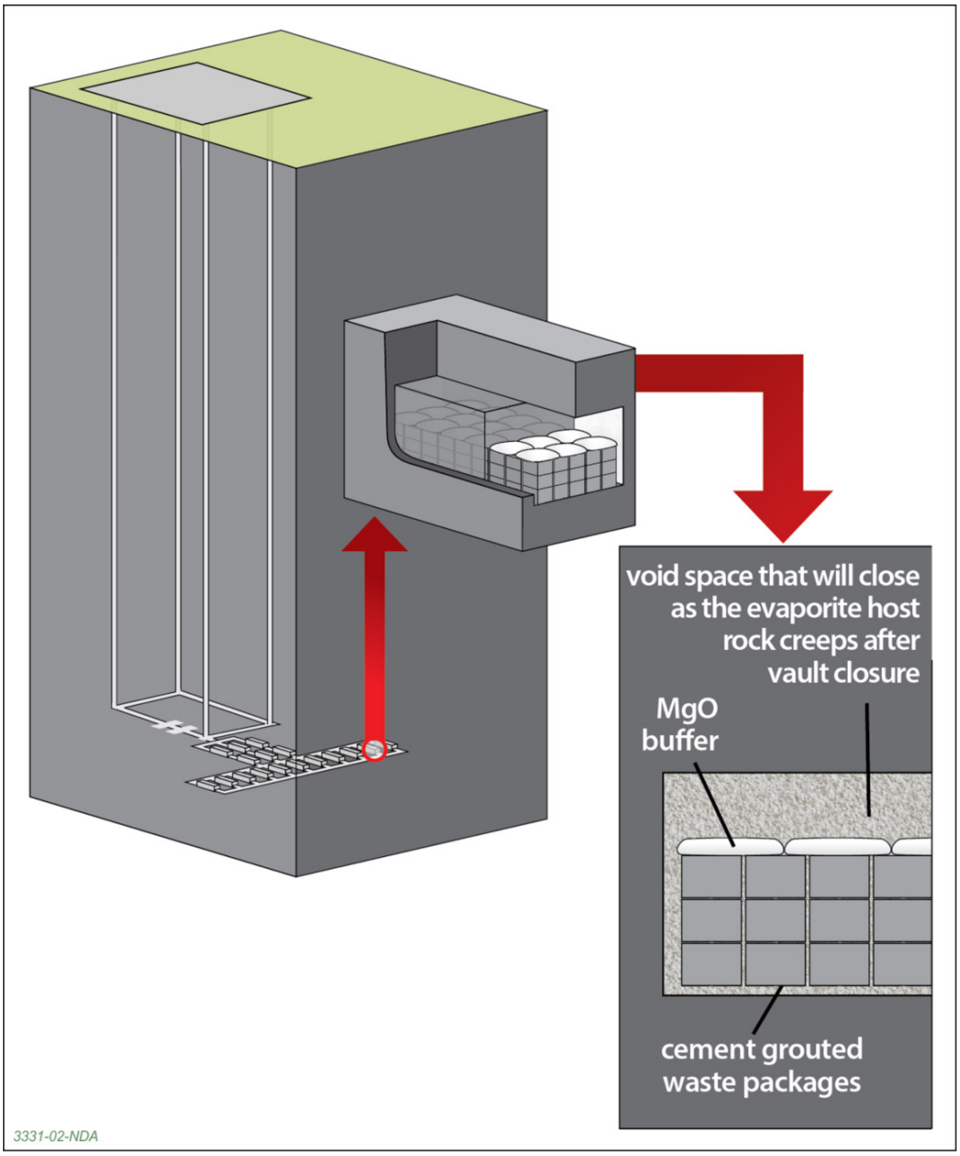
- The barrier function of the host rock could be by-passed if shaft seals did not fulfil their environmental safety functions, for example, as a result of quality control failures on shaft sealing materials. Such failures could result in the presence of pathways for groundwater flow and contaminant transport through seals between the GDF and overlying formations.
- Human intrusion by drilling could result in the presence of pathways for brine flow and contaminant transport between the GDF, overlying formations and the ground surface.
- If brine does enter the disposal facility, then gas pressurisation due to waste package corrosion could result in the generation of fractures in the host rock that could provide pathways for contaminant migration whilst they remain open [27, §6.3.7].
- Waste packages could collapse as they corrode, leading to redistribution of voidage [67]. As a result, the integrity of the backfill and host rock could be disrupted, which could introduce groundwater flow and transport pathways through the host rock before the pathways close by creep [27, §6.3.6].

The occurrence of these conditions depends on factors such as controls on seal emplacement and factors specific to the properties of the host rock. The assessment of these variant scenarios is discussed in Section 10.3. RWM's approach to addressing human intrusion is discussed in Section 10.5.

9 LHGW Disposal in Evaporite

The illustrative concept for the disposal of LHGW in evaporite involves stacking waste packages in unlined vaults [3, §6.1]. The vaults will not be backfilled, but the void space in the vaults will be limited such that convergence as a result of creep will result in closure of the vaults in a period of decades. In this concept, sacks of magnesium oxide (MgO) placed on top of the waste package stacks will consume carbon dioxide gas and will provide some control on chemical conditions in the unlikely event that brine enters the disposal vaults. The disposal concept is illustrated in Figure 15. The actual profiles and dimensions of the vaults at the GDF site will be determined based on the prevailing host rock geotechnical characteristics and the *in situ* stress regime at disposal depth.

Figure 15 Illustrative concept for the disposal of LHGW in an evaporite rock [3, Figure 5]



9.1 Geological environmental safety functions

The isolation and containment environmental safety functions provided by evaporite rock are described in Section 8.1 for the illustrative disposal concept for HHGW.

9.2 Wasteform environmental safety functions

The environmental safety functions provided by the LHGW wasteforms are as described in Section 5.2 for the higher strength rock disposal concept.

9.3 Container environmental safety functions

9.3.1 Prevention or limitation of the release of contaminants

In the dry environment of an evaporite (halite) rock, container corrosion will not occur. However, mechanical loading by creep closure may affect containment. If brine did access the metal containers, the steel corrosion process would support the maintenance of reducing conditions, which would support the low solubility of many radionuclides [63, §4.3.5].

9.3.2 Prevention of disruption through over-pressurisation

Most LHGW containers have vents for gas release, thus preventing waste package over-pressurisation and damage [63, §4.3.5].

9.3.3 Stabilisation of the structure and geometry of the engineered barriers

Stainless steel containers (and the stillages that hold 500 litre drums) and stacks of robust shielded waste containers will provide mechanical stability [62, §9.3.1-§9.3.2], although they may not have sufficient strength to withstand the mechanical loading caused by host rock creep in the vaults. The concrete containers will have good mechanical properties and durability under disposal conditions [62, §9.3.3].

9.3.4 Limitation of the potential for nuclear criticality

The container walls will shield and separate fissile wasteforms from each other in a vault (limiting neutron interaction between packages), thus supporting the prevention of criticality while the containers remain intact after GDF closure [12, §3.3].

9.4 Local buffer/backfill environmental safety functions

9.4.1 Protection of the container

The bags of magnesium oxide in the disposal vaults will absorb moisture, which will limit the potential for any brine present to come into contact with the containers and cause corrosion [63, §3.7.3, §4.3.5]. The magnesium oxide will react with the brine to buffer the pH to alkaline conditions (pH 9) [31, §3.3.3], which will reduce corrosion rates [63, §4.3.5].

9.4.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The magnesium oxide does not have a role in providing mechanical stability. Instead, the disposal concept relies on the mechanical instability of the evaporite rock in order for creep closure to encapsulate the waste packages (which also ruptures the magnesium oxide bags, thereby enabling the magnesium oxide to provide its environmental safety functions in the event of brine ingress).

9.4.3 Limitation of the release of contaminants

In the unlikely event that brine enters the disposal vaults, the buffering of the pH to alkaline conditions and buffering of the carbon dioxide fugacity and carbonate ion concentration in the brine by the magnesium oxide will have the effect of reducing the solubility of many radionuclides (including actinides) [63, §4.3.5; 31, §3.3.3].

9.4.4 Prevention of disruption by over-pressurisation

In the expected absence of brine, gas generation is unlikely to be significant. Also, the magnesium oxide will absorb carbon dioxide [63, §4.3.5], although this is a minor effect relative to the volume of hydrogen that could be generated if brine is present.

9.5 Mass backfill environmental safety functions

9.5.1 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The crushed salt mass backfill in the access tunnels will be compressed by rock creep, thereby providing stability.

9.5.2 Limitation of the release of contaminants

As the porosity of the backfill is reduced by creep, its permeability will reduce, which will limit the potential for migration of contaminants should the mass backfill become saturated, although such saturation will be unlikely because of the expected absence of mobile brine.

9.5.3 Prevention of disruption through over-pressurisation

The mass backfill does not have a significant role with regard to the prevention of disruption through over-pressurisation.

9.6 Plugs and seals environmental safety functions

9.6.1 Limitation of the release of contaminants

Low permeability seals in shafts and access tunnels will act to prevent groundwater ingress to the disposal modules from the ground surface and overlying aquifers, thus ensuring that dry conditions are maintained in the disposal facility and contaminant migration is prevented [63, §4.3.5]. Seals in access tunnels and shafts will isolate the waste by providing a barrier to the access of people to the GDF.

9.6.2 Stabilisation of the surrounding host rock and the structure and geometry of the engineered barriers

The seals will provide mechanical stability in resistance to rock creep.

9.6.3 Prevention of disruption through over-pressurisation

The seals do not have a significant role with regard to the prevention of disruption through over-pressurisation.

9.7 Base scenario

The following sub-sections discuss the key processes that influence how conditions in the GDF are expected to evolve with respect to the three timeframes described in Section 3.3. The discussions draw on the descriptions of barrier environmental safety functions for the illustrative disposal concept and the descriptions of system evolution presented in the Engineered Barrier System Status Report [63, §4.3.6] and the Geosphere Status Report [27, §6.8.6].

9.7.1 Evolution during GDF construction and operation

During the GDF construction and operational period:

- An EDZ will be induced around the excavations.
- Openings, and the EDZ around them, will begin to close as a result of rock creep, driven by the stress field perturbation caused by the excavation.
- Oxidising conditions will predominate in the EBS, but conditions will quickly become reducing once the GDF is closed.
- Some dewatering is likely to occur due to ventilation during the operational phase.
- Some brine may seep into the GDF after waste emplacement and vault closure. However, full saturation is unlikely to occur, or will be extremely slow because of the low permeability of halite.

9.7.2 Early post-closure evolution

During the early post-closure phase:

- The low-permeability components of the shaft seals (such as concrete, clay and asphalt) will prevent inflow of water to the GDF from the surface.
- Compaction of the crushed salt components of the tunnel and shaft seals by rock creep will render their permeability similar to that of the host rock within approximately 200 years.
- Recovery of the EDZ by creep around the shafts will be aided by the resistance of the rigid components of the shaft sealing system.
- Cooling of the host rock in the vicinity of cementitious seal components after heat from cement curing has been dissipated may cause cracking of the evaporite rock due to thermal contraction. However, this cracking is unlikely to be spatially extensive and, over a short period, will recover through rock creep.
- The seals will prevent any circulation of groundwater in the disposal region and flow to the accessible environment.
- Rock creep and the closure of the vaults will cause the magnesium oxide sacks to burst and the magnesium oxide will be spread as a powder around the waste packages. The magnesium oxide will provide some chemical buffering if there is moisture present, reducing humidity and protecting the waste packages from chemical degradation.
- Some waste packages may be breached due to the convergence of the walls, floors and ceiling of the vaults.
- Some saturation of the disposal area may occur where the rock permeability is sufficient to allow brine movement, but conditions are generally expected to remain dry in halite.

- Gas pressurisation due to waste package degradation (corrosion) and the generation of radionuclides in the gas phase is likely to be limited by the lack of availability of water in an evaporite rock. Magnesium oxide will absorb carbon dioxide, but this will not be significant compared to any hydrogen gas generation.

9.7.3 Late post-closure evolution

Even if containers are breached as a result of compaction, complete containment of the waste in the GDF will be provided by the host rock and no contaminant releases to the accessible environment are expected to occur. If brine does enter the disposal vaults, the magnesium oxide will provide some buffering capability that will promote package longevity and reduce radionuclide solubility, but this buffering may not be effective in the very long term (hundreds of thousands of years).

9.8 Variant scenarios

The dryness of the disposal vaults and encapsulation of the waste packages by creep closure are important features of this disposal concept that ensure long-term environmental safety. Therefore, the identification of variant scenarios has focused on the environmental safety functions provided by the host rock:

- The barrier function of the host rock could be by-passed if shaft seals do not fulfil their environmental safety functions, for example, as a result of quality control failures on shaft sealing materials. Such failures could result in the presence of pathways for water flow from upper layers and contaminant transport to overlying formations.
- Human intrusion by drilling into the disposal vaults could result in the presence of pathways for brine flow and contaminant transport between the GDF, overlying formations and the ground surface. In this case, the chemical buffering by magnesium oxide may be important.
- If brine does enter the disposal facility, then gas pressurisation due to waste package degradation could result in the generation of fractures in the host rock that could provide pathways for contaminant migration whilst they remain open [27, §6.3.7].
- As the vaults close, roof falls could occur, leading to redistribution of voidage [67]. As a result, the integrity of the host rock could be disrupted, which could introduce groundwater flow and transport pathways through the host rock before the pathways close by creep [27, §6.3.6].

The occurrence of these conditions depends on factors such as controls on seal emplacement and factors specific to the disposal facility’s location. The assessment of these variant scenarios is discussed in Section 10.3. RWM’s approach to addressing human intrusion is discussed in Section 10.5.

10 Evaluating Post-closure Safety

Post-closure environmental safety relies on the intrinsic passive safety of an appropriately sited and designed GDF. Confidence that the GDF can provide the required level of safety is achieved by demonstrating a detailed understanding of the way the various barriers of the GDF work together to isolate and contain the wastes as conditions evolve after GDF closure and to ensure that individuals, society and the environment are protected against radiological and other hazards in the long term. Assessing environmental safety requires demonstration of an understanding of how radionuclides and potential non-radiological contaminants might be released from waste packages (in groundwater and gas) and transported through the barrier system, and showing that there would be no harmful effects should any contaminants reach the biosphere. These environmental safety requirements are set out in RWM's Disposal System Specification (Part B) [11, §9] as discussed in Section 3.1 (Table 4) and are consistent with the requirements of the environment agencies' GRA [20].

Sections 4 to 9 presented the expected evolution of conditions in the GDF following disposal of HHGW and LHGW according to different disposal concepts in different geological environments (that is, the base scenario). Variant scenarios were also identified that describe how certain post-closure events and processes could detrimentally affect the environmental safety functions provided by particular barrier components, although these potentially disruptive events and processes are considered highly unlikely to occur. This section presents assessments of the base scenario for each disposal concept and discusses how the GDF will be robust to the variant scenarios identified if they did occur, as far as is possible at this generic stage of GDF development.

The assessments cover requirements to demonstrate that any radionuclides released from the wastes, either in groundwater or in the gas phase, will not compromise safety. The assessments also address requirements to consider the potential consequences of human intrusion, as well as measures for reducing the likelihood of human intrusion; and consideration of the potential for post-closure criticality to affect the performance of the disposal facility. Also, requirements relating to the protection of non-human species and habitats and protection against the potential impacts of non-radiological hazards presented by the wastes, packaging materials and GDF construction materials are considered.

The assessments draw on different lines of argument (both qualitative and quantitative) in order to support a demonstration of how the disposal concepts identified for the different combinations of wasteform and potential geological environment will provide long-term environmental safety. The assessments are based on:

- **An understanding of how barriers are expected to perform under disposal conditions, drawing on the knowledge base expressed in RWM's research status reports.** This knowledge base is founded on theoretical and experimental understanding of material behaviour and contaminant migration that has been acquired through many years of research undertaken on radioactive waste disposal in the UK and overseas, including in multi-national projects. Laboratory-scale experiments and observations of natural indicators of material behaviour give confidence that the GDF can be designed and constructed in a way that will provide environmental safety in the very long term after GDF closure.
- **Evaluations of how barrier components provide their containment safety functions through the use of models of contaminant transport, supported by the knowledge base of barrier and contaminant behaviour.** The simplest analytical models are described as 'insight' models that provide a high level understanding of disposal system behaviour and enable the identification of key issues and uncertainties in barrier environmental safety functions (see

Section 2.4.3). More detailed total system models have been developed in order to undertake illustrative calculations of disposal system performance in terms of evaluations of the migration of radionuclides in groundwater through the barrier system and the potential risks associated with any exposure to radionuclides that might migrate from the GDF to the surface environment in the long term. The total system models are probabilistic in nature in that they allow representation of uncertainties in disposal system behaviour through specification of probability distributions for uncertain parameter values. The parameter values are sampled randomly from these distributions in order to generate many realisations of potential disposal system performance. Such models enable quantification of the radiological risks associated with geological disposal, for comparison with the regulatory risk guidance level [20, §6.3.10], and hence justify confidence that the risks are acceptably low. Details of the insight models and total system models used in these assessments are provided in the generic PCSA [5, §4-§5]. The total system models are described in detail in the Model Report [46] and the parameter value distributions are presented in the Data Report [47].

The current lack of knowledge of the GDF location presents a significant challenge in evaluating the environmental safety of geological disposal. In order to address this challenge, RWM has identified various geological environments as a basis for developing, designing and assessing disposal concepts for different categories of waste. As discussed in Section 1.1, descriptions of these geological environments are based on consideration of three potential types of host rock (higher strength rock, lower strength sedimentary rock and evaporite rock) with various sequences of cover rocks based on the types of geological environment that may be suitable for a GDF in the UK.

The Geosphere Status Report presents high level descriptions of the geological, hydrogeological and hydrogeochemical characteristics of these geological environments [27, §5.3]. However, in order to undertake a quantitative assessment of the performance of the GDF, it is necessary to develop these descriptions to a more detailed level in which the pathways along which contaminants may migrate from the GDF located in the host rock, potentially to the surface environment, are characterised. Such detailed descriptions have been developed to undertake assessments of radionuclide transport in groundwater for the illustrative disposal concepts in higher strength rock and lower strength sedimentary rock (Sections 4 to 7), but are not required for the illustrative disposal concepts in evaporite rock (Sections 8 to 9) because such host rocks will not include groundwater transport pathways.

Of course, uncertainties in the hydrogeological and hydrogeochemical characteristics of these geological environments, particularly with respect to the location of the GDF, are large. Thus, the deterministic descriptions of potential radionuclide transport pathways used in the assessments should only be seen as illustrations of the potential characteristics of a GDF in environments judged to be representative of idealised potential UK GDF sites. The transport pathways have been defined as a means of undertaking calculations to identify the relative contributions (in terms of waste groups and radionuclides) to calculated radiological risk, and to demonstrate how quantitative assessments could be undertaken to support a post-closure safety case in the future when potential disposal sites are identified.

This total system modelling approach represents a progression from that taken in the 2010 PCSA [68], where advective transport pathways in the geological environment were characterised by a small number of key parameters that focused on the assessment of a GDF in higher strength rock. However, although the approach taken in this generic ESC is based on more detailed descriptions of the hydrogeological and hydrogeochemical characteristics of illustrative geological environments, the level of detail at which the transport pathways are represented in the models and the deterministic approach to their parameter specification is necessarily similar to that adopted in the 2010 PCSA calculations.

The detailed transport pathway descriptions developed for this post-closure analysis assume that hydraulic head gradients and connected pathways will exist for the eventual transport of contaminants to the surface environment. In reality, the GDF may be developed at a location where there are no inter-connected permeable features or where there are no driving forces for groundwater movement. That is, there may be no pathways for the transport of contaminants to the surface environment in the actual GDF. The illustrations of potential flow and transport pathways for different geological environments that have been developed for this post-closure safety assessment are presented in the generic PCSA [5, §5.1 and §5.4].

The illustrations of the geological environments assume that hydrogeological and hydrogeochemical conditions are reasonably steady for an assessment period of 300,000 years after GDF closure. Various natural transient processes could affect groundwater flow distributions and groundwater geochemistry and, hence, contaminant migration behaviour and the performance of the GDF over such timescales. For example, the performance of the GDF could be affected by climate change (such as glaciation), seismic activity or erosion. It is anticipated that the GDF will be located such that its performance is robust to expected natural changes, but, as discussed in Section 2.4.5, detailed assessments of the impacts of large-scale natural processes on GDF performance will not be undertaken until specific GDF sites have been identified.

Illustrative calculations of risk associated with human exposure to radionuclides in the gas phase (the main concern being C-14 in methane) have not been undertaken specifically for this generic ESC. However, reference is made to RWM's research on C-14 behaviour that has been undertaken as part of an integrated project to develop a holistic approach to C-14 management in the GDF [15; 16], which included risk calculations for a number of post-closure C-14 migration and release scenarios. Potential gas generating processes are well understood for the different waste groups under possible disposal conditions. However, there are many uncertainties regarding how gas will be transported through different types of geological environment and impact the biosphere. In many geological environments, conditions will be such that gas generated as a result of waste degradation in the disposal facility will become dissolved in groundwater as the gas migrates and therefore any exposure will occur via the groundwater pathway. In other geological environments, gas may reach the biosphere and the associated radiological risk will depend on assumptions made about the area over which the gas is released and potential exposure pathways. These gas generation and potential migration processes are discussed based on consideration of the illustrative disposal concepts, with reference to the example calculations of risk reported as part of RWM's integrated project on C-14 management [16]. When a site for the GDF has been identified, RWM will develop a site-specific understanding of radioactive gas generation and migration and hence be in a position to undertake a detailed risk assessment of the gas pathway.

The results of the GDF post-closure safety assessment undertaken for this generic ESC and the status of RWM's ongoing research in different areas of environmental safety assessment are discussed in the following sub-sections. Specifically, the derived inventory of higher activity wastes and alternative scenarios for waste generation that have been considered in the assessment are discussed in Section 10.1. The radiological hazard presented by these wastes is discussed in Section 10.2; and the assessments of groundwater-mediated and gas-mediated releases are presented in Sections 10.3 and 10.4, respectively. The potential impacts of inadvertent human intrusion and hypothetical criticality on GDF performance are presented in Sections 10.5 and 10.6, respectively. RWM's ongoing work on the impacts of the radiological hazard on non-human biota is discussed in Section 10.7 and work on the non-radiological hazard presented by the waste is discussed in Section 10.8. The results of the assessments are discussed in the context of the regulatory requirements that will need to be met in support of the demonstration of post-closure environmental safety as part of an ESC for an actual GDF. Section 10.9

discusses the sensitivity of the illustrative assessments to alternative radioactive waste inventory scenarios. Conclusions of the post-closure safety evaluation are presented in Section 10.10.

10.1 Radioactive waste inventory scenarios

RWM has developed a derived inventory of higher activity wastes and other materials that may require geological disposal [7], as summarised in the Technical Background [3, §2]. The 2013 Derived Inventory contains data from the 2013 UK Radioactive Waste Inventory (UKRWI) [69] and the other materials defined in the inventory for disposal in the 2014 White Paper [2], and forms the basis for the generic disposal system design work and the associated safety, environmental, social and economic assessments.

The waste categories, groups and sub-divisions defined in the 2013 Derived Inventory are shown in Table 7. These waste groups have been used by RWM to distinguish between different types of waste for design and assessment studies and to reflect the key differences in emplacement location within the GDF, time of arising and choice of waste packaging. Thus, for example, legacy wastes and spent fuel are distinguished from future wastes and spent fuel arising from new build reactors.

Table 7 Derived inventory waste groups [3, Table 1; 10, Table 2]

	Waste groups	**Subdivision**
LHGW	Legacy Shielded ILW (SILW) and Shielded LLW (SLLW)	
	Legacy Unshielded ILW (UILW) and Unshielded LLW (ULLW)	
	Robust Shielded ILW Containers (RSCs)	
	DNLEU	
	New Build SILW	
	New Build UILW	
HHGW	HLW	
	Plutonium	
	HEU	
	Legacy Spent Fuels	Advanced Gas-cooled Reactor (AGR) Spent Fuel
		Exotics, such as Prototype Fast Reactor (PFR) Spent Fuel
		Metallic Spent Fuel, such as Magnox Spent Fuel
		Sizewell B Pressurised Water Reactor (PWR) Spent Fuel
	New Build Spent Fuel	
	Mixed Oxide (MOX) Spent Fuel	

The 2013 Derived Inventory presents information that is based on the best available data and assumptions regarding, for example, spent fuel reprocessing and the timing and extent of a nuclear new build programme. Inevitably there are uncertainties associated with both the volumes and radionuclide contents of the currently identified wastes and materials and the assumed scenarios for the future operation of the nuclear plants that produce those wastes and materials. The generic DSSC assesses the effects of uncertainty in the disposal inventory by identifying twelve alternative scenarios for radioactive waste arisings and exploring the sensitivity of the DSSC to the different scenarios [10]. These twelve scenarios are listed in Table 8.

The post-closure safety assessment has focused on assessing the environmental safety of radioactive waste disposal based on consideration of the waste groups in the 2013 Derived Inventory. The sensitivity of the assessment to alternative assumptions about the inventory, according to the scenarios listed in Table 8, has been analysed. The modular approach to defining the waste groups, as shown in Table 7, facilitates this sensitivity analysis because it enables the analysis to focus on changes in the inventory of distinct waste groups for each scenario. The results of this analysis are presented in Section 10.9.

Table 8 Alternative inventory scenarios in terms of the differences in assumptions compared to the 2013 Derived Inventory [10, §2.1]

No.	Scenario description
1	All oxide spent fuel from existing civil reactors (that is, PWR spent fuel and all AGR spent fuel) is reprocessed
2	Not all Magnox spent fuel is reprocessed
3	Reactor operational lifetimes are extended
4a	Uncertainty in UKRWI considered by using the lower volume estimate
4b	Uncertainty in UKRWI considered by using the upper volume estimate
4c	Uncertainty in UKRWI considered by using the lower activity estimate
4d	Uncertainty in UKRWI considered by using the upper activity estimate
5	Plutonium is not recycled, but instead is immobilised in ceramic form for direct disposal and there is no MOX spent fuel requiring disposal
6	Some LLW from the Low Level Waste Repository (LLWR) is disposed of in the GDF
7	Changes in the depleted, natural and low enriched uranium inventory
8	Changes in the programme of new nuclear reactor construction
9	The disposal of small amounts of foreign wastes and materials is permitted where other options are, for example, impracticable
10	Alternative assumptions are made about waste packaging (that is, different waste treatment and waste container options are considered)
11	Graphite wastes are not disposed of in the GDF
12	Exclusion of ILW that could be disposed of as LLW in a near-surface facility following suitable treatment or decay storage

10.2 The radiological hazard

Insights into the hazard presented by radioactive waste and the importance of the containment safety functions provided by the GDF's barrier system can be obtained by examining how the total activity of the waste changes with time. The total activity of a given type of waste at any time is the sum of the activities of each of the radionuclides it contains, taking into account radionuclide decay and the generation of chains of daughter radionuclides. As the total activity of the waste and the composition of the component radionuclides change, the radioactive hazard the waste poses changes, generally reducing with time. For example, Figure 16 and Figure 17 show how the total activities of the various HHGW and LHGW groups will vary after GDF closure. The combined total activity of all HHGW and LHGW groups falls by about an order of magnitude (that is, to about 10% of the original activity) as a result of decay over a period of 1,000 years after disposal and by two orders of magnitude (that is, to about 1% of the original activity) over a period of 100,000 years. These figures highlight the safety benefits of a multi-barrier system that provides containment for timescales of the order 100,000 years, especially for HHGW.

In the longer term, the rate of fall in total activity reduces as higher-activity daughters of long-lived uranium isotopes in the various waste groups ingrow. After around 750,000 years the activity of spent fuel reduces to the activity of natural uranium ore of a mass equivalent to that from which the fuel was produced [49, §3.3]. The total activity of HEU peaks after about 250,000 years as a result of the ingrowth of Th-230 (and its progeny) from the decay of U-234, and the total activity of DNLEU begins to increase and dominate, although it remains a small fraction of the initial activity of HHGW and LHGW. Thus, over these longer periods, the radiological hazard presented by the wastes changes only very slowly and containment *per se* does not reduce the hazard significantly, but it does prevent the hazard being realised in terms of potential risk to exposed groups. Instead, if transport pathways from the disposal facility to the accessible environment exist at a particular site, then factors such as dilution, diffusion and dispersion will affect radionuclide concentrations, reducing the fluxes of radionuclides that reach the biosphere.

The containment safety functions of different GDF barrier components are assessed in Sections 10.3 and 10.4 in terms of how radionuclides released from waste packages could be transported through barriers in groundwater and gas, respectively. At this generic stage in GDF implementation, the assessments focus on understanding the roles that the EBS and components of the geological environment are expected to play in ensuring that environmental safety is maintained as conditions in the GDF evolve for different illustrative disposal concepts. That is, the assessments focus on presenting an understanding of how the barrier components act together to ensure that radionuclides are contained in the GDF barriers and any migration of radionuclides to the biosphere is at an acceptably low level. The assessments are supported by calculations of key performance measures for each disposal concept. These include the length of time after disposal over which containers are expected to prevent the release of radionuclides, the flux of radionuclides across EBS components and the geological barrier (once radionuclides are eventually released from degraded disposal containers) and the radiological risk associated with any radionuclides that migrate to the biosphere.

The assessments focus on the expected evolution of the GDF (that is, the base scenario). However, approaches to assessing the robustness of a multi-barrier disposal system to potential variant scenarios defined by unlikely events are also considered. The assessment of variant scenarios has generally focused on scenarios relating to more rapid container degradation than expected. Variant scenarios that depend on data on facility design and site characteristics will be assessed in detail at a site-specific stage. Variant scenarios involving inadvertent human intrusion events and post-closure criticality are discussed in Sections 10.5 and 10.6, respectively. Section 10.7 notes the need for the impacts of potential radiological dose to non-human biota to be assessed and describes RWM's developing approach to such assessments.

Figure 16 Effects of radioactive decay on the total activity of HHGW groups; the combined total activity of all LHGW and HHGW is also shown

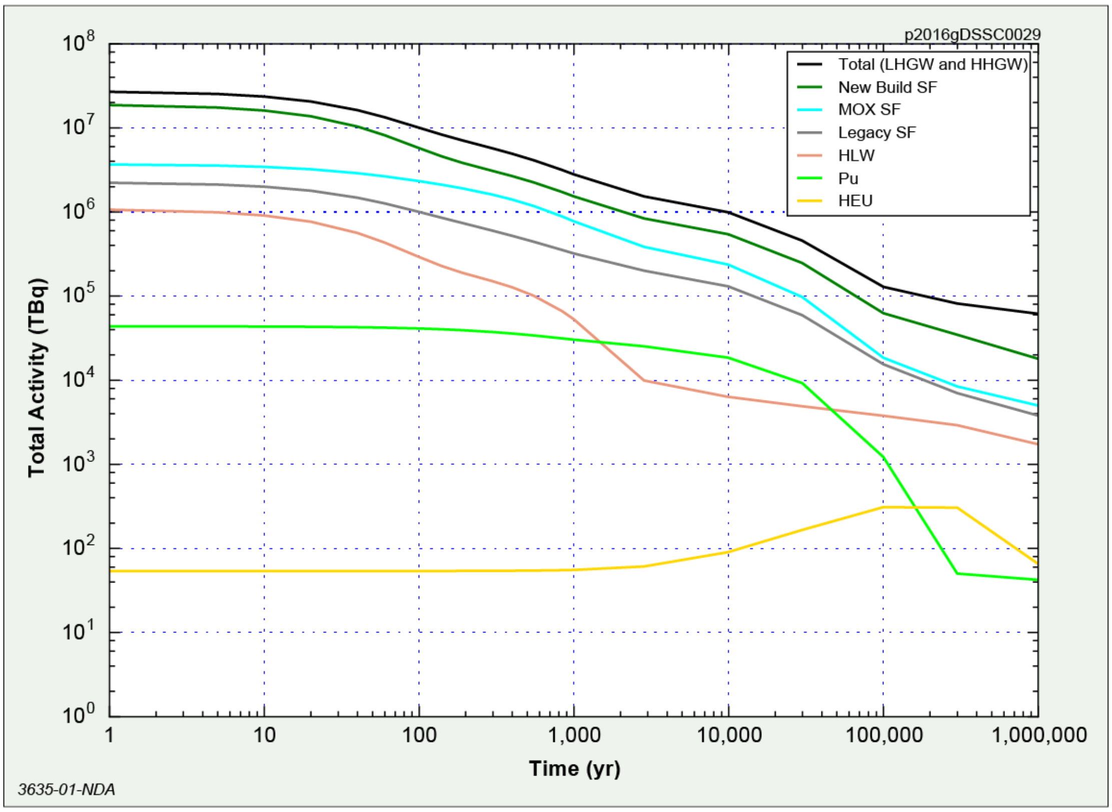
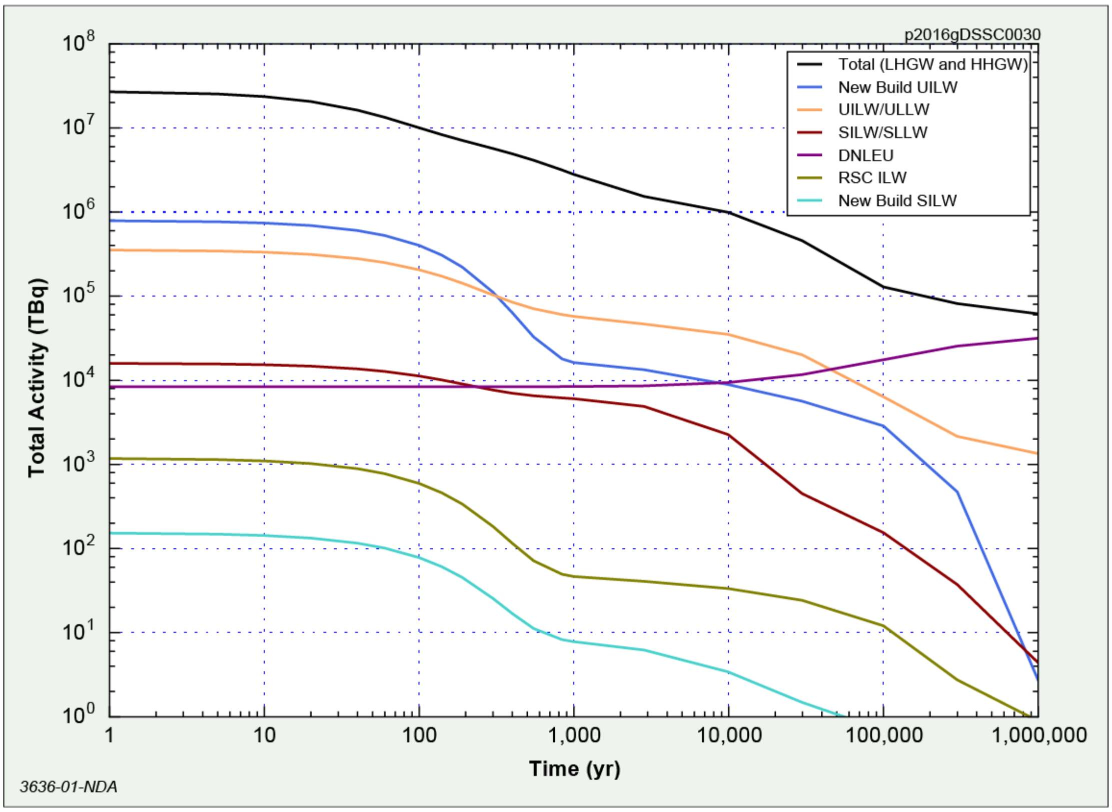


Figure 17 Effects of radioactive decay on the total activity of LHGW groups; the combined total activity of all LHGW and HHGW is also shown



10.3 Radiological assessment: radionuclides in groundwater

This section presents assessments of the base and variant scenarios for each illustrative disposal concept in terms of the behaviour of radionuclides released into groundwater.

10.3.1 HHGW disposal in higher strength rock

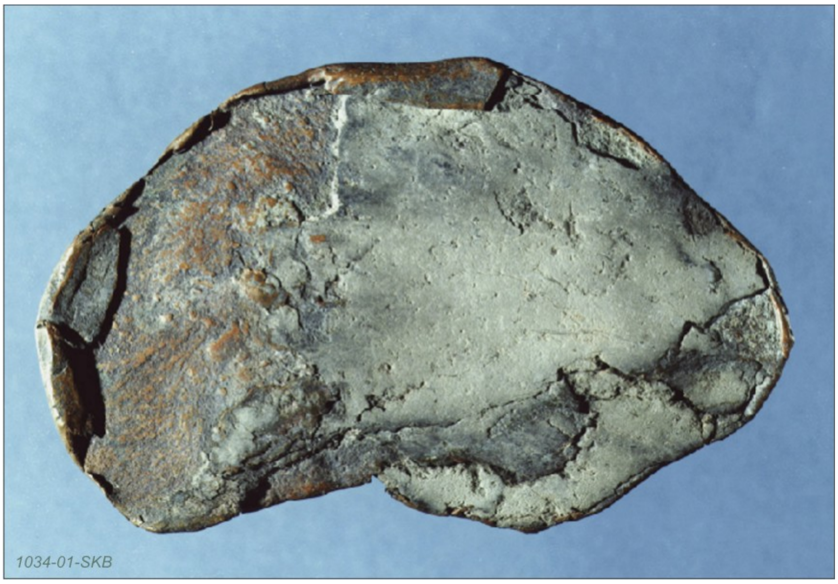
Base scenario

The base scenario, describing the expected evolution of conditions in a facility for HHGW disposal in higher strength rock, is presented in Section 4.7. The integrity of the copper container is an important feature of this disposal concept. Under expected hydrogeological and geochemical conditions, the corrosion rate of copper will be so low that the lifetime of a 50 mm thick copper container is expected to be in excess of 100,000 years [62, §11.2.1]. This expectation is founded on a theoretical understanding of copper corrosion behaviour and the results of laboratory experiments on copper corrosion, including those carried out in underground research laboratories [62, §10.6.2].

Observations of natural analogues support the view that, in suitable geological conditions, copper can remain stable for very long timescales. As discussed in the Waste Package Evolution Status Report [62, §10.6.2], there are many cases of native copper deposits around the world, including extensive deposits in Michigan, USA and the UK (see Figure 18). Also anthropogenic analogues of copper stability are available that date from the Bronze Age (as early as 3000 BC) [62, §10.6.2].

Thus, by the time a copper container is breached a high proportion of the radionuclide inventory will have decayed. As the copper containers are not expected to fail under base scenario conditions until well beyond 300,000 years (as discussed in Section 2.4.5), no total system model calculations have been undertaken for the base scenario.

Figure 18 Native copper sample embedded in Devon mudstone (>176 million years old). The sample was found in the Littleham Mudstone formation (Devon, UK). See the Waste Package Evolution Status Report for further discussion of natural analogues of copper behaviour [62, §10.6.2].



Variant scenario

The quantitative analysis has focused on a variant scenario in which there is early breach of a copper container. The variant scenario involves early container breach as a result of enhanced sulphide concentration/transport in the buffer and accelerated copper corrosion. Such a scenario could occur if the bentonite buffer density was too low (for example as a result of failures in material quality control) to ensure that sulphate-reducing bacteria populations were suppressed when the bentonite saturated. This scenario results in the generation of large concentrations of sulphide in the vicinity of the container surface but no biofilm development (see Section 4.8). Container failure times as a result of this process have been estimated to be between 50,000 years and 500,000 years [47].

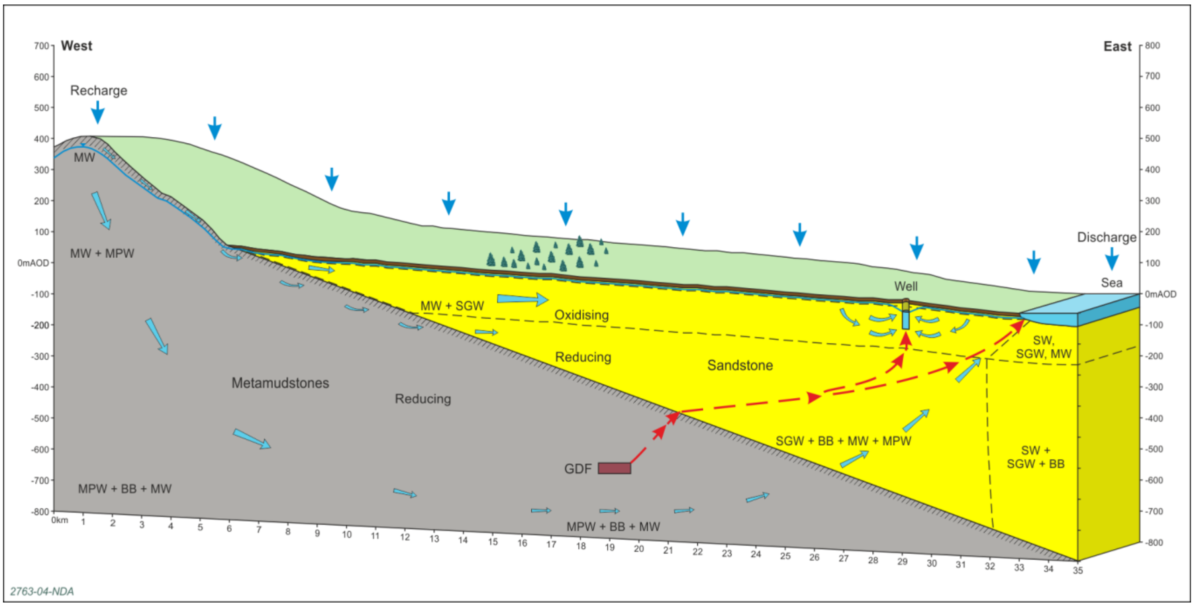
Total system model calculations have been undertaken for this variant scenario based on the failure of a single container of each type of HHGW in order to understand the significance of the environmental safety functions provided by different barrier components. Once water penetrates the disposal container, it is assumed that the wasteform starts to dissolve and any radionuclides that have not decayed *in situ* start to be released. For spent fuel, the portion of the instant release fraction that has not decayed is released rapidly; the spent fuel matrix then dissolves slowly, congruently releasing the remaining radionuclides. For HLW, slow dissolution of the glass matrix leads to the slow, congruent release rate of any remaining radionuclide inventory. Similarly, ceramic plutonium residues and HEU wasteforms dissolve and release radionuclides slowly and congruently. Radionuclides are released into and diffuse through the bentonite buffer, before entering the fracture network in the host rock.

Migration of radionuclides after they enter the host rock has been evaluated based on the specification of an illustrative geological environment, as shown in Figure 19. This environment represents an example of a higher strength rock overlain by higher permeability sedimentary rocks, as discussed in the Geosphere Status Report [27, §5.3.2]. The definition of the geological sequence and its parameterisation are based on drawing a balance between representing a ‘realistic’ setting for the GDF and correlating the setting with rock types for which the data required in numerical modelling are available. Although the illustrative geological environment is not representative of any particular location in the UK, it has hydrological and geochemical features that could in practice be found in the UK.

The illustrative geological environment has been described in a way that provides no more than the minimum information required for modelling radionuclide transport along potential flow paths. The required information has been obtained through expert understanding of the hydrogeological and geochemical characteristics of such environments rather than through any detailed modelling. These conditions have been assumed to remain stable for the 300,000 year assessment period. The illustrative environment is described in detail in the PCSA [5, §5.1] and is summarised here.

The higher strength rock considered for this illustration is a low grade metamudstone in which fractures are not self-healing [27, §3.1.3]. The GDF is located 650 metres below ground level within the metamudstone; a component of the GDF assumed to represent a radionuclide release region is indicated in Figure 19, but the actual GDF is of much greater lateral extent than illustrated. The metamudstone host rock immediately overlying the GDF is 350 metres thick (from the assumed location of radionuclide release from the GDF to the top of the metamudstone), the upper 20 metres of which is weathered. The rocks overlying the metamudstone host rock consist of fine-to-coarse grained sandstone containing localised silt and clay layers. The sandstone is 300 metres thick immediately above the GDF. Superficial deposits are present at the surface in the low-lying areas below 70 metres AOD (above ordnance datum), comprising silt with sand and gravel lenses.

Figure 19 Possible groundwater pathway from a GDF to the surface environment where the higher strength rock is overlain by a sequence of sedimentary formations[10]; a component of the GDF is illustrated – the complete GDF is of much greater lateral extent



High ground, shown in the west of the section, forms both the surface water and groundwater catchment divide. Recharge occurs through the superficial deposits, as well as directly to the metamudstones where they outcrop. Groundwater flows from the superficial deposits and the metamudstones into the sandstone.

The permeability of the rocks is anisotropic because of the interconnected fractures and bedding planes in the metamudstone and sandstone, and the permeability of the metamudstones is less than that of the overlying sandstone. Groundwater in the upper 150 metres is oxidising and below 150 metres it is chemically reducing.

A downward hydraulic gradient exists beneath the metamudstone where it outcrops and an upward hydraulic gradient exists towards the coast in the east. The vertical hydraulic gradient in this simplified system is lower in the vicinity of the GDF than elsewhere, so that groundwater movement will be predominantly sub-horizontal. Downstream from the GDF, groundwater flows upwards under a comparatively slight hydraulic gradient. Note that it has been assumed that the steady-state flow conditions would have been reached following saturation of the GDF after closure.

Any radionuclides released from the GDF in groundwater would enter the assumed network of interconnected and hydraulically conductive fractures in the host rock. Thereafter, the direction and rate of radionuclide migration will depend on the properties of the fracture network and the hydraulic head distribution. The GDF will be located away from any major hydraulically conductive faults that could channel radionuclide transport out of the host rock. Potentially, at the GDF location, groundwater movement and radionuclide transport could be downwards deeper into the basin via bedding and shallow dipping fractures, away from the surface environment. However, for the illustrative assessment calculations, it has been assumed that a radionuclide transport pathway exists from the GDF to the biosphere. That is, there is a transport pathway through the engineered barriers of the GDF and through the host rock and overlying lower sandstone unit to the

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[10] BB is basement brine, MPW is mudrock porewater, MW is meteoric water, SGW is fresh sandstone groundwater and SW is sea water.

near-surface in upwelling water. Groundwater flow in the sandstone is via fractures and interconnected intergranular pore spaces.

Radionuclides reaching the near-surface groundwater are transported downstream and diluted in the drainage network, before eventually entering a river and discharging to the sea landward of a saline/groundwater interface. A resource area is assumed to become contaminated as a result and radiological risks to PEGs are calculated (the marine pathway). The calculation of risk includes consideration of exposure to contaminated well-water used for domestic purposes and small-scale irrigation (the well pathway). The capture zone for the well, which is assumed to persist throughout the post-closure period, is the upper part of the sandstone. The inclusion of such a well pathway enables the robustness of the safety case to assumptions about biosphere properties to be explored.

A GoldSim total system model (TSM) has been developed to evaluate radionuclide transport along this illustrative pathway (selection of this transport path should not be taken to imply that it is any more likely to be present than many other paths that could be conjectured for such a geological environment; it is simply an illustration). The TSM includes the calculation of risks to groups exposed to radionuclides via either the marine pathway or the well pathway [46]. The transport path has been parameterised to support the assessment modelling according to the distinct hydrogeological, geological and hydrogeochemical conditions indicated in Figure 19 along the transport paths.

The TSM includes the representation of advective radionuclide transport along fractures in the host rock. The sensitivity of results to the effects of radionuclide diffusion into the rock matrix alongside the fractures and retardation by sorption in the matrix has been evaluated. Transport through the overlying sandstones is by advection in a porous medium with retardation by sorption. The effects of transverse and longitudinal dispersion along the transport paths, and radionuclide decay and ingrowth are included in the model. Full details of the parameter values used in these calculations are presented in the Data Report [47] and details of the model are presented in the Model Report [46].

TSM calculations have been undertaken for each of the HHGW groups shown in Table 7, except the small inventory of exotic fuels[11]. Separate calculations were undertaken in which a single container of each type of wasteform was subject to early failure according to the above-noted failure time distribution. In each case, 2,000 realisations were undertaken; that is, 2,000 GoldSim code runs were generated based on random sampling from each of the parameter value distributions. A full discussion of the results of the calculations is provided in the PCSA [5, §5.2].

In all cases, the initial inventory of the shorter-lived radionuclides (with half-lives of less than about ten thousand years) decays to insignificant activities during the period of containment in the waste package, including many fission and activation products. Longer-lived radionuclides are released from the degrading wasteform and migrate slowly through the bentonite buffer, with some radionuclides retarded by sorption, before entering the host rock. Figure 20 shows the calculated mean of the radionuclide activity fluxes (Bq/year) entering the host rock for the example involving early failure of a PWR spent fuel container. Results are shown for a period of three hundred thousand years (as discussed in 2.4.5) in order to present an understanding of the behaviour of long-lived radionuclides.

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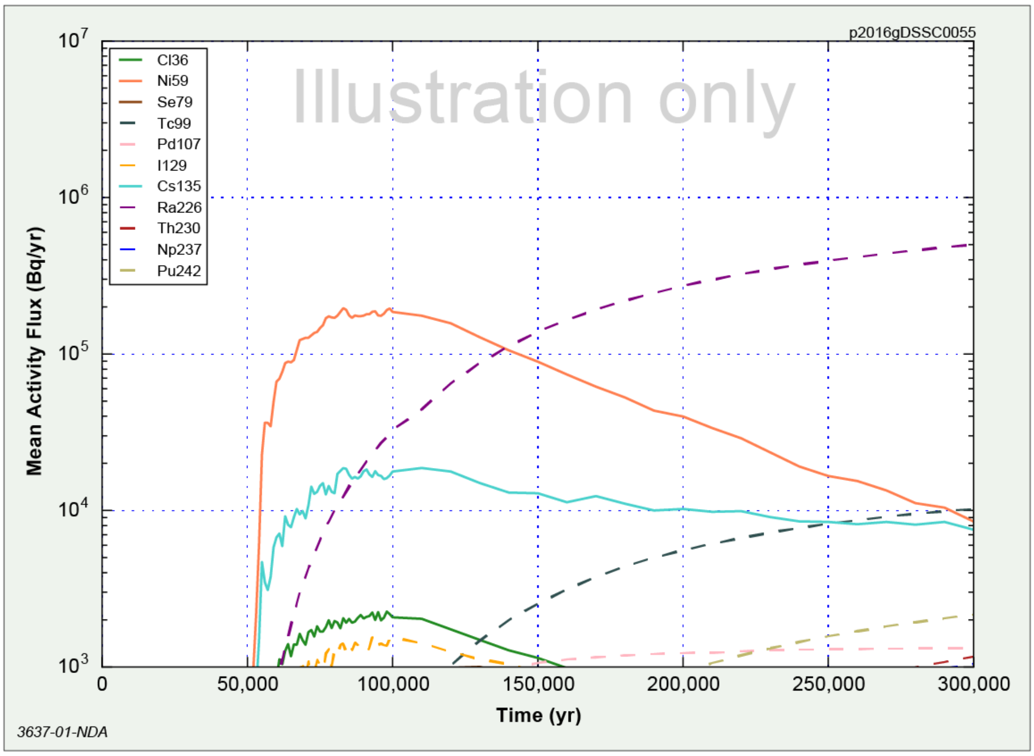
[11] RWM is in the process of developing waste package designs for exotic spent fuels, which arise mainly from experimental reactor programmes, and undertaking research on the dissolution behaviour of such fuels under disposal conditions [62, §11.5.4]. Insufficient information is currently available to undertake TSM calculations for these fuels.

Figure 20 **Mean radionuclide activity flux from bentonite buffer to host rock following failure of a PWR spent fuel container disposed of in higher strength rock**



The greatest activity flux on a timescale of a hundred thousand years is calculated for Ni-59 (half-life of 7.6×10^4 years [47]), which is an activation product that, in this assessment, is released in its entirety from the spent fuel as part of the instant release fraction, although this is a cautious assumption. Ni-59 is highly soluble and only sorbs weakly as it diffuses through the bentonite buffer. Other significant isotopes in terms of activity reaching the host rock are Cs-135, Cl-36 and I-129. Fractions of these isotopes form part of the instant release fraction and they are also highly soluble. Furthermore, Cl-36 and I-129 do not sorb in the buffer and Cs-135 sorbs only weakly.

Ra-226 contributes the greatest activity on a timescale of several hundred thousand years. Although Ra-226 has a relatively short half-life (1.6×10^3 years [47]), it occurs as a result of the decay of Th-230 (which has a half-life of 7.54×10^4 years [47]) and, unlike Th-230, Ra-226 is only weakly sorbed in the buffer. Th-230 is generated by the decay of U-234 (half-life of 2.46×10^5 years [47]).

Radionuclides that enter the host rock are advected through fractures towards the cover rock. In this example, there is no matrix diffusion or sorption of any radionuclides in the fractures. Figure 21 shows the calculated mean radionuclide activity fluxes entering the cover rock for the PWR spent fuel example. The most significant radionuclides in terms of activity are the same as those calculated to enter the host rock, except that Pb-210 also contributes to the activity flux into the cover rock in the long term, because it is a short-lived (half-life of 22.3 years [47]) isotope in the Ra-226 decay chain that is in secular equilibrium with Ra-226 and does not sorb to the host rock. Pb-210 does not contribute significantly to the activity flux entering the host rock from the bentonite buffer (Figure 20) because it sorbs strongly to the bentonite as it is generated, where it decays.

Figure 21 Mean radionuclide activity flux from the host rock to the cover rocks following failure of a PWR spent fuel container disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock

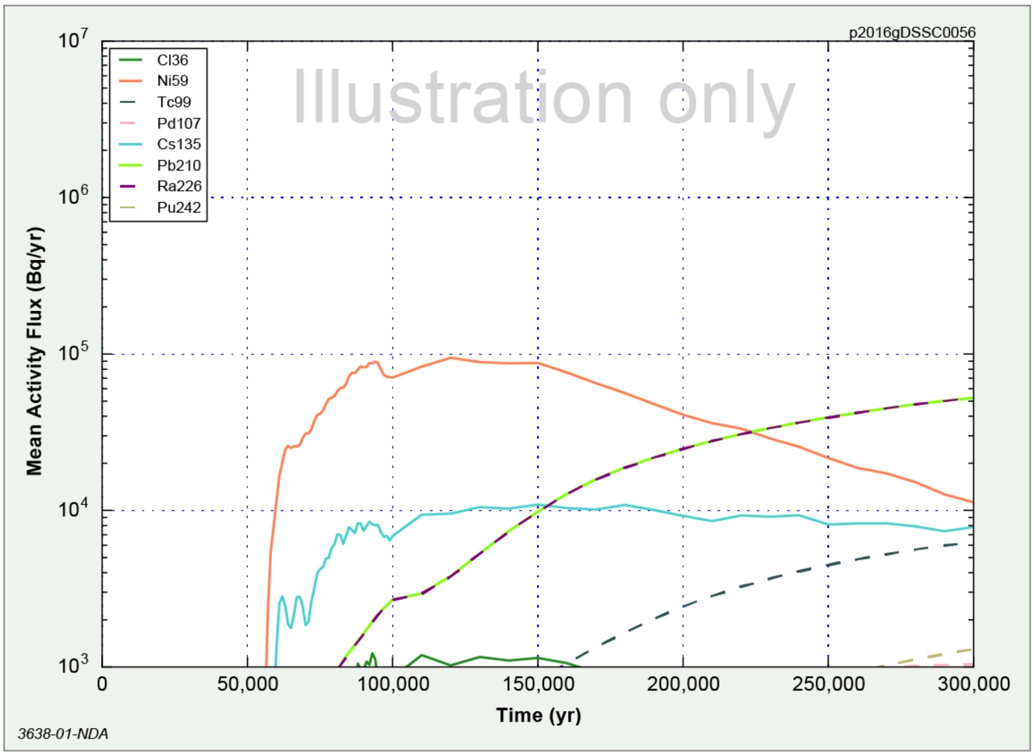
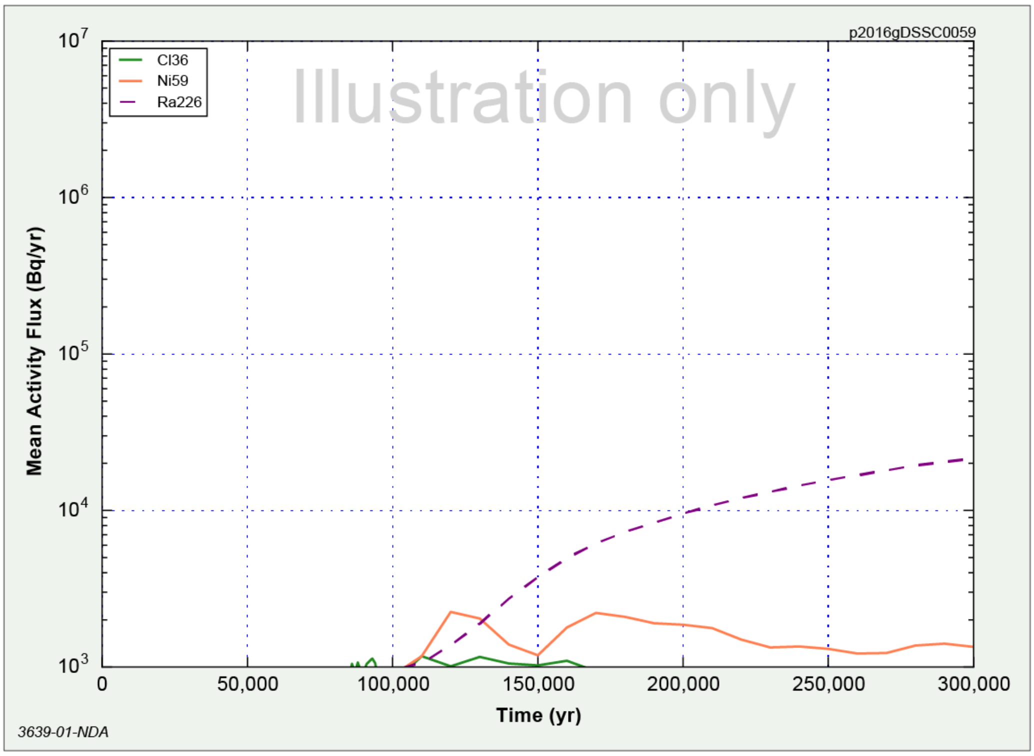


Figure 22 Mean radionuclide activity flux from the host rock to the cover rocks following failure of a PWR spent fuel container disposed of in higher strength rock, with matrix diffusion and radionuclide sorption in the host rock



In reality, in a typical higher strength rock, it is likely that radionuclides will be retarded by diffusion into, and sorption in, the host rock matrix. Therefore, calculations have been undertaken in which a narrow matrix diffusion zone (1 mm thick) with a high sorption capacity is assumed to be present next to host rock fractures. The largest mean radionuclide activity fluxes from the host rock into the cover rocks for a PWR spent fuel waste package are reduced as a result of these retardation processes, as shown in Figure 22. Again, a flux of Ra-226 into the cover rocks from decaying Th-230 is apparent, but Pb-210 is sorbed on the host rock.

In this illustration, small concentrations of long-lived radionuclides eventually migrate through the cover rocks to the biosphere. The radiological risks resulting from human exposure to these radionuclides (and their daughters) via the marine pathway have been calculated. The calculated mean risk is very low, being less than 10^{-12}/year in the assessment period, irrespective of assumptions about host rock retention properties.

If a well is assumed to be present at a location that results in contaminated water being used domestically and for irrigation, without the contamination being detected, then the calculated risk is as indicated in Figure 23. Definition of the well pathway includes specification of a groundwater flow rate through the aquifer from which water is extracted. The flowing groundwater acts to dilute the well water. A deterministic approach has been taken in which a single value of aquifer hydraulic conductivity has been specified in order to provide an illustration of risk associated with such an exposure route [47].

Based on the well pathway calculations, the main contributors to risk for all realisations are the non-sorbing I-129 (half-life of 1.57×10^7 years [47]) and Cl-36 (half-life of 3.07×10^5 years [47]) radionuclides. The calculated total mean risk is substantially below the risk guidance level of 10^{-6}/year in the 300,000 year assessment period [20, §6.3.10]. The calculated mean risk is also substantially lower than the risk associated with the radiological dose that might be received from natural background ionising radiation (about 1.3×10^{-4}/year, as discussed in Section 2.4.4). This background level risk is indicated in Figure 23.

Note that assumptions about the radionuclide retention properties of the host rock make little difference to calculated mean risk for this illustration, as indicated by Figure 24. That is, the calculated risks from I-129, Cl-36 and Se-79 are little affected by the presence of the thin matrix diffusion zone in the host rock.

The different types of spent fuel show similar characteristic behaviour with regard to radionuclide activity fluxes through the barrier system and calculated mean risk. For example, in each case, when assuming a well to be present, the largest calculated risks occur as a result of exposure to I-129, as shown in Figure 25, with the highest calculated risk being associated with a failed new build reactor spent fuel waste package.

There is a limited instant release fraction of radionuclides from HLW, but calculations of mean risk are not greatly influenced by such effects. The key contributor from HLW disposal is Cs-135, but the calculated risk associated with Cs-135 will be less if it is assumed to sorb in the host rock. There is no instant release fraction for plutonium and HEU wasteforms. The plutonium waste comprises actinides and only a very small fraction of fission products; HEU comprises actinides only. Furthermore, the plutonium and HEU ceramic wasteforms degrade slowly. Therefore, the calculated risks from the disposal of plutonium and HEU waste packages are only apparent after several hundred thousand years and are associated with long-lived actinides.

Figure 23 Mean radiological risk (total and significant contributors) via the well pathway following failure of a PWR spent fuel container disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock; the risk guidance level (RGL) [20, §6.3.10] and estimated risk from background level (BL) ionising radiation are shown

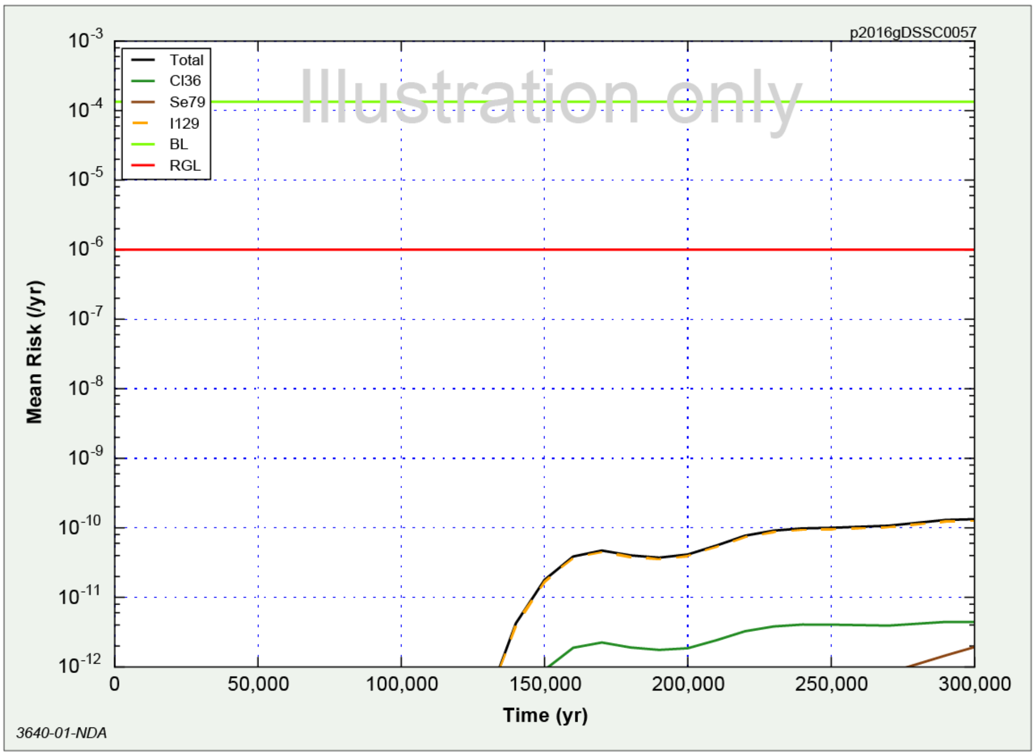


Figure 24 Mean radiological risk (total and significant contributors) via the well pathway following failure of a PWR spent fuel container disposed of in higher strength rock, with matrix diffusion and radionuclide sorption in the host rock

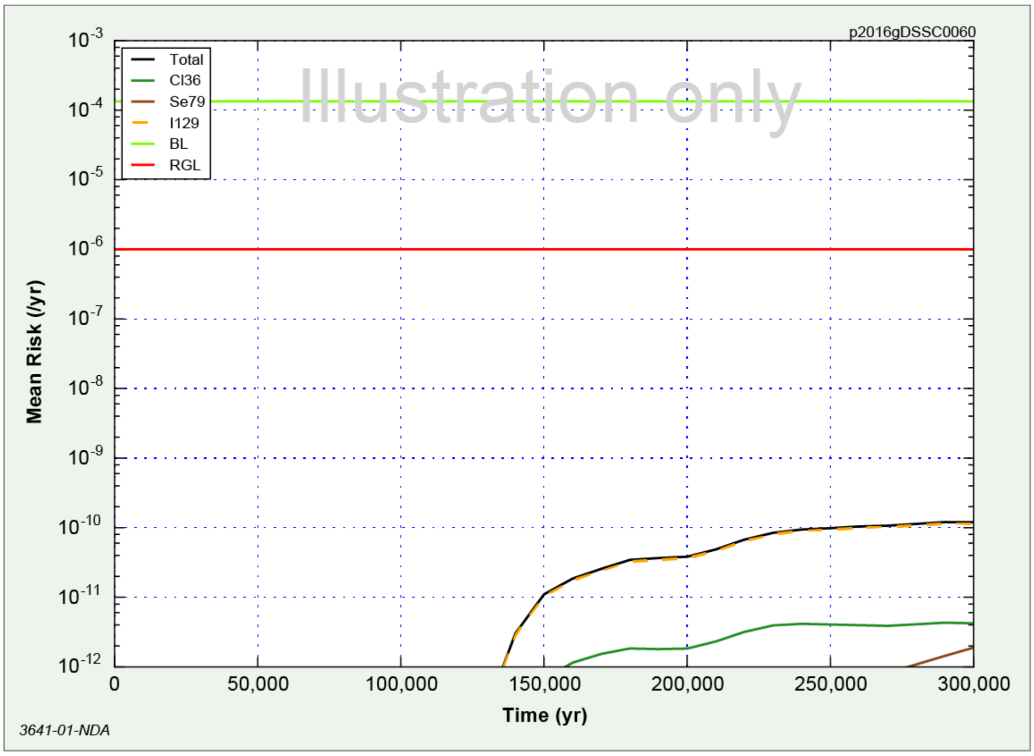
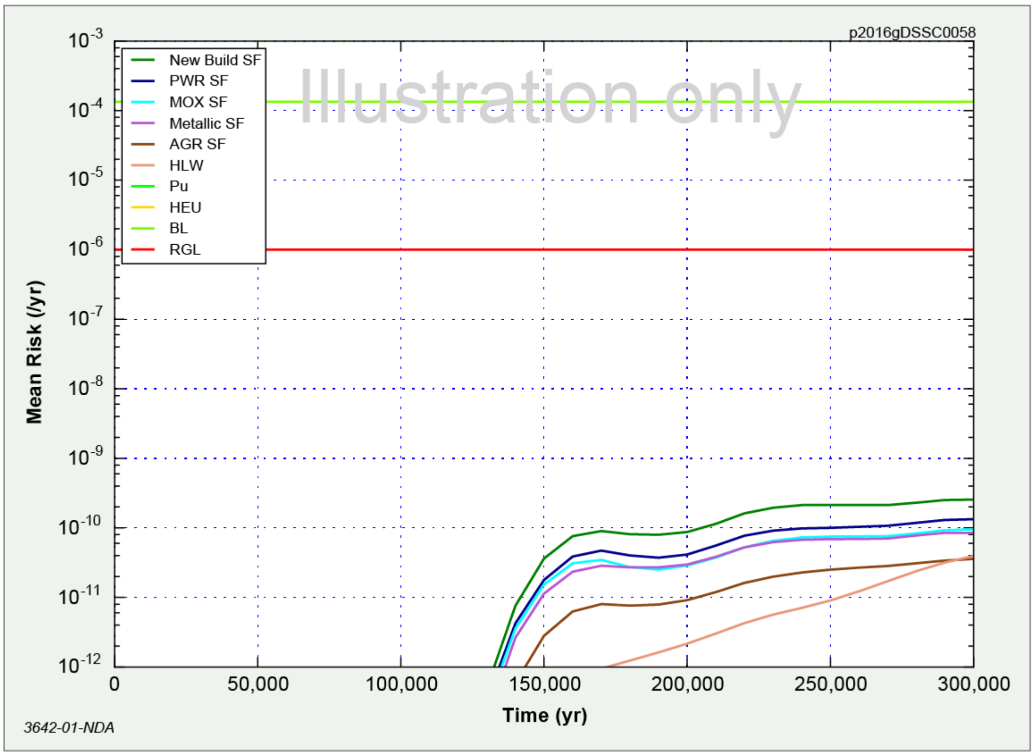


Figure 25 **Total mean radiological risk via the well pathway following failure of a container for each type of HHGW disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock; calculated mean risks associated with HEU and Pu waste packages are too low to be shown on the figure**



These calculations indicate that the illustrative concept for the disposal of HHGW in higher strength rock is robust to early failure of a single HHGW package by accelerated corrosion. Indeed, based on simple scaling of the calculated risk, the concept is robust to the early failure of several thousand HHGW packages by this corrosion mechanism, but it will be important to demonstrate confidence in the long-term containment function provided by the container under expected conditions.

Mobile and long-lived radionuclides, such as I-129 that forms part of the spent fuel instant release fraction, have the potential to dominate calculated risk. Although calculated risks for this illustration are low, understanding the behaviour of these radionuclides in each component of the barrier system is important to the demonstration of environmental safety of the disposal concept. Factors such as diffusion and dispersion, the existence of transport pathways to the biosphere and assumptions about human activity in the biosphere influence the potential for such radionuclides to contribute to radiological risk. Understanding such factors will be an important requirement of site characterisation. Note that, because of the expected long-term integrity of the containers and the slow leaching of actinides from spent fuel, plutonium and HEU wasteforms, assumptions about the radionuclide retention properties of the host rock are not significant in terms of the calculated risk associated with this concept for HHGW disposal in higher strength rock.

10.3.2 LHGW disposal in higher strength rock

Base scenario

The base scenario for LHGW disposal in higher strength rock, describing the expected evolution of conditions in the GDF, is presented in Section 5.7. The establishment of alkaline and reducing conditions is key to ensuring that the corrosion rates of metal containers are low and that the rate of release of radionuclides from the waste packages is limited. For example, the corrosion rate of stainless steel in the presence of a high pH cement is expected to be such that containers just a few millimetres thick could last as long as 100,000 years [62, §12.2.1].

Thick-walled carbon steel and cast iron containers are also likely to provide very long periods of containment in both alkaline and near-neutral pH conditions. For example, 10 mm of carbon steel may not be perforated by corrosion for up to around 100,000 years in alkaline conditions and 10,000 years in near-neutral pH conditions [62, §12.2.2]. Confidence in the expected durability of steel in near-neutral pH conditions is provided by anthropogenic analogues. In these conditions, the large majority of observations indicate corrosion depths of less than 10 mm in 1,000 years. Examples of well-preserved iron artefacts from the Roman era include a large hoard of iron nails buried in clay soil in Scotland almost 2,000 years ago (see Figure 26).

However, after hundreds of thousands of years, it is likely that the engineered barriers will have degraded significantly. On such timescales, the containment function of the geological environment becomes increasingly important. In order to understand how the different barrier components contribute to environmental safety over long post-closure periods, total system model calculations have been undertaken to assess the base scenario. The calculations provide an illustration of how radionuclides may eventually be transported through the barrier system once released from LHGW packages and provide estimates of the risks to potentially exposed groups on a timescale of 300,000 years.

Figure 26 A 30-cm-long Roman nail that had been buried in clay soil in Scotland almost 2,000 years ago [62, §10.7.2]

The analysis has focused on the evolution of conditions in a single vault containing SILW/SLLW, UILW/ULLW, ILW in RSCs, DNLEU, New Build SILW or New Build UILW. The containers modelled for each waste group are as follows:

- Stainless steel containers are used for SILW/SLLW, UILW/ULLW and DNLEU[12]. The time for the containers of each waste group to fail has been estimated to be between 1,000 years and 100,000 years [47]. All containers are assumed to fail at the same time.
- Concrete containers are used for New Build SILW and New Build UILW. The time for the containers of each waste group to fail is between 50 years and 200 years [47]. Again all containers are assumed to fail at the same time.
- RSCs are made from cast iron. The time for the first container of each waste group to fail has been estimated to be between 1,000 years and 100,000 years [47]. Other containers in the waste group are assumed to fail within the subsequent 200 year period.

Once the containers have been breached, radionuclides are released from the waste packages and are advected into the fractured host rock under a prescribed hydraulic gradient, before migrating to the surface environment through the cover rocks. Note that all LHGW containers are vented, but any diffusion of radionuclides through the container vents up until the time of container failure is considered to be negligible and has not been modelled. The illustrative geological environment (and the hydrogeological and hydrogeochemical conditions) assumed for the calculations is as modelled in the analysis of HHGW disposal in higher strength rock (see Figure 19). GoldSim TSM calculations have been undertaken for each of the LHGW groups shown in Table 7. Separate calculations have been undertaken for each type of LHGW; in each case, all of the vaults that contain a specific type of LHGW have been included in the model. A full discussion of the results of the calculations is provided in the PCSA [5, §5.3].

The calculated mean of the radionuclide activity fluxes (Bq/year) entering the cover rocks from the host rock is shown in Figure 27 for radionuclides released from degraded stainless steel UILW/ULLW containers. The period of containment in the waste packages is sufficient for radionuclides with half-lives of less than about one hundred years (such as Cs-137 and Sr-90) to decay to negligible activities in the packages. The most significant radionuclides that reach the cover rocks (in terms of activity flux) on a timescale of 300,000 years are Ni-59, Pu-239 and Pu-240.

As in the assessment for HHGW, calculations have been undertaken to evaluate the sensitivity of results to rock matrix diffusion and sorption in the host rock. Strongly sorbed radionuclides such as plutonium and uranium are retained in the host rock in all realisations and the activity flux of Ni-59 is greatly reduced, but the activity fluxes of more mobile radionuclides such as C-14 and Cl-36 are less affected (see Figure 28).

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[12] In this analysis, all DNLEU has been assumed to be grouted into stainless steel drums for disposal, which is different to RWM's recently revised disposal concept for DNLEU that contains less than 1 weight percent U-235. The revised concept involves placing storage containers of DNLEU oxide powders in large transport and disposal containers that are infilled with grout (see Section 5.2.1). However, the results of the TSM calculations will be similar for these two disposal concepts primarily because differences in the containment period provided by the two types of stainless steel container will be insignificant and uranium concentrations will be solubility limited in a similar way in each case according to the groundwater conditioning provided by the grout.

Figure 27 **Mean radionuclide activity flux from the host rock to the cover rocks for the entire UILW/ULLW group disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock**

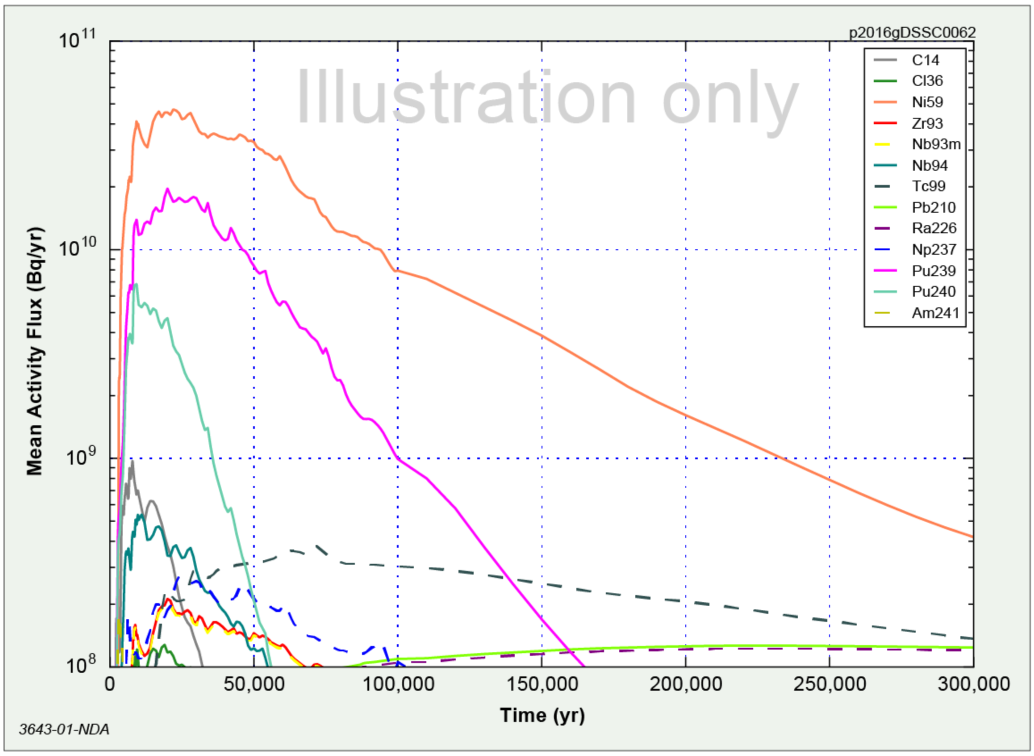
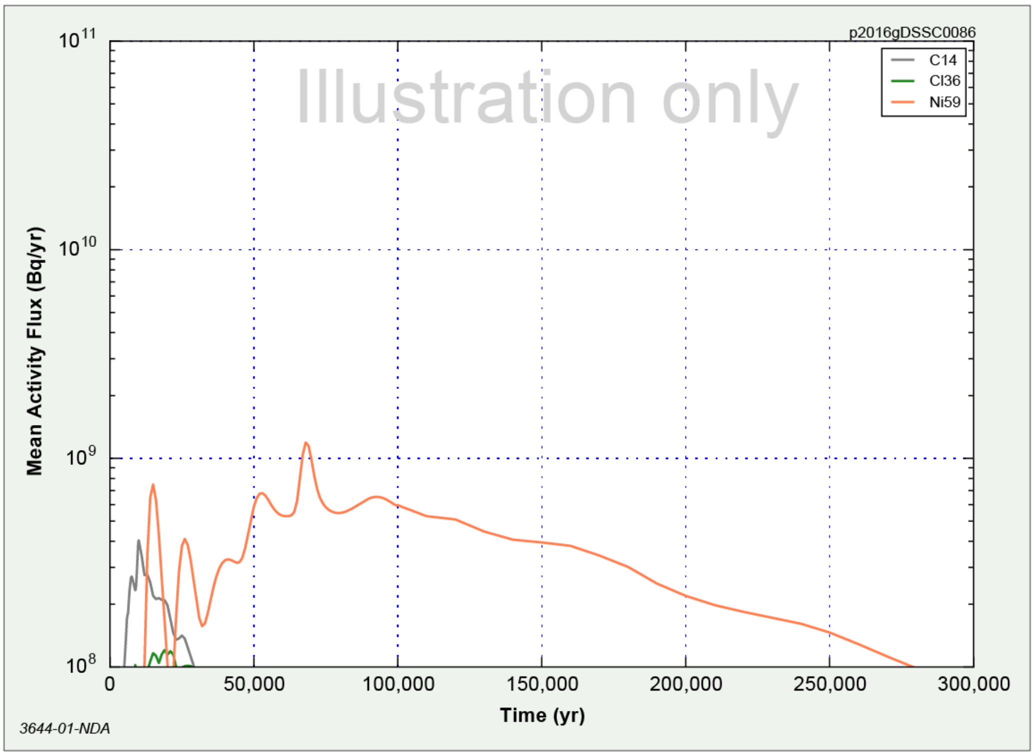


Figure 28 **Mean radionuclide activity flux from the host rock to the cover rocks for the entire UILW/ULLW group disposed of in higher strength rock, with matrix diffusion and radionuclide sorption in the host rock**



Long-lived radionuclides eventually migrate through the cover rocks to the biosphere. The calculated mean radiological risk from the marine pathway is small (several orders of magnitude less than the regulatory risk guidance level). The main contributors to calculated risk in the first 150,000 years after GDF closure are Cl-36 and I-129 and the results are similar in this period irrespective of whether rock matrix diffusion in the host rock is excluded (see Figure 29) or included (see Figure 30). However, if rock matrix diffusion in the host rock is excluded, risks from Ra-226, U-233, Sn-126, Th-229 and Th-230 gradually become more significant (Figure 29). Note that the calculated mean risk via the marine pathway is substantially below the risk guidance level for each type of LHGW.

As in the assessment for HHGW, in order to explore the robustness of the disposal concept to assumptions about the biosphere, radionuclides have been assumed to migrate to an aquifer from which water is extracted via a well. As before, the amount of dilution has been controlled by specifying the hydraulic conductivity of the aquifer. Calculations of risk have been undertaken based on different assumptions about rock matrix diffusion and sorption in the host rock.

The most significant contributors to calculated risk via the well pathway for this illustration are indicated in Figure 31 for the case in which rock matrix diffusion and sorption in the host rock are excluded. The main contributors to risk in the period up to 150,000 years for all realisations are I-129 and Cl-36. In addition, one realisation in which uranium is soluble and only weakly sorbed in the cover rocks generates an early arrival of uranium isotopes in the biosphere, peaking at around 70,000 years, and this realisation dominates the calculated mean risk via the well pathway at this time. In most realisations, radionuclides such as Ra-226, U-233, U-234 and U-238 only become significant contributors to the total calculated risk after around 200,000 years. At these later times, the calculated total mean risk for the well pathway is of the same order of magnitude as the risk guidance level. However, the results are strongly dependent upon the assumptions made in the illustration about the radionuclide transport pathway to the biosphere, the properties of the aquifer and the presence and characteristics of the well. Note that for this illustration, the calculated mean risk is substantially lower than the estimated risk associated with radiological dose that might be received from natural background ionising radiation.

If rock matrix diffusion and sorption are assumed to occur in the host rock, radionuclides such as uranium are retained in the host rock in all realisations and no longer contribute significantly to risk on a 300,000 year timeframe, as indicated in Figure 32. However, I-129 and Cl-36 are not retarded in the host rock, so that they still contribute significantly to calculated mean risk. Thus, understanding I-129 and Cl-36 behaviour in the multi-barrier system is important to the demonstration of environmental safety of the disposal concept and remains a focus of RWM's research. Also, as was found in the assessment for HHGW disposal in higher strength rock, diffusion and dispersion, the existence of transport pathways to the biosphere and assumptions about human activity in the biosphere strongly influence risk calculations.

The calculated total mean risk via the well pathway for each type of LHGW is shown in Figure 33, for illustrations in which diffusion of radionuclides into, and their sorption in, the host rock matrix is not represented. The combined total mean risk from all types of LHGW is also shown, although to add the risks from each waste type is highly cautious because it assumes that radionuclides migrating from different LHGW disposal regions over a large lateral area of the GDF converge and enter the same area of the aquifer in the vicinity of the assumed well. However, even in this conservative scenario, the combined total mean calculated risk is of the same order of magnitude as the regulatory risk guidance level and is substantially lower than the estimated risk associated with natural background ionising radiation.

Figure 29 Mean radiological risk (total and significant contributors) via the marine pathway for the entire UILW/ULLW group disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock

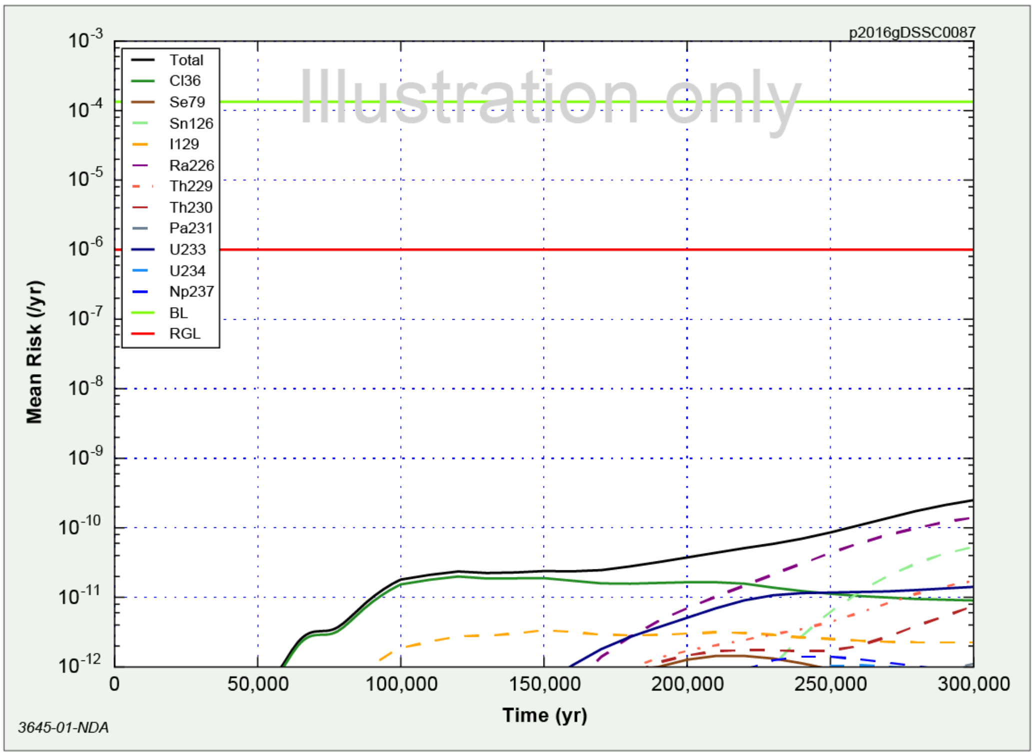


Figure 30 Mean radiological risk (total and significant contributors) via the marine pathway for the entire UILW/ULLW group disposed of in higher strength rock, with matrix diffusion and radionuclide sorption in the host rock

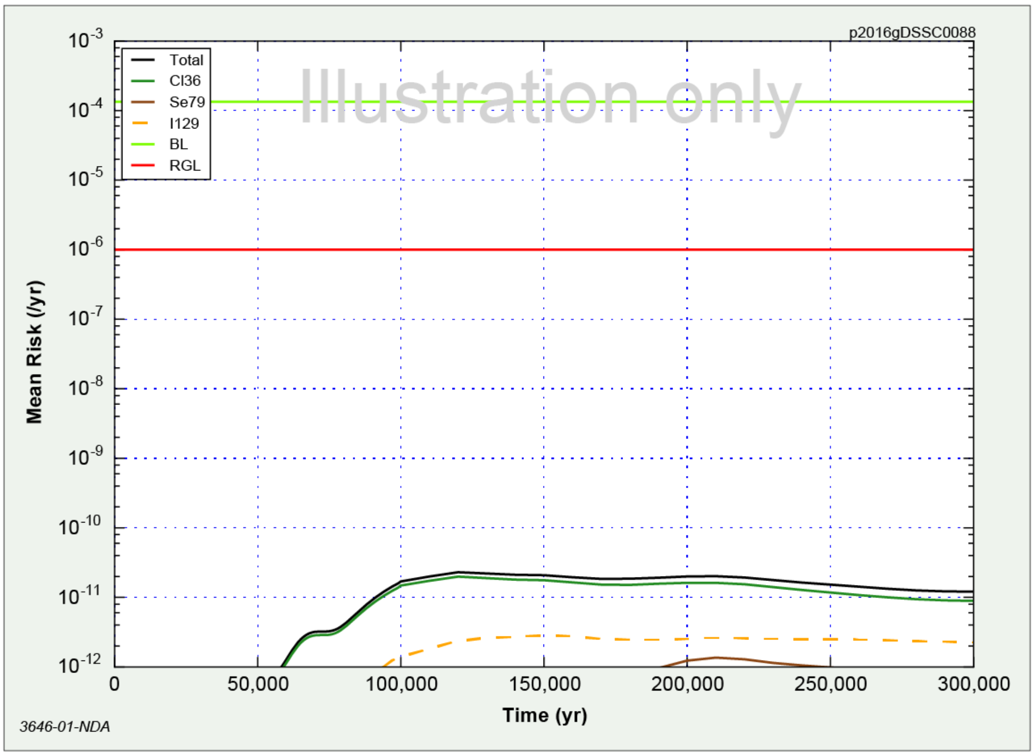


Figure 31 Mean radiological risk (total and significant contributors) via the well pathway for the entire UILW/ULLW group disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock

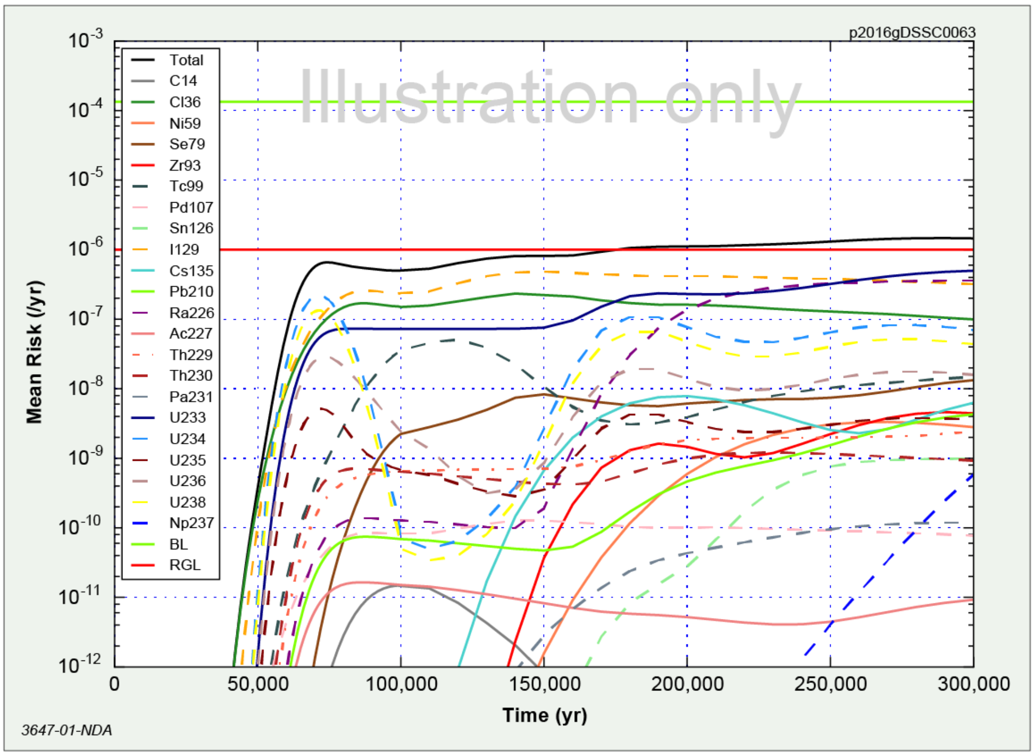


Figure 32 Mean radiological risk (total and significant contributors) via the well pathway for UILW/ULLW disposed of in higher strength rock, with matrix diffusion and radionuclide sorption in the host rock

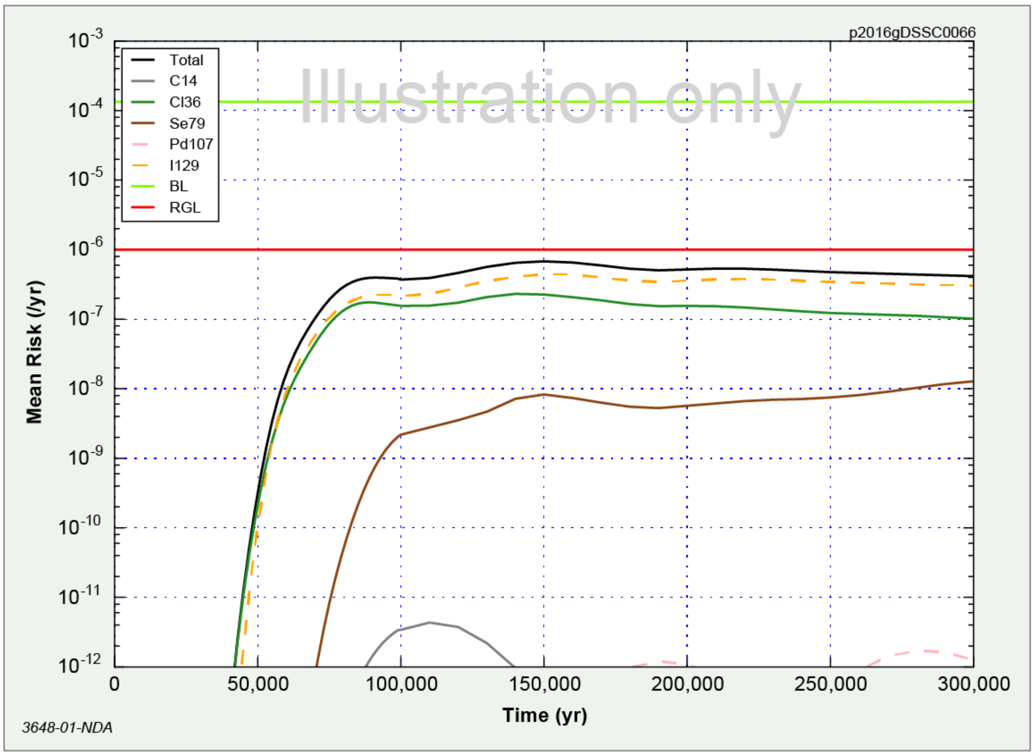
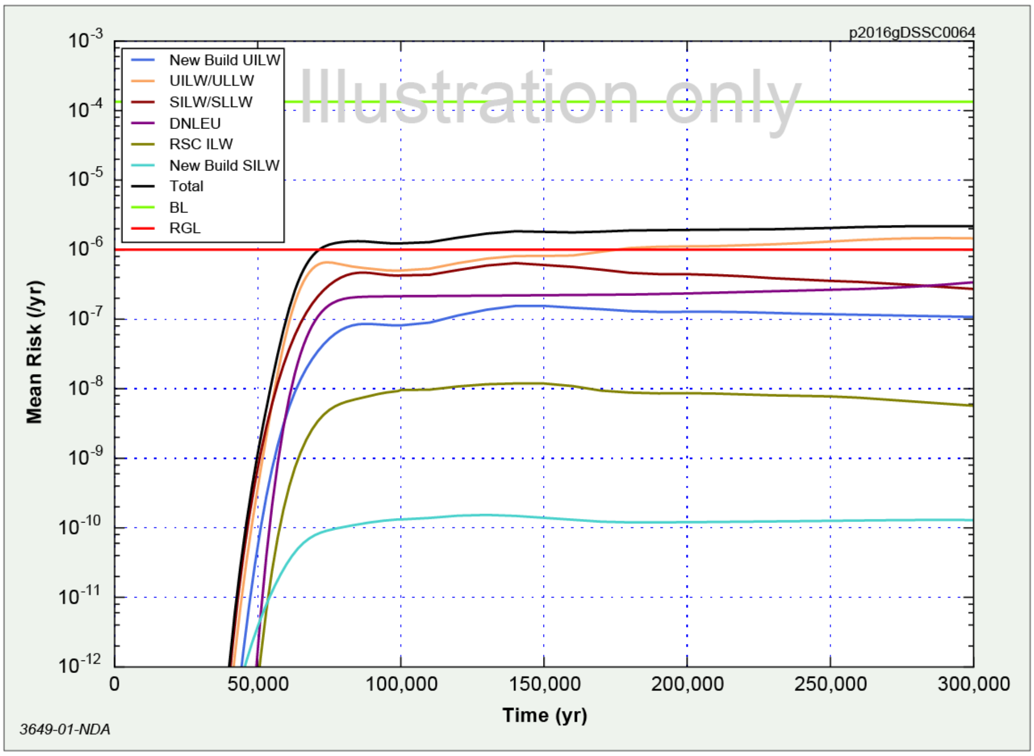


Figure 33 **Total mean radiological risk via the well pathway for each type of LHGW disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock**



The contributors to risk for each type of LHGW are similar, except that for SILW/SLLW, the calculated total mean risk is almost entirely due to exposure to Cl-36, and for DNLEU, the most significant contributors to risk are U-234 and U-238. By accounting for diffusion and sorption in the host rock, the calculated risk from uranium isotopes would decrease substantially.

Variant scenario

As discussed in Section 5.8, the identification of variant scenarios has focused on the environmental safety functions provided by the backfill. The variant scenario involves early breach of stainless steel containers (after 10 years) as a result of corrosion under oxic and low pH conditions in the presence of groundwater rich in chloride. The conditions for radionuclide transport are otherwise as assumed for the analysis of the base scenario.

Some realisations show earlier migration of the most mobile radionuclides such as I-129 and Cl-36 to the biosphere than in the base scenario. However, even for these radionuclides, a reduced period of waste package containment does not have a significant impact on environmental safety.

10.3.3 HHGW disposal in lower strength sedimentary rock

Base scenario

The base scenario describing the expected evolution of conditions in a facility for HHGW disposal in lower strength sedimentary rock is presented in Section 6.7. The environmental safety function provided by the host rock in limiting radionuclide migration is important to the environmental safety of the disposal concept, as demonstrated by the results of total system modelling. The assessment is based on the specification of an illustrative geological environment for HHGW disposal in lower strength sedimentary rock and radionuclide transport calculations on a post-closure timescale of 300,000 years. Conditions in the geological environment have been assumed to remain stable in this period.

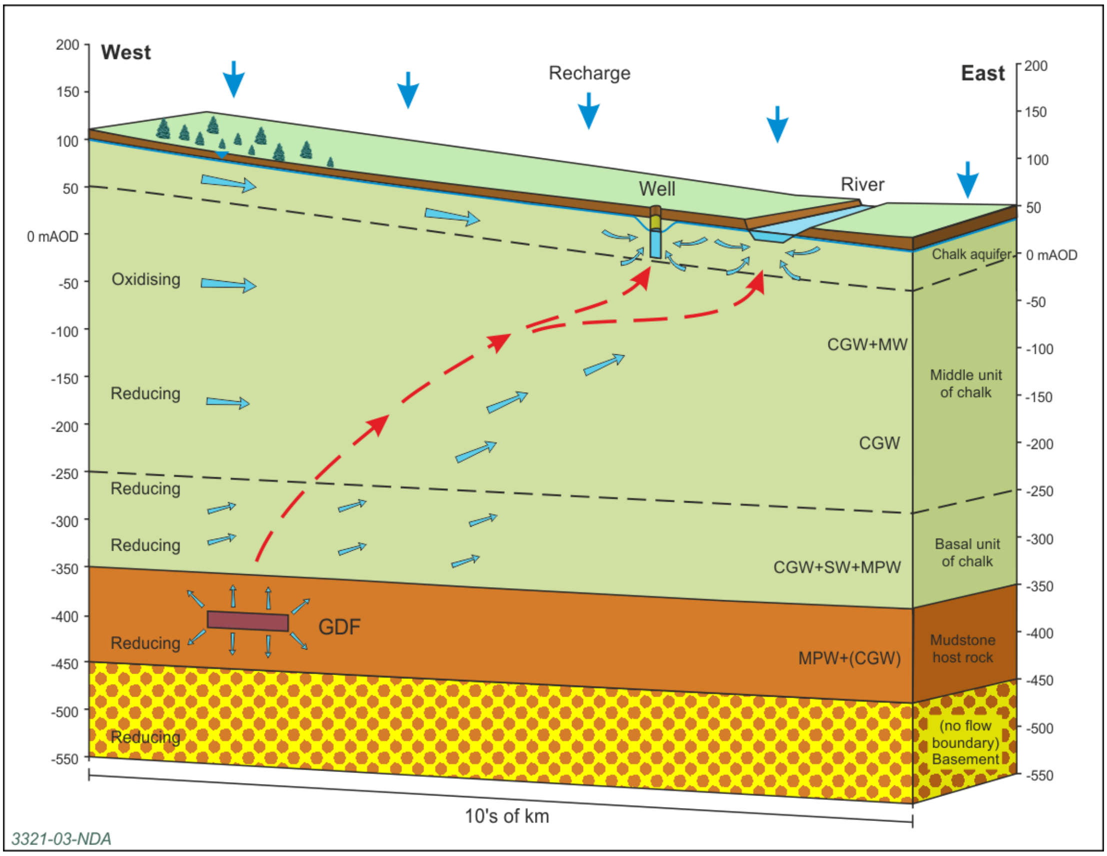
In the model, the carbon steel containers degrade and are breached some time after GDF closure. For the purposes of this illustrative calculation, the failure of the first container is specified to occur between 10,000 years and 90,000 years after GDF closure. The remaining containers are assumed to fail thereafter over a period of between 1,000 and 25,000 years. Once water penetrates the disposal container, the wasteform starts to dissolve and any radionuclides that have not decayed *in situ* are released. For spent fuel, the portion of the instant release fraction that has not decayed is released rapidly; the spent fuel matrix then dissolves slowly and releases the remaining radionuclides. For HLW, slow dissolution of the glass matrix limits the release rate of any remaining radionuclide inventory. Similarly, ceramic plutonium residues and HEU wasteforms dissolve and release radionuclides slowly. Radionuclides are released into and diffuse through the bentonite buffer, before entering the host rock, where transport is diffusion-dominated. Any radionuclides that diffuse to the top of the host rock are advected to the surface environment through the cover rocks.

The illustrative geological environment assumed for these calculations is described in detail in the PCSA [5, §5.4] and is summarised here. The host rock comprises a 100-metre-thick mudstone formation with its base at about 550 metres below the ground surface on the west edge of the section as shown in Figure 34. The GDF is assumed to be in the middle of the host rock at a depth of 500 metres below the ground surface. The lithology and physical properties of the mudstone are assumed to be uniform across its entire thickness.

The cover rock overlying the mudstone formation is chalk. The chalk fills almost the entire thickness from the upper surface of the mudstone to the ground surface, with only a minor thickness of up to a few metres of superficial deposits (comprising clayey silt with sand and gravel lenses) being present across the whole surface area. The relatively shallow chalk (the uppermost 50 metres) generally has high permeability due to the abundance of fissures and this represents an aquifer. At greater depths, the chalk has less frequent fissuring and is also more compacted; its permeability therefore tends to decrease with depth. In order to represent these depth-dependent characteristics, the chalk is subdivided into three segments, which are, from the top downwards: an upper unit of chalk (the ‘chalk aquifer’), a middle unit of chalk, and a basal unit. Note that the terms upper, middle and basal chalk are used to distinguish between layers of chalk of differing properties. These terms do not correlate to any current or historic stratigraphic nomenclature applied to UK chalks.

The middle chalk unit thins accordingly towards the east edge of the section. The total thickness of chalk cover over the mudstone host rock varies across the section because of the sloping topography on the upper surface and its flat-lying base on top of the mudstone. The redox state of the two uppermost chalk units is described as ‘oxidising’, whereas the basal chalk unit is described as ‘reducing’.

Figure 34 Possible groundwater pathway from a GDF to the surface environment where the lower strength sedimentary rock is overlain by a sequence of sedimentary formations and a river is the receptor[13]



The mudstone host rock has very low permeability and as a consequence the dominant mechanism for movement of solutes is diffusion. Radionuclides that diffuse vertically upwards to the chalk cover rock sequence would be transported by advection in the chalk towards the biosphere. Lateral hydraulic head gradients in the chalk are likely to be greater than vertical hydraulic gradients, especially in the chalk aquifer. Therefore, groundwater movement in thick sequences of chalk is dominantly lateral, with more subsidiary vertical movement as shown by the arrows in Figure 34 (the vertical movement could be upwards or downwards, depending on topographic position and other factors; in this illustrative example it is upwards). The resulting predominant trajectory of groundwater movement and solute transport is, in this setting, as shown by the blue and red arrows in Figure 34.

The groundwater discharge location is an incised river (terrestrial pathway), as shown in Figure 34. The discharge point is a secondary river within a sub-catchment of a primary river. If radionuclides from the GDF were transported to the near surface in upwelling groundwater, they would initially be diluted in meteoric water within the sub-catchment of the secondary river. Subsequently, the radionuclides would be transported downstream in the drainage network, being subject to additional dilution downstream of confluences in that network before eventually entering the primary river and discharging to the sea.

As for the calculations of risk for the higher strength rock disposal concepts, a well pathway has also been included to enable evaluation of the robustness of the safety case to assumptions about biosphere properties (see Figure 34). A well depth of 75 metres has

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[13] CGW is chalk groundwater, MPW is mudrock porewater, MW is meteoric water and SW is sea water.

been assumed and where a plume of radionuclides exists in the vicinity of the well, part or all of it is captured by the well. Again, the concentration of radionuclides in the abstracted water is calculated by considering the dilution of all, or part, of the flux of radionuclides entering the aquifer (by considering the vertical cross-sectional area of the plume at the location of the well and the groundwater flow rate in the aquifer).

GoldSim TSM calculations have been undertaken for the HHGW groups shown in Table 7 (except exotic fuels for the reasons noted in Section 10.3.1). Full details of the parameter values used in these calculations are presented in the Data Report [47]. Separate calculations were undertaken for each type of HHGW; in each case, all tunnels containing the specific wasteform were considered. A full discussion of the results of the calculations is provided in the PCSA [5, §5.5].

The initial inventory of shorter-lived radionuclides (half-lives of less than about one thousand years) decays to insignificant activities during the period of containment in the waste package. As the wasteform degrades after container breach, any released radionuclides diffuse slowly through the bentonite backfill into the host rock. The calculated mean of the radionuclide activity fluxes entering the host rock from the backfill is shown in Figure 35 for the example involving PWR spent fuel containers. The characteristics of the radionuclide flux distribution from these containers are similar to those shown in Figure 20 for radionuclide transport from a single PWR container in the higher strength rock disposal concept, although the magnitudes of the fluxes are of course proportionately different. The greatest activity flux on a timescale of tens of thousands of years is calculated for Ni-59. Other significant isotopes in terms of activity reaching the host rock are Ac-227, Cs-135 and Ra-226.

The host rock has an important radionuclide containment function as indicated by Figure 36, which shows the mean of the total radionuclide activity fluxes entering the cover rocks from the host rock. Only the most mobile and long-lived radionuclides reach the cover rocks on a timescale of 300,000 years, with I-129, Cl-36, Nb-94 and Se-79 dominating contributions to radionuclide activity flux.

Long-lived radionuclides eventually migrate through the cover rocks to the biosphere, although in this illustration the travel time to the biosphere is long. The calculated mean risk via both the terrestrial pathway and the well pathway on a timescale of 300,000 years is substantially less than 10^{-12}/year for the illustrative example involving PWR spent fuel. Even if the calculations are continued for a one-million-year assessment period, the calculated mean risk via the well pathway remains below 10^{-9}/year (dominated by I-129). Similarly, the calculated total mean risk via each pathway for other types of HHGW is substantially less than 10^{-12}/year on a timescale of 300,000 years, because of the containment safety function provided by the host rock and the long travel time to the biosphere.

Figure 35 **Mean radionuclide activity flux from backfill to the host rock for PWR spent fuel disposed of in a lower strength sedimentary rock**

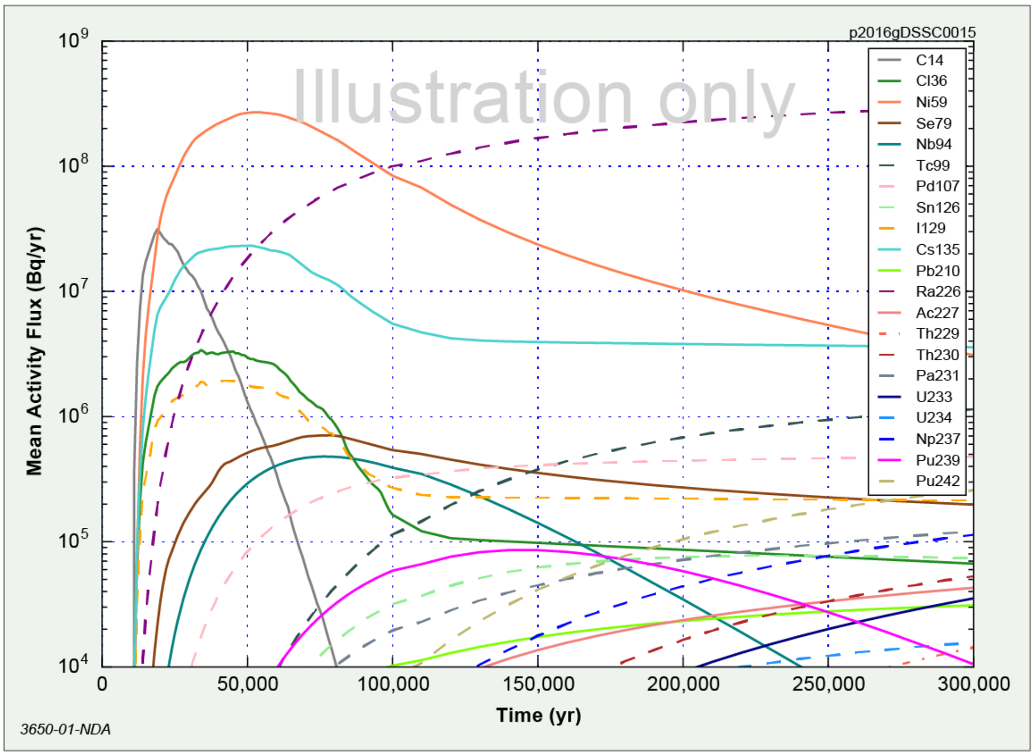
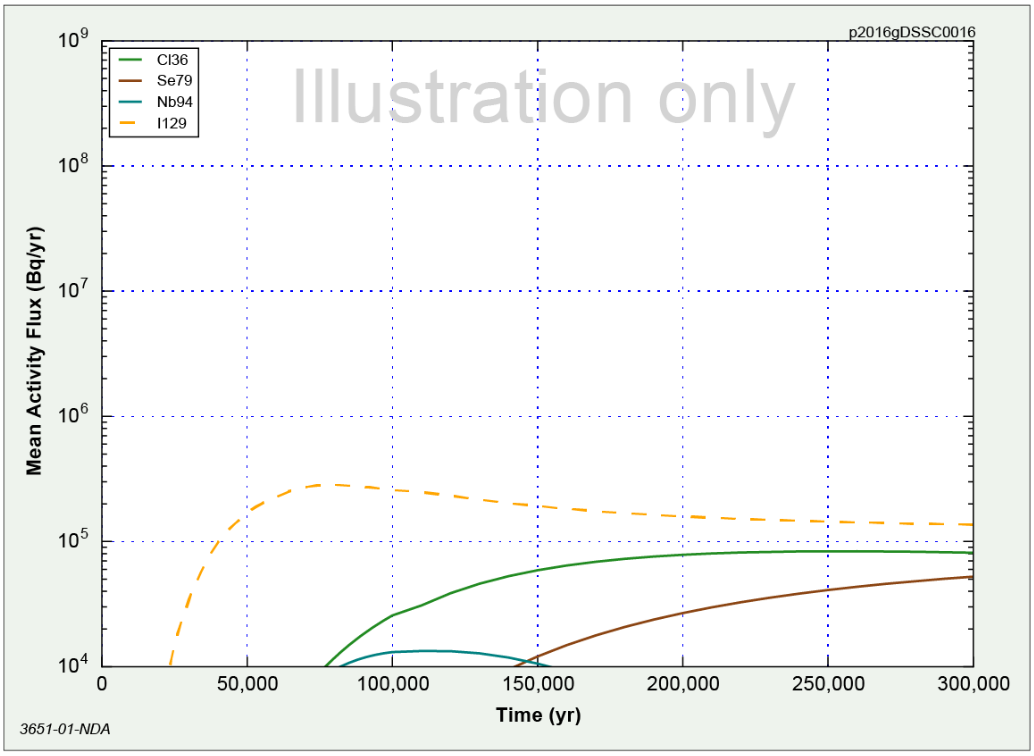


Figure 36 **Mean radionuclide activity flux from the host rock to the cover rocks for PWR spent fuel disposed of in a lower strength sedimentary rock**



Variant scenario

As discussed in Section 6.8, the identification of variant scenarios has focused on the environmental safety functions provided by the containers. The variant scenario considered involves early breach of a single carbon steel container (immediately after GDF closure) as a result of a weld failure due to large, undetected defects under the mechanical stresses imposed by swelling bentonite, with other containers behaving according to their expected evolution under the base scenario. The conditions for radionuclide transport are as assumed for the analysis of the base scenario. Early failure of a single PWR spent fuel container has negligible impact on the mean flux of radionuclides out of the host rock or calculated risks via the well and terrestrial pathways. Calculations indicate that the risks remain less than 10^{-12}/year over a 300,000-year timescale.

10.3.4 LHGW disposal in lower strength sedimentary rock

Base scenario

The base scenario describing the expected evolution of conditions in a facility for LHGW disposal in lower strength sedimentary rock is presented in Section 7.7. Again, the environmental safety function provided by the host rock in limiting radionuclide migration is important to the environmental safety of the disposal concept. Also, the establishment of alkaline and reducing conditions in the EBS ensures that the corrosion rates of metal containers are low and that the rate of release of radionuclides from the waste packages is limited. Total system model calculations have been undertaken for the base scenario to provide an illustration of how the components of the multi-barrier system contribute to the environmental safety of LHGW disposal, based on a post-closure timescale of 300,000 years. As discussed in Section 2.4.5, site-specific ESCs will include stylised deterministic calculations to evaluate the impacts of natural processes over timescales in excess of a few hundred thousand years, based on descriptions of possible long-term environmental conditions at the GDF site.

The LHGW analysis has focused on the evolution of conditions in vaults containing SILW/SLLW, UILW/ULLW, ILW in robust shielded containers, DNLEU, New Build SILW or New Build UILW. The containers used for each waste group and the container failure times are as discussed above for the disposal of LHGW in higher strength rock, except that concrete containers are assumed to fail between 5,000 years and 20,000 years after GDF closure [47].

In each case, after container breach radionuclides are released from the waste packages and diffuse into the host rock. The illustrative geological environment (and the hydrogeological and hydrogeochemical conditions) assumed for these calculations is as modelled in the analysis of HHGW disposal in lower strength sedimentary rock (see Figure 34), with transport pathways assumed to exist from the host rock to the biosphere. Again, radionuclide transport through the host rock is by diffusion, with retardation by sorption. Transport through the overlying chalk rocks is by advection with retardation by sorption. The effects of transverse and longitudinal dispersion along the transport paths, and radionuclide decay and ingrowth, are included in the model.

The radionuclide activity fluxes (Bq/year) across each barrier have been evaluated using the total system model. The calculated mean of the radionuclide activity fluxes entering the cover rocks from the host rock is shown in Figure 37 for radionuclides released from degraded stainless steel UILW/ULLW containers. The calculated radionuclide activity fluxes are similar to those shown in Figure 27 for radionuclide transfer from higher strength host rock to cover rocks when there is no sorption or matrix diffusion in the host rock. Again, the most significant radionuclides that reach the cover rocks (in terms of activity flux) on a timescale of 300,000 years are Ni-59 and Pu-239.

Figure 37 **Mean radionuclide activity flux from the backfill to the host rock for UILW/ULLW disposed of in a lower strength sedimentary rock**

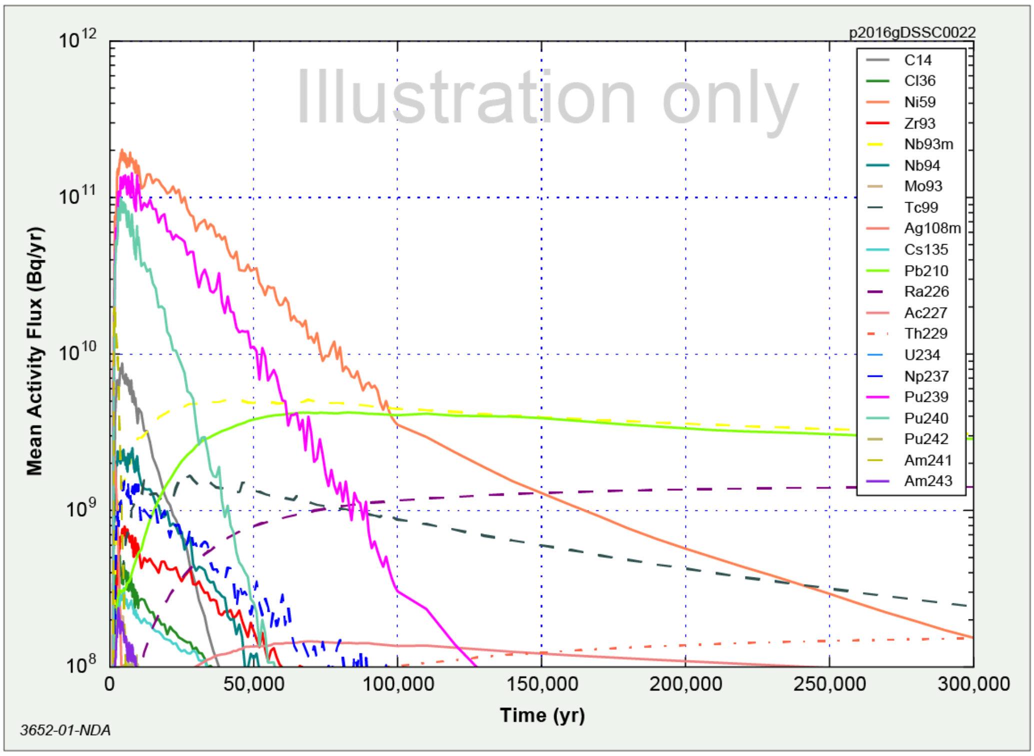
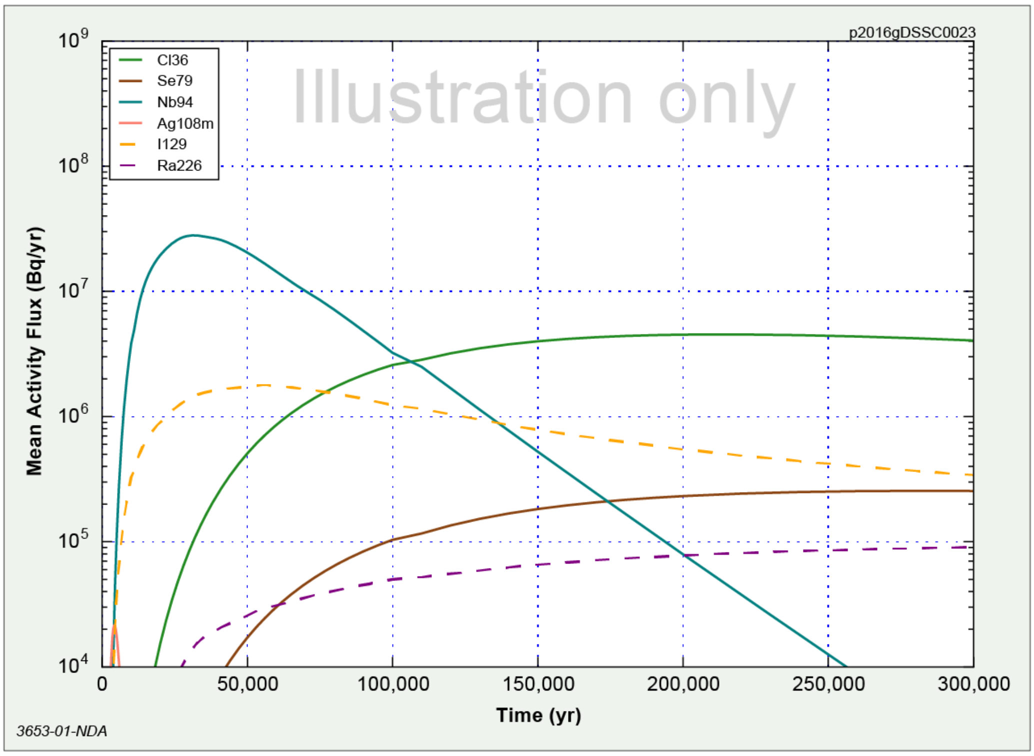


Figure 38 **Mean radionuclide activity flux from the host rock to the cover rocks for UILW/ULLW disposed of in a lower strength sedimentary rock**



The host rock provides a significant radionuclide containment function as indicated by Figure 38, which shows the mean of the total radionuclide activity fluxes entering the cover rocks from the host rock as a result of release from UILW/ULLW vaults. In this illustration, only the most mobile and long-lived radionuclides reach the cover rocks on a timescale of 300,000 years, with Nb-94, I-129, Cl-36, Se-79 and Ra-226 dominating contributions to radionuclide activity flux. The calculated mean risk via the terrestrial and well pathways on a timescale of 300,000 years is substantially less than 10^{-12}/year, and only approaches 10^{-9}/year (dominated by I-129) for the well pathway if the calculations are continued for a one-million-year assessment period. Similarly, the calculated total mean risk via each pathway for each type of LHGW is insignificant on a timescale of 300,000 years, because of the containment safety function provided by the host rock and the long travel time to the biosphere. A full discussion of the results of the calculations is provided in the PCSA [5, §5.6].

Variant scenario

As discussed in Section 7.8, the identification of variant scenarios has focused on the environmental safety functions provided by the backfill. The variant scenario involves errors in backfill emplacement, leading to early breach of stainless steel containers (after 10 years) as a result of corrosion under oxic and low pH conditions in the presence of groundwater rich in chloride. The conditions for radionuclide transport are otherwise as assumed for the analysis of the base scenario. However, calculated risks via the terrestrial pathway and the well pathway on a timescale of 300,000 years remain substantially less than 10^{-12}/year. Again, calculations indicate that the risks (predominantly from I-129) remain less than 10^{-9}/year even after one million years.

10.3.5 HHGW disposal in evaporite

Base scenario

The expected evolution (base scenario) of the disposal facility in evaporite rock (halite) is not expected to result in any radionuclide releases to the biosphere via groundwater, primarily because there is little or no water available to facilitate radionuclide migration and rock creep is expected to encapsulate the wastes after disposal, closing any fractures and voidage that could act as radionuclide transport pathways (see Section 8.7).

Variant scenario

The dryness of the disposal tunnels and encapsulation of the waste packages by creep closure are important features of the disposal concept that ensure long-term environmental safety (see Section 8.8). The barrier function of the host rock could be by-passed if the shaft seals did not fulfil their environmental safety functions, for example, as a result of quality control failures of shaft sealing materials. Such failures, although unlikely, could result in the presence of pathways for groundwater flow and radionuclide transport through seals between the GDF and overlying formations. However, at this generic stage in GDF development, there is little merit in presenting stylised assessment calculations for such a variant scenario. This is because such scenarios cannot readily be constrained in terms of the induced pathways for groundwater flow in the disposal facility, the rate of groundwater flow, and its impacts on barrier system behaviour and radionuclide transport.

10.3.6 LHGW disposal in evaporite

Base scenario

Again, the base scenario is not expected to result in radionuclide releases to the biosphere via groundwater, primarily because there is little water available to facilitate radionuclide migration and rock creep is expected to encapsulate the wastes after disposal, closing any fractures and voidage that could act as radionuclide transport pathways (see Section 9.7).

Variant scenario

The dryness of the disposal tunnels and encapsulation of the waste packages by creep closure are important features of this disposal concept that ensure long-term environmental safety (see Section 9.8). The barrier function of the host rock could be by-passed if the shaft seals did not fulfil their environmental safety functions, for example, as a result of quality control failures on shaft sealing materials. Such failures could result in the presence of pathways for groundwater flow and radionuclide transport through seals between the GDF and overlying formations. As noted above for the concept involving HHGW disposal in evaporite, there is little merit in presenting stylised assessment calculations at this generic stage.

10.4 Radiological assessment: radionuclides in gas

This section discusses the assessment of gas generation and its consequences for each waste group and illustrative disposal concept. RWM's analysis of gas generation and migration is discussed in detail in the generic PCSA [5, §6] and is based on the consideration of gas behaviour in different geological environments reported in the Gas Status Report [53, §6] and RWM's supporting research on C-14 behaviour [15; 16]. Key findings with regard to the assessment of the radiological impacts of gas for different waste groups and disposal concepts are discussed here.

Gases will be formed from processes occurring in many waste packages, for example, corrosion of metals in the waste or radiolysis of water [53, §2.2.3]. Components of the EBS will also contribute to gas generation after closure (for example anaerobic corrosion of steel waste containers and gamma radiolysis of porewater in a cementitious backfill). Some of the gas will consist of radioactive molecules (for example tritiated hydrogen) and, although these may be insignificant in terms of the volumes of gas generated, their release from waste packages could contribute to the radionuclide uptake by people and non-human biota [53, §2]. The generation and migration of gas after closure of the GDF will depend on the combined properties of the waste, EBS and geology.

The main radioactive gas requiring consideration in a GDF post-closure safety assessment is C-14 (which has a half-life of 5.73×10^3 years [47]). Any tritiated gas generated in a disposal facility after closure would not be significant because tritium has a short half-life (about 12 years [47]). The gas Rn-222 is produced from radioactive decay as part of the uranium series (the U-238 decay chain), but has a short half-life (approximately four days [47]) and, as such, is not a significant concern for post-closure safety. However, if long-lived radionuclides in the uranium series (that is, U-238, U-234, Th-230 and Ra-226) migrate to the near-surface environment in groundwater, where they accumulate, then Rn-222 ingrowth may be significant in terms of potential radiological risk, depending on exposure pathways. Such potential exposure to Rn-222 (and its daughters) may be an important consideration in a site-specific safety assessment. Bulk (non-radioactive) gas that is generated in the disposal facility may act as a carrier of radioactive gases.

Gas that is generated after GDF closure may dissolve in water, undergo chemical reactions or form a free gas phase. The amount of a free gas phase, its effect on the EBS and the geological barrier, and its migration through the EBS and the geological barrier will depend strongly on the geological disposal concept and on the properties of the geological environment, in particular the host rock. The following sub-sections discuss the generation and migration of radionuclides in the gas phase based on consideration of the illustrative concepts for HHGW and LHGW in different geological environments.

10.4.1 HHGW disposal in higher strength rock

The illustrative concept for HHGW disposal in higher strength rock involves packaging the wastes within cast iron inserts inside copper containers (see Section 4) and placing the containers in vertical deposition holes lined with a bentonite buffer.

The chemical form of the spent fuel (apart from metallic fuel) and its dryness means that the wasteform will produce negligible volumes of gas; small amounts of radioactive gases could leak from any defective fuel pins, but the gas would be retained within the high-integrity containers [53, §4.4]. Likewise, vitrified HLW and the stainless steel canister within which it is contained will not generate gas when dry within the intact disposal container.

Under anaerobic conditions in the disposal facility, the corrosion of the copper containers is expected to be negligible and no gas will be generated. Hydrogen may be generated from radiolysis of groundwater in contact with the outer surface of disposal containers [53, §6.1.4; 62, §9.2.1, §11.2.1], although the presence of the bentonite will limit the availability of water in contact with the container.

Copper corrosion is only likely to proceed in the presence of sulphide, but this reaction is not expected to generate gas. If sulphide attack, or some other disruptive event, were to result in container breach and groundwater ingress, then gas could be generated from the corrosion of metals in the container, especially the iron insert, and from radiolysis of water [53, §6.1.4]. Small amounts of radioactive gases could leak from any defective or degrading fuel pins. These gases are likely to dissolve in groundwater as they migrate from the EBS, although this depends on the properties of the geological environment, as discussed in Section 10.4.2 for LHGW disposal.

10.4.2 LHGW disposal in higher strength rock

The illustrative concept for the disposal of LHGW in higher strength rock involves stacking waste packages in large unlined vaults. The vaults will be backfilled with NRVB, which is a cementitious material, once all the vaults have been filled (see Section 5). Wastes will continue to undergo reactions after they have been emplaced in the GDF and in some cases will generate gas prior to backfilling. In particular, corrosion of the more reactive metals (for example Magnox) and degradation of organic materials may result in high rates of gas generation. Some container metals and structural metals (used in the construction of the GDF) will also contribute to gas generation [53, §6.1.1]. The geological environment will affect the rate of gas generation after backfilling through the chemical composition of the groundwater and through the rate of groundwater supply.

The generic PCSA [5, §6.1.2] discusses calculations of radioactive gas generation (H-3, Rn-222 and $^{14}CH_4$) for the LHGW disposal concept. The Ra-226 inventory, and therefore the rate of Rn-222 generation, was calculated to increase in the long term as the Ra-226 tends towards secular equilibrium with U-234 (which will take about one million years). Carbon dioxide (CO_2) (and any C-14 it contains) was assumed to react with cementitious materials in the EBS and, thus, not to be released into the host rock as a free gas. Methane (including $^{14}CH_4$) was estimated to be generated mainly from the microbial degradation of organic molecules over a period of about 10,000 years (although the major waste stream contributing to $^{14}CH_4$ generation in the long term may now not be disposed of in the GDF [5, §6.1.2]). In addition, C-14 in the gas phase could be generated from the corrosion of stainless steel, carbon steel and Zircaloy wastes, radiolysis of organic molecules and releases from irradiated graphite. Recent calculations of C-14 gas generation undertaken as part of RWM's research on C-14 behaviour [15; 16] found that the corrosion of Magnox metal, irradiated stainless steel AGR fuel cladding, fuel assembly components and Zircaloy fuel cladding are the main contributors to the generation of C-14-bearing gas.

Illustrative calculations of gas migration through higher strength rocks are discussed in the Gas Status Report [53, §6.3.2] and are summarised in the generic PCSA [5, §6.2.1]. The calculations indicate that, on a timescale of a few tens of years, the gas pressure will become comparable to hydrostatic pressure and the gas may begin to move out of the facility into the surrounding rock. Fractured rocks typically do not form a significant barrier to gas migration. As the gas phase migrates through the geological environment, it will come into contact with groundwater. Some of the gas will dissolve into, and will be transported by, the groundwater. The amount of gas that dissolves will depend on the volume of groundwater contacted and the gas solubility. If, as the gas migrates, it encounters a large flow of groundwater in permeable rocks (as indicated in the illustration discussed in the generic PCSA [5, §6.2.1]), it may dissolve to the extent that a free gas phase ceases to exist. Clearly, gas transfer through the geological environment of a disposal facility will be complex and specific to the characteristics of the disposal site and the design of the GDF.

If a free gas phase does reach the biosphere, then the presence of methane that includes C-14 presents the most significant potential concern with regard to radiological risk. Calculations of risk depend on assumptions made about the area over which the gas is released and potential human exposure pathways. Such issues have been considered as part of RWM's research on C-14 behaviour [15; 16]. The C-14 research included a number of illustrative calculations of risk associated with exposure to C-14 based on different assumptions about how the gas will migrate through fractures in the host rock and about features in the overlying geological environment that could delay or prevent gas reaching the biosphere and affect the area over which any gas would be released.

The calculated radiological impact from gaseous C-14 is dominated over the first thousand years following GDF closure by the release of C-14 from irradiated reactive metals as they corrode [16, §13.1-§13.2]. In this period, the calculated risk from gaseous C-14 is below the risk guidance level provided the proportion of C-14 released from reactive metals as methane or carbon monoxide is limited (to less than about 30% of the inventory) and any gas that does migrate to the biosphere is released over an area roughly equivalent to the GDF footprint or larger. A more focused release of gaseous C-14 results in the calculation of risk above the risk guidance level.

In the longer term, calculated risks are dominated by the generation of methane from steel wastes [16, §13.1-§13.2]. Calculated risks are below the risk guidance level if no more than 10% of the C-14 inventory is released as gas, irrespective of the assumed release area. The risk guidance level is exceeded only if release to the biosphere is assumed to occur over a more focused area and the proportion of C-14 released in the gas phase as a result of steel corrosion is greater than about 30%.

10.4.3 HHGW disposal in lower strength sedimentary rock

The illustrative concept for the disposal of HHGW in lower strength sedimentary rock involves packaging the wastes within thick-walled carbon steel containers. The waste packages will be placed on bentonite plinths in tunnels and the tunnels will be backfilled with pelleted bentonite (see Section 6).

The main source of gas (hydrogen) after GDF closure will be corrosion of the carbon steel containers, although the slow movement of water through the host rock and bentonite backfill will limit water availability for corrosion reactions [5, §6.1.3]. Similar to the concept for HHGW disposal in higher strength rock, the chemical forms of spent fuel (apart from metallic fuel) and vitrified HLW are such that they will produce negligible volumes of gas following water ingress after container breach. Small amounts of radioactive gases could leak from defective or degraded fuel pins, although this is unlikely to have a significant impact on disposal system performance.

10.4.4 LHGW disposal in lower strength sedimentary rock

The illustrative concept for the disposal of LHGW in lower strength sedimentary rock involves stacking waste packages in vaults that are backfilled with a cementitious material; each vault is backfilled when full (see Section 7). Gas generation reactions will be similar to those described for LHGW disposal in higher strength rock (see Section 10.4.2), although the slow movement of groundwater through the host rock and backfill will limit the availability of water for gas generation reactions and a complex coupling between water inflow and gas generation and flow could develop [5, §6.1.4; 53, §6.1.2].

The hydraulic conductivity of a lower strength sedimentary rock, such as a clay, could be too low, and the pressure for the gas to enter the host rock could be too high, for all the gas that is generated in the disposal facility to be dissolved. Furthermore, a free gas phase that enters the undisturbed host rock may migrate so slowly that the gas pressure becomes sufficient for micro-fissures to be created [5, §6.2.2; 53, §6.3.3]. The gas will migrate through such micro-fissures, which may then close as the gas pressure falls, depending on the properties of the host rock. Eventually, self-sealing of fractures may occur, as is observed in laboratory experiments for lower strength sedimentary rocks such as the Boom Clay in Belgium and the Opalinus Clay in Switzerland [70]. Any significant gas generation could result in displacement of contaminated groundwater from the GDF [53, §6.4]. A more detailed understanding of gas generation and its effects will be developed as necessary for a disposal concept in lower strength sedimentary rocks as relevant site-specific and GDF design-specific information becomes available.

Whether the free gas phase (including radioactive gas such as C-14) reaches the biosphere will depend on the specific characteristics of the geological environment, including the cover rocks. The generic PCSA includes discussion of illustrative calculations of gas migration from a GDF in clay, which show how free gas dissolves as it migrates through the rock, but the free gas phase eventually reaches the top of the host rock [5, §6.2.2].

RWM's research on C-14 behaviour included illustrative calculations of radiological risk from gaseous C-14 migration for a lower strength sedimentary rock disposal concept [15; 16]. No releases of gaseous C-14 were calculated to occur in the first thousand years following GDF closure [16, §13.1-§13.2]. In the longer term, calculated risks are below the risk guidance level irrespective of assumptions about the release area and the fraction of C-14 that is released in the gas phase.

Note that assumptions about the performance of the shaft seals and their prevention of water movement into the disposal region are important to assessments of the environmental safety of LHGW disposal in lower strength sedimentary rock with regard to the potential impacts gas generation [53, §6.3.3].

10.4.5 HHGW disposal in evaporite

The illustrative concept for the disposal of HHGW in evaporite involves packaging the wastes within thick-walled carbon steel containers. The waste packages will be placed on the floor of tunnels, which will be backfilled with crushed host rock (see Section 8).

Gas generation will be limited because evaporites are dry and so there will be little water available for gas generation reactions after GDF closure. The water content of the waste packages will constrain the amount of gas that could be generated [53, §6.1.3], although the granular salt backfill may provide a source of water if it is wetted to facilitate compaction [5, §6.1.5]. As discussed in Section 10.4.1, the form of the packaged HHGW is such that there is not expected to be any water available for gas generation reactions. Therefore, in this illustrative concept, it is very unlikely that there will be significant amounts of gas generated.

10.4.6 LHGW disposal in evaporite

The illustrative concept for the disposal of LHGW in evaporite involves stacking waste packages in unlined vaults. Sacks of magnesium oxide will be placed on top of each waste package stack, but the vaults will not be backfilled. Rock creep will reduce void space and close the vaults naturally over a period of decades (see Section 9).

Again, gas generation after GDF closure will be limited because of the lack of water to drive gas generation reactions. The water content of the waste packages at closure will constrain the amount of gas that could be generated [53, §6.1.3]. It is likely that there will only be a small volume of gas generated from the degradation of LHGW in the evaporite disposal concept under expected conditions.

Undisturbed evaporite rock is virtually impermeable to gas. If gas is generated, it would only migrate if sufficient gas pressures are generated to result in fracturing of the rock. The fractures would self-heal by creep on subsequent pressure reduction. Assumptions about the performance of the shaft seals and their prevention of water movement into the disposal region are important to assessments of the environmental safety of this disposal concept with regard to the potential impacts gas generation [53, §6.3.4].

10.5 Human intrusion assessment

A key safety function for the GDF is to isolate the wastes from the human environment. As discussed in Section 3.2.1, RWM currently assumes that the disposal facility is likely to be constructed between 200 and 1000 metres below the ground surface and has assumed certain disposal depths for planning purposes. However, there is a possibility that in the future knowledge of the location of the GDF and the hazardous nature of its contents could be lost and future human actions may lead to the inadvertent disruption of the engineered barriers. In view of this possibility, one of the variant scenarios that needs to be considered in an ESC is the potential for human intrusion.

The GRA [20, §6.3.35] requires RWM to assess the potential consequences of human intrusion after the period of authorisation; that is, when the environmental permit has been surrendered and the GDF site is no longer under active institutional control. The regulatory guidance states that human intrusion should be assumed to be highly unlikely to occur, but that the GDF developer should also consider and implement any practical measures that might reduce this likelihood further.

The GRA only requires consideration of inadvertent human intrusion, there is no requirement to consider any deliberate acts of breaking into the engineered barriers of the GDF [20, §6.3.38]. The GRA also states that the timing, type and extent of human intrusion into the GDF are so uncertain that they should be explored as ‘what-if’ scenarios, separately from the base scenario [20, §6.3.27]. It is also not expected that such ‘what-if’ scenarios should be assessed against the regulatory risk guidance level. However, the risk guidance level does need to be applied to intrusion events where the radionuclides have spread beyond the engineered barriers of the GDF and are subject to mechanisms of dilution; for example, the risks associated with the use of water from a well sunk into an aquifer contaminated by radionuclides from the GDF do require assessment against the risk guidance level [20, §6.3.40], and hence such exposure pathways have been considered in the assessment of radionuclide transport in groundwater discussed in Section 10.3.

The role of human intrusion in decision-making in radioactive waste disposal programmes, and its treatment in safety cases, is currently being considered at the international level within the IAEA HIDRA project [71].

Whilst there is active institutional control of the GDF site it can be assumed that inadvertent intrusion will not occur. Even beyond the period of active control, passive controls can delay the timing of intrusion, for example by ensuring that memory of the GDF location is retained. Passive safety features of the GDF, in particular its depth, can reduce the likelihood of intrusion, as can siting the GDF away from any known resources that may attract future investigations. The implications of active and passive controls on the likelihood of human intrusion are summarised in Table 9.

Table 9 **Impact of controls on human intrusion (HI) potential (from IAEA HIDRA project) during different periods after GDF closure**[14]

	Period of active control	Period of passive control	Time after which memory of the site is lost
Societal control	Physical security at site, knowledge management, records, site markers	Knowledge management, records, land use restrictions, site markers	No knowledge of hazardous nature of site
Design safety features	Depth of disposal, multi-barriers	Depth of disposal, multi-barriers	Depth of disposal, but multi-barriers may be degrading
Implications for likelihood of HI	No inadvertent HI	Inadvertent HI extremely unlikely – safety case can justify exclusion of major HI scenarios	Inadvertent HI is a possibility, but may still be mitigated by enduring design safety features
Hazard of facility	Disposal inventory	Decaying inventory	Decay may be significant

The HIDRA project considered an approach to identifying measures to reduce the likelihood of human intrusion. The most effective measures against inadvertent intrusion involve establishing the disposal facility in deep geological formations, establishing appropriate siting criteria, and providing for long-term knowledge preservation. There may also be potential design features that could be considered to reduce the likelihood or consequences of human intrusion.

When considering design features that may make a disposal facility more robust to human intrusion scenarios, it is essential also to consider the impact on other aspects of the GDF safety. For example, introducing additional metal to potentially ‘divert’ a drill bit, could lead to the generation of additional gas which may lead to other post-closure exposure pathways, more likely than human intrusion. It is important not to reduce the overall robustness of the GDF in order to mitigate potential, hypothetical future human intrusion scenarios.

The HIDRA project has identified a range of stylised scenarios for the consideration of human intrusion in safety cases. The use of stylised scenarios based on current practices near the disposal site (or globally accepted technologies) is the internationally agreed approach for the consideration of human intrusion as it avoids the need for speculation about future human behaviour (see for example [72, §6.52-§6.65]). This is consistent with the ‘what-if’ scenario approach required by the GRA.

However, the intent of human intrusion considerations is to provide added confidence in the robustness of the disposal system and to identify any protective measures that could be effective in reducing the potential for and/or consequences of inadvertent human intrusion, as part of the overall GDF optimisation process. Therefore, at this generic stage there is considered little merit in presenting even stylised human intrusion calculations as they could only be based on assumptions about an illustrative design in an illustrative geological environment and would not be relevant for any optimisation considerations. Instead, the

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[14] Passive controls will be in place after the end of the expected period of active control but, eventually, memory of the site could be lost.

PCSA [5, §7] discusses steps that are being taken at this generic stage, for example siting criteria, to build confidence that direct human intrusion into the GDF is very unlikely to occur. Safety arguments are presented to justify the length of time for which any inadvertent human intrusion event can be regarded as being extremely unlikely and are discussed in the context of the rate of decay of the disposal inventory.

Human intrusion needs to be considered carefully in the context of the overall safety of the GDF and its function of isolating the wastes from the human environment. It is important to maintain an overall focus on the end goal of effectively communicating the robustness of the GDF safety case and integrating evidence-based safety arguments to support a demonstration of regulatory compliance.

10.6 Criticality assessment

Radioactive wastes include substantial quantities of fissile radionuclides (mostly U-235 and Pu-239). As noted in Section 3.2.1, under certain conditions, fissile radionuclides can fission, which could result in nuclear criticality, releasing radiation and energy, and changing the radionuclide inventory. Controls on the packaging of wastes that include fissile material will ensure that nuclear criticality does not occur in the disposal facility while the waste packaging provides containment. The Criticality Safety Status Report [12, §3.3] discusses how controls, such as fissile material limits, are established for waste packages. However, in the long term after GDF closure, deterioration of the physical containment provided by the waste packages and relocation of fissile material could in principle result in a criticality event [12, §2.1]. The host rock and any cover rocks would provide radiation shielding from such a criticality event, but criticality could adversely affect the performance of the GDF by damaging its multi-barrier system. Therefore, it is important to consider the potential for criticality to occur in the GDF and the robustness of the GDF to a criticality event if it does occur.

RWM has undertaken substantial research to understand the likelihood [73] and potential consequences of post-closure criticality [74], which provides support for the view that post-closure criticality is not a significant concern; the results of this research are discussed in the Criticality Safety Status Report [12, §5-§6]. The research on post-closure criticality supports RWM's response to the regulatory requirements on criticality safety set out in the GRA [20, §6.4.27, §7.3.31]. The GRA identifies the need to demonstrate that the possibility of a local accumulation of fissile material, such as to produce a neutron chain reaction, is not a significant concern, and requires investigation, as a 'what-if' scenario, of the impact of a postulated criticality event on the performance of the disposal system.

As discussed in the Criticality Safety Status Report [12], RWM's research on the likelihood of post-closure criticality [73] has demonstrated that the likelihood of criticality is low because:

- all waste containers will be emplaced in the GDF in a sub-critical configuration; for example, fissile material in LHGW will be dispersed within waste packaging materials and emplaced in disposal vaults at concentrations well below those required for criticality
- the safety functions provided by the multiple engineered barrier system will minimise the potential for fissile material relocation (see Section 3.1); for example, the majority of LHGW is/will be encapsulated in cement and some LHGW disposal concepts are based on the inclusion of a cementitious backfill, the properties of which will hinder the movement of fissile material, and most HHGW, such as spent fuel and possible plutonium wasteforms, comprise stable matrices that will only release fissile material very slowly under disposal conditions

- Pu-239 is expected to be contained in waste packages for sufficient time that it will largely decay to U-235 before it can be mobilised; U-235 has a lower reactivity than Pu-239
- as waste packages degrade in the long term under expected conditions in the GDF, system reactivity is expected to reduce; for example, enriched uranium in LHGW vaults will gradually mix with the much greater quantities of depleted uranium present
- the formation of critical configurations involving spent fuel is not possible provided the irradiation of the fuel is above a certain modest amount
- for a GDF in an evaporite rock, conditions are expected to be sufficiently dry that the processes required to lead to waste package degradation and fissile material relocation will not occur; if the disposal vaults did become saturated with brine, the concentration of chlorine[15] in the brine would mean that there is little potential for fissile material accumulations to result in criticality

RWM's research into the consequences of post-closure criticality [12; 74] has demonstrated that, in the unlikely event that a critical mass of fissile material was to accumulate after GDF closure, the consequences would be low. This demonstration is based on consideration of the two types of criticality that could occur:

- Quasi-steady state criticality, in which negative feedback mechanisms coupled with the continuous arrival of fissile material in the affected region allow a steady-state to be reached in which a just-critical configuration is maintained
- Rapid transient criticality, in which positive feedback mechanisms lead to rapid increases in temperature and pressure, with high power output, until expansion of the affected region terminates the criticality.

The research on the consequences of hypothetical criticality showed that:

- the consequences of a quasi-steady state criticality in the GDF are highly localised (involving a small power output and temperature increase) and would not affect the surrounding host rock significantly
- rapid transient criticality could only occur for a narrow range of hypothetical conditions, generally involving Pu-239, and is considered not to be credible after about 100,000 years due to the decay of Pu-239; as noted above, wasteforms that contain potentially significant quantities of Pu-239 are expected to be stable and to contain the Pu-239 for such a period

Thus, the research on the likelihood and consequences of criticality has demonstrated that that post-closure criticality is not a significant concern.

In order to address the requirement to assess 'what-if' criticality scenarios, RWM has drawn on the findings of its research into the likelihood and consequences of criticality to further develop an understanding of how potential disruptions to the GDF's multi-barrier system caused by a criticality could affect the environmental safety of the GDF in terms of calculated radiological risk. The results of this research are presented in a post-closure criticality consequences assessment (PCCCA) [75] and are summarised in the PCSA [5, §8]. The potential impacts of criticality were assessed in terms of how the environmental safety functions provided by the engineered and natural barriers in the GDF could be affected and how, as a result, the calculated radiological risk could change for different exposure pathways (groundwater, gas and human intrusion).

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[15] Chlorine is an effective neutron absorber, which means that it has a high probability of capturing neutrons, reducing the potential for fission through interactions of fissile isotopes with neutrons.

Broadly, the PCCCA focused on the impacts of criticality in disposal facilities for LHGW and HHGW in higher strength rock and lower strength sedimentary rock [75]. As noted above, post-closure criticality is not considered to be credible for a GDF in an evaporite rock under expected conditions. The PCCCA concluded that:

- **For the groundwater pathway**, criticality would be localised, would result in only a small change to the radionuclide inventory, and would be inconsequential in terms of environmental safety. For example, in the analyses of LHGW and HHGW disposal facilities in higher strength rock, a criticality was assumed to result in localised effects on the rate of waste dissolution, uranium and plutonium sorption and solubility limitation, and the properties of backfill or buffer material. Assessment calculations in which such impacts were represented showed that the effects on calculated peak radiological risk were minor. For LHGW and HHGW disposal facilities in lower strength sedimentary rock, the calculated peak radiological risk via the groundwater pathway is primarily dependent on the containment safety function provided by the host rock. Therefore, disruption to the EBS and the host rock in a small region around a criticality event will have an insignificant effect on calculated radiological risk.
- **For the gas pathway**, increased temperatures associated with criticality could increase the rate of gas generation reactions, which could increase the rate of C-14 generation in the gas phase. However, the half-life of C-14 (5.73×10^3 years [47]) is short compared to credible timescales for post-closure criticality, and any radiological risk associated with C-14 is negligible after about 50,000 years. In the unlikely event that a criticality occurred before substantial decay of C-14, the potential for increased radiological risks as a result of enhanced waste dissolution rates, early container failure or release of carbon dioxide previously trapped by carbonation would be small because the region affected by the criticality would be small. In other words, the increase in the inventory of radioactive gases associated with a criticality would be negligible.
- **For the human intrusion pathway**, if human intrusion were to occur after a criticality event in the GDF, the additional activity resulting from the criticality event would be modest compared to the disposal inventory. Consequently, the radiological dose to potentially exposed groups at the time of intrusion would not be changed significantly.

Thus, RWM's analysis of what-if criticality scenarios has found that a hypothetical criticality event would not affect the environmental safety of the GDF and has provided further confidence that post-closure criticality is not a significant concern.

10.7 Radiological impacts on non-human biota

The GRA [20, § 6.3.64] requires that all aspects of the accessible environment (including non-human species and habitats) are adequately protected from the radiological effects of a disposal facility. RWM is supporting on-going collaborative studies aimed at developing understanding and assessing potential impacts of radioactivity on wildlife. However, requirements for the evaluation of potential radiological dose to wildlife are yet to be fully established at an international and national level, as discussed in the Biosphere Status Report [51, §5.4].

Although developments in approach are ongoing, RWM has undertaken a preliminary assessment of the potential radiological impacts of the GDF on wildlife using the ERICA tool (developed as part of the EC Project on 'Environmental Risk from Ionising Contaminants: Assessment and Management') [76]. The results of this preliminary assessment indicate that there is likely to be a low risk to wildlife associated with releases of radionuclides from the GDF [51, §5.4].

10.8 Non-radiological contaminant assessment

In addition to the potential radiological impacts, it is important to consider the assessment of non-radiological species in the GDF. Some of the wastes, their packaging materials (including those used in the conditioning of the waste) and materials used in the construction of the GDF may be potentially harmful to humans and to the wider environment, including non-human biota.

As discussed in the Technical Background [3, §2], all existing waste and known future waste arisings are detailed in the UKRWI [69]. In order to support the implementation of geological disposal, RWM has developed a derived inventory. As discussed in Section 10.1, the 2013 Derived Inventory [7] contains quantitative data for the higher activity wastes from the 2013 UKRWI destined for the GDF and for the other wastes and materials defined in the inventory for disposal in the 2014 White Paper [2]. The derived inventory includes information on some of the non-radiological species associated with the wastes.

The GRA [20, §6.4.1] contains a high level requirement (R10) on protection against non-radiological hazards and indicates that:

> *"The developer/operator of a disposal facility for solid radioactive waste should demonstrate that the disposal system provides adequate protection against non-radiological hazards."*

The GRA [20, §4.5.1] states:

> *"…solid radioactive waste shall be disposed of in such a way that the level of protection provided to people and the environment against any non-radiological hazards of the waste both at the time of disposal and in the future is consistent with that provided by the national standard at the time of disposal for wastes that present a non-radiological hazard but not a radiological hazard."*

The GRA also states that [20, §6.4.3]:

> *"The environmental safety case will need to demonstrate that a suitable level of protection is provided against non-radiological hazards."*

The assessment of non-radiological contaminants is not new to RWM; in the 2010 generic DSSC, the Biosphere Status Report documented work on this topic [77]. Previously RWM referred to this topic as the 'assessment of chemotoxic substances'. This work focused on the assessment of chemically toxic substances and their impact to humans, predominantly through analysis of their release from the disposal facility and their transport in groundwater (with some consideration to the developing area of impact to non-human biota [77, §5.6]). RWM has documented its latest understanding on the chemically toxic impacts to humans in the update to the Biosphere Status Report [51].

Since the work reported in the 2010 generic DSSC, there has been a change in the regulatory framework, with the publication of the Groundwater Daughter Directive, which is discussed below in Section 10.8.1. This has increased the scope of RWM's work in this area, which has been renamed 'non-radiological contaminant assessment', as a wider range of receptors (or endpoints) and pathways than just chemically toxic impacts to humans is now considered.

10.8.1 Non-radiological contaminants in groundwater

The updated Disposal System Specification [11, §3.4] notes the changes in the groundwater regulations as described in the Environmental Permitting (England and Wales) Regulations 2010 (EPR 2010) [18]:

> *"In accordance with the groundwater protection provisions of the Environmental Permitting (England and Wales) Regulations 2010, it shall be demonstrated that all necessary technical precautions will be observed to:*
>
> - *prevent the input of hazardous substances to groundwater; and*
> - *limit the input of non-hazardous pollutants to groundwater so as to ensure that such inputs do not cause pollution of groundwater."*

Following adoption of the Groundwater Daughter Directive (GWDD) into UK legislation, the Environment Agency issued supplementary guidance [78] (to be read alongside the GRA [20]) explaining how a developer could meet requirement R10 of the GRA and meet the requirements of EPR 2010. Box 1 contains some definitions of key terms used in the description of the GWDD.

The manner in which these requirements are addressed for a specific site will need to take account of RWM's understanding of the characteristics of the site and, in particular, the characteristics of any groundwaters at depth.

Box 1. Key terms associated with the GWDD

Hazardous substances

Hazardous substances can be defined as substances or groups of substances that are toxic, persistent and liable to bio-accumulate, and other substances or groups of substances that give rise to an equivalent level of concern [18]. The UK environment agencies' Joint Agencies Groundwater Directive Advisory Group (JAGDAG) has confirmed that radioactive substances should also be considered as hazardous. JAGDAG has produced a list of hazardous substances on its website [79].

Non-hazardous pollutants

EPR 2010 [18] defines non-hazardous pollutants as *'any substance liable to cause pollution'* and pollution as *'the direct or indirect introduction, as a result of human activity, of substances or heat into the air, water or land which may:*

- *be harmful to human health or the quality of aquatic ecosystems or terrestrial ecosystems directly depending on aquatic ecosystems,*
- *result in damage to material property, or*
- *impair or interfere with amenities or other legitimate uses of the environment;'*

Groundwater

Groundwater is defined as '*all water which is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil*' [18].

Saturated Zone

The saturated zone is the '*zone in which the voids of the rock or soil are filled with water at a pressure greater than atmospheric; the water table is the top of the saturated zone in an unconfined groundwater system.*' [18].

Groundwater Body

A groundwater body is *'a distinct volume of groundwater within an aquifer or aquifers'* [18].

Hazardous substances

A hazardous substance is any pollutant identified as such by the UK environment agencies' JAGDAG [79]. The list of hazardous substances is not fixed and will change over time as JAGDAG's knowledge of the properties and effects of such pollutants improves. The UK

Government considers that, due to their nature, radioactive substances are hazardous substances within the meaning of the Water Framework Directive and GWDD [80]. The current list contains more than 250 substances including hydrocarbons, organohalogens, organophosphorus compounds, mercury (and its compounds) and cadmium.

In the same way that RWM does not require information on all known radionuclides (only those that are important in terms of safety) [81] in order to demonstrate that the GDF can be safely implemented, RWM will not require information for all defined non-radioactive hazardous substances. RWM is currently developing an approach to identifying the most important hazardous substances from a geological disposal perspective. An initial study has been undertaken to identify which hazardous substances are likely to be present in the inventory for disposal [82]; this is reported in more detail in the generic PCSA [5].

The legislative requirement adopted in the Disposal System Specification for this generic DSSC is:

> *"…it shall be demonstrated that all necessary technical precautions will be observed to prevent the input of hazardous substances to groundwater."* [11]

Defra guidance [80, §3.5] is clear that water in the unsaturated zone is not groundwater. Defra has stated that it will be a technical decision for the Environment Agency to determine what is considered as groundwater in specific circumstances for the purposes of the regulations (EPR 2010). The Defra guidance states [80, §3.5]:

> *"For example, in very low permeability strata such as clays, evaporites and dense crystalline rocks it may not be possible to define a zone of saturation because the water is bound to the rock or is relatively immobile."*

The saturated zone is defined as the zone in which the voids of the rock or soil are filled with water at a pressure greater than atmospheric; the water table is the top of the saturated zone in an unconfined groundwater system [18]. It is clear that the definition and identification of groundwater is a highly site-specific issue.

The requirement from EPR 2010 [18] concerning hazardous substances is that their input to groundwater should be prevented. The Defra permitting guidance [80, §4.18] considers that *"input of hazardous substance to groundwater would be prevented, for example, if:*

- there is no discernible concentration of a hazardous substance in the discharge …; or
- there are no discernible concentrations of hazardous substances attributable to the discharge in groundwater immediately down-gradient of the discharge zone … ; or
- there are (or are predicted to be) discernible concentrations of hazardous substances in the groundwater down-gradient of the discharge zone attributable to the discharge but all the following conditions apply:
    a) *concentrations will not result in any actual pollution or a significant risk of pollution in the future; and*
    b) *there is no progressive increase in the concentration of hazardous substances outside the immediate discharge zone, ie there will be no statistically and environmentally significant and sustained upward trend or significant increasing frequency in pollutant 'spikes'; and*
    c) *all necessary and reasonable measures to avoid the entry of hazardous substances into groundwater have been taken…."*

RWM is engaging with relevant stakeholders, including the environment agencies, to develop an agreed approach to non-radiological contaminant assessment in line with the GWDD. The generic PCSA [5, §9] includes a discussion of current research on approaches to addressing the impacts of hazardous substances in the GDF.

Non-hazardous pollutants

For non-hazardous pollutants (as defined in Box 1), the legislative requirement (which is adopted in the Disposal System Specification [11]) is:

> *"It shall be demonstrated that all necessary technical precautions will be observed to limit the input of non-hazardous pollutants to groundwater so as to ensure that such inputs do not cause pollution of groundwater."*

Article 6 of the GWDD [19] considers a groundwater pollutant to be a substance causing one or more of the following:

- harm to human health or the quality of aquatic ecosystems or terrestrial ecosystems directly depending on aquatic ecosystems
- damage to material property (for example crops, livestock, building foundations, subsurface utilities)
- the impairment or interference with amenities or other legitimate uses of the environment
- deterioration (in status of a groundwater body) or significant and sustained upward trends in the concentration of pollutants in a groundwater body.

In this context a 'groundwater body' is a unit for the management of groundwater resources that are either exploited by man or support surface ecosystems (UKTAG[16]) and, as Box 1 explains, groundwater may exist both within and outside a groundwater body.

UKTAG has advised on standards for non-hazardous pollutants in groundwater that is, or could feasibly be, abstracted for drinking, namely the 'drinking water standard' (DWS). UKTAG has also advised on 'environmental quality standards' (EQS) to protect surface waters and terrestrial ecosystems that are directly dependent on the quality of groundwaters.

Impacts on Humans

The impacts of non-radiological species that could potentially be released from the GDF have been examined in various screening studies (for example [83; 84]). This work identified beryllium, cadmium, chromium, lead and uranium[17] as priorities for human health risk assessment based on their presence in the radioactive waste inventory, toxicological properties and previous work.

For beryllium, cadmium, chromium, lead and uranium, human health risk assessments were undertaken for three different calculation cases, with each successive case including a smaller degree of conservatism [85]. The outputs from this study are reported in the Biosphere Status Report [51, §5.3.2].

Uranium is an example of an element identified as being of both radiotoxic and chemotoxic significance. For this reason, RWM has undertaken a detailed review of the relative importance of its radiotoxic and chemotoxic properties, giving consideration to both the ingestion and inhalation of different physical and chemical forms of the element, the degree of enrichment or depletion, and the extent of ingrowth of radioactive daughters. This study has shown that either radiotoxicity or chemotoxicity may be the dominant consideration, depending on details of the exposure regime [86].

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[16] UKTAG (United Kingdom Technical Advisory Group) is a partnership of the UK environment and conservation agencies which was set up by the UK-wide WFD policy group consisting of UK Government administrations. It was created to provide coordinated advice on the science and technical aspects of the European Union's Water Framework Directive (2000/60/EC).

[17] The UKRWI already collects information on beryllium, lead and uranium, and the 2016 UKRWI will ask waste producers for information on cadmium and chromium in the wastes.

Impacts on non-human biota

At this stage in the siting process, RWM is focusing non-radiological assessment work on human receptors and impacts on groundwater. However, impacts on non-human biota will be considered in more detail as RWM develops understanding of non-radiological assessment as part of its future work programme.

Impacts on groundwater

The generic PCSA [5] provides a qualitative assessment of the base scenario and some consideration of variant scenarios for each illustrative disposal concept in terms of the behaviour of non-radiological substances released into groundwater. At the current stage in the siting programme for the GDF, RWM has focused on hazardous substances, with consideration of non-hazardous pollutants being addressed in its ongoing work programme [13, Tasks 051, 052 and 053].

10.8.2 Non-radiological contaminants in gas

At this stage in the siting process, RWM is focusing non-radiological assessment work on human receptors and impacts on groundwater. Consideration has primarily been given to transport of non-radiological species in groundwater. RWM has undertaken work in the area of non-radiological gases (as discussed in [63; 53]) but no consideration of impacts on humans or non-human biota has been undertaken at this stage. However, as part of RWM's future work programme in this area, a more detailed consideration will be given to the potential impacts from any non-radiological gases that may arise from the geological disposal of higher activity wastes.

10.9 Assessment of alternative inventory scenarios

Section 10.1 described how uncertainties in the radioactive waste disposal inventory have been explored by identifying twelve alternative scenarios for radioactive waste arisings. This sub-section considers the sensitivity of the environmental safety of geological disposal to these alternative inventory scenarios.

The inventory scenarios may be grouped into one or more of the following categories in terms of how they may affect the GDF:

- those that increase or decrease the waste volume within one or more waste groups
- those that involve changes in the characteristics of a wasteform (such as its physical or chemical properties)
- those that increase or decrease activity within one or more waste groups

The effects of these changes on the post-closure performance of the GDF will depend on the performance of the multi-barrier system and its robustness to such changes. For example, an increase in the amount of high heat generating wastes could result in local increases in temperature, which could enhance the rate of processes such as corrosion and dissolution in the affected area. However, controls on the design and layout of the GDF will ensure that such effects are tolerable, although this is likely to require an increased GDF footprint.

Changes to the radionuclide inventory are likely to be the most significant in terms of effects on the environmental safety of the GDF. In particular, inventory changes that increase the quantity of long-lived radionuclides that are highly soluble, weakly-sorbing and are already key contributors to calculated radiological risk (such as I-129 and Cl-36) are likely to be most significant to post-closure safety on timescales of hundreds of thousands of years. On longer timescales, changes in the inventory of long-lived but less mobile actinides could be important. However, for an inventory scenario in which there is an increase in the activity content of a radionuclide that is solubility limited when leached from a degrading waste package, the period over which the radionuclide is released from the waste package may be prolonged, but the calculated peak radiological risk from the radionuclide would not be affected.

The following sub-sections discuss the potential effects of each alternative inventory scenario on the post-closure performance of the GDF.

Scenario 1: More reprocessing of oxide fuel

The 2013 Derived Inventory assumes that all Sizewell B spent fuel, some AGR spent fuel and all spent fuel from new build reactors will not be reprocessed, therefore disposal of this spent fuel has been included in the ESC analysis. However, under Scenario 1, some of this oxide fuel is assumed to be reprocessed, resulting in an increased inventory of operational ILW, HLW, low-enriched uranium and plutonium [10, §3.1].

Increased reprocessing of oxide fuels would have little effect on the inventories of most radionuclides [10, §3.1]. However, the activities of volatile species such as I-129, C-14 and H-3 in the disposal inventory may be reduced, because some of this inventory will be discharged during reprocessing. Also, the incorporation of fission products, such as I-129, in robust HLW glass for disposal would have the important benefit of reducing the long-term post-closure risk from the release of such radionuclides from degraded spent fuel containers as part of a spent fuel instant release fraction. However, some of the instant release fraction (fission products and activation products) would be included in ILW, which would increase the potential risk from ILW disposal.

The effect of the Scenario 1 strategy on the total disposal inventory would depend on whether the uranium and plutonium from reprocessing was re-used (for example as MOX fuel) or disposed of directly – the quantity of plutonium, uranium and spent fuel requiring disposal has not been conjectured for this scenario.

Scenario 2: Less reprocessing of Magnox fuel

The 2013 Derived Inventory assumes that most Magnox spent fuel is reprocessed. Under Scenario 2, less Magnox fuel is reprocessed. As a result, the quantity of depleted uranium, HLW, operational ILW and MOX spent fuel would reduce, while the quantity of metallic spent fuel requiring disposal would increase substantially. The quantity of MOX spent fuel would reduce because there would be less plutonium available for its manufacture. According to the Alternative Inventory Scenarios Report [10, §3.2], the change to the total inventory volume and activity would be small; there would be small increases in the total activities of I-129 and C-14 as a result of reduced reprocessing.

The potential risk from the disposal of legacy metallic spent fuel would increase, especially as a result of the increased activity of I-129 in metallic spent fuel wastes, which would otherwise be immobilised in HLW. However, a reduction in I-129 and C-14 in operational ILW may have significant benefits for some disposal concepts (see for example Figure 31, which shows the calculated risk for the illustrative example of UILW/ULLW disposal in higher strength rock). Hydrogen gas generation will occur as a result of fuel corrosion after container failure and water ingress. Conceivably, gas pressures could be high enough to cause some disruption to low-permeability engineered and natural barriers, although such effects may be mitigated by limited water availability for corrosion reactions in some cases. For the illustrative disposal concepts for HHGW disposal in higher strength rock (see Section 4.4.4) and lower strength sedimentary rock (see Section 6.4.4), if the gas pressure becomes sufficiently large that dilatant pathways occur in the bentonite buffer around the breached disposal container, then gas will migrate along these pathways, but the pathways will close when the gas pressure falls. Similarly, micro-fissures could be generated in a lower strength sedimentary host rock if gas pressures become large enough, creating pathways for radionuclide transport, although such micro-fissures are likely to close and eventually seal after the gas pressure has reduced.

Scenario 3: Lifetime extensions for existing reactors

In Scenario 3, the operational lifetimes of AGRs and the Sizewell B PWR are assumed to be increased, resulting in an increase in ILW and spent fuel volumes and activities [10, §3.3]. However, these activity increases are minor with regard to their effects on calculated risk for the illustrative analysis presented in Section 10.3. For example, the activities of I-129 and Cl-36 in UILW/ULLW, SILW/SLLW and legacy spent fuel increase by a factor of less than two, which is not significant with regard to the post-closure safety assessment.

Scenario 4: Recognising UKRWI uncertainty

Scenario 4 considers estimates of uncertainties in the volumes and activities of the HLW, UILW/ULLW, SILW/SLLW and RSC waste groups (uncertainty factors are only available for these waste groups). The uncertainty in the activities of some key isotopes is large. For example, it is estimated that the activities of I-129 and Cl-36 in UILW/ULLW could be respectively five and ten times the activities assumed for UILW/ULLW in the 2013 Derived Inventory [10, §3.4]. These radionuclides are key contributors to calculated risk in the illustrative examples considered in Section 10.3. However, even if such upper inventories were to be realised, the illustrative calculations of risk via the marine pathway for the UILW/ULLW higher strength rock disposal concept and via the terrestrial pathway for the UILW/ULLW lower strength sedimentary rock disposal concept, as discussed in Section 10.3,would remain substantially below the risk guidance level. If a well pathway is assumed to be present, then, depending on assumptions made about radionuclide retention in the host rock and aquifer and the properties of the well, the calculated mean radiological risk could exceed the regulatory risk guidance level.

Scenario 5: Plutonium not disposed of as MOX

The 2013 Derived Inventory assumes that the majority of the UK's plutonium will be re-used in the form of MOX fuel. Any plutonium that could not be converted to MOX would be immobilised and treated as waste for disposal. The direct disposal of plutonium as a ceramic wasteform rather than its re-use as MOX fuel [10, §3.5] is likely to reduce overall estimated post-closure risks. Estimated risks would be reduced because the assumed ceramic immobilisation matrix for plutonium is robust and highly leach resistant and there would be less fission and activation product activity in the disposal facility (see for example the discussion of calculated risks from MOX spent fuel disposal and plutonium ceramic waste disposal in Section 10.3.1).

Scenario 6: Geological disposal of some LLW from the LLWR

Scenario 6 assumes that some LLW from the LLWR in Cumbria (that is, LLW known to contain high concentrations of thorium and uranium) would be retrieved and disposed of in the GDF. However, such retrieval is not anticipated and has not been considered in any detail in the Alternative Inventory Scenarios Report [10, §3.6], although the nature of the LLW is such that the change in total activity would be relatively small.

Scenario 7: Changed depleted, natural and low enriched uranium inventory

As discussed in the Alternative Inventory Scenarios Report [10, §3.7], DU tails that arise from enrichment activities are the dominant component of the DNLEU inventory. Other contributors to the DNLEU inventory include uranium from the reprocessing of spent Magnox and oxide fuels.

The quantity of DNLEU in the inventory for disposal would change if, for example, the assumptions regarding the enrichment of uranium or the operational lifetime of the reprocessing plants changed. Most DNLEU from reprocessing has already arisen and, as a result, it is not anticipated that the quantity of DNLEU associated with these streams will change significantly. Also, it is not anticipated that there will be any further arisings from other DNLEU streams (miscellaneous DNLEU and DU from defence enrichment). However, the NDA is assessing high level credible options for the management of the uranics and so there is some uncertainty in the quantity of DNLEU that will eventually require disposal.

The most significant contributors to calculated risk from DNLEU disposal are U-234 and U-238, which are long-lived uranium isotopes (see Section 10.3.2). Key factors in the calculation of risk from these isotopes once leached from degraded waste packages are the extent to which uranium migration is assumed to be retarded by sorption in the geological environment and the assumed magnitude and direction of groundwater movement (and associated uranium dilution and dispersion). Although it is not possible to quantify the effects of DNLEU inventory uncertainty on calculated risk at this generic stage of GDF development, inventory uncertainties are likely to be less significant than uncertainties in uranium migration behaviour.

Scenario 8: Change in new build programme

The 2013 Derived Inventory assumes a UK nuclear new build programme comprising six European Pressurised Reactors (EPRs) and six Westinghouse Advanced Passive Pressurised Water Reactors (AP1000s), but plans for new reactors are progressing differently, including the potential use of Advanced Boiling Water Reactors (ABWRs) [10, §3.8]. The ESC analysis is based on the 2013 Derived Inventory assumptions about new build reactors and a spent fuel inventory associated with a fuel burn-up of 65 GWd/tU has been assumed for each fuel type. The total estimated post-closure risk following radionuclide release from a nuclear new build spent fuel waste package, based on the illustrative example of disposal in higher strength rock, is many orders of magnitude lower than the risk guidance level (see Figure 25). Therefore, this analysis suggests that any variations from the assumed programme are unlikely to be significant in terms of their effects on environmental safety.

Scenario 9: Foreign waste and materials included

Scenario 9 is concerned with situations in which there is permission for the disposal of small quantities of foreign wastes and materials in the UK GDF where other options are less practicable. For example, the import of sealed sources manufactured in the UK or wastes from small users (for example medical users) in another EU or developing country for disposal in the UK may be allowed. There are substantial uncertainties relating to this scenario, although the impact of its realisation on the inventory for disposal is anticipated to be small. The scenario has not been investigated in any detail [10, §3.9].

Scenario 10: Alternative packaging assumptions

The Alternative Inventory Scenarios Report [10, §3.10] discusses a number of options for packaging wastes that are different to those assumed in the ESC, including thermal treatment of ILW, increased use of robust shielded containers, the use of multi-purpose containers and polymer encapsulation. Thermal treatments have the potential to reduce the organic content and voidage in ILW packages, which reduces the potential for such FEPs to have detrimental impacts on the environmental safety functions provided by the EBS. The greater use of robust shielded containers, for example, for geological disposal of wastes currently planned for disposal at the LLWR, would increase the waste volume, the number of waste packages and the mass of lead in the GDF; the latter would increase the GDF’s non-radiological hazard. The use of alternative containers and waste encapsulation/immobilisation options would not affect the disposal inventory, but any significant differences in the environmental safety functions compared to those currently assumed in the ESC would require consideration.

Scenario 11: Graphite wastes not disposed of in the GDF

This scenario assumes that graphite wastes, which are currently anticipated for disposal in the GDF, are disposed of via an alternative route. This would result in a significant reduction in the SILW/SLLW inventory and a small reduction in the UILW/ULLW inventory. Most importantly, the C-14 inventory would reduce by about 40% (graphite is a major source of C-14 bearing gases) and the Cl-36 inventory would reduce by about 25% (Cl-36 is a key contributor to calculated risk via the groundwater pathway in the illustrative calculations, as indicated in Figure 31) [10, §3.11].

Scenario 12: Remove ILW that is intended to be disposed of as LLW

In Scenario 12 it is assumed that a number of waste streams that are currently classed as ILW, and intended for disposal in the GDF, could be disposed of as LLW in the LLWR following treatment or decay storage. As a result, the volume and total activity of waste requiring geological disposal would reduce, but the changes would be minor, resulting in small reductions in the number of robust shielded containers and UILW/LLW and SILW/SLLW packages [10, §3.12].

10.10 Conclusions of the post-closure safety evaluation

The assessment and analysis presented in this section have aimed to demonstrate how various lines of argument will be constructed to demonstrate that geological disposal of the UK's higher activity radioactive wastes will meet environmental safety requirements as set out in the GRA [20] and RWM's Disposal System Specification [11], when a GDF site is available. The illustrative disposal concepts considered in this assessment are based on safety concepts that meet the requirements of the Disposal System Specification [11], as discussed in Section 3.1. Findings are summarised below.

10.10.1 Assessment of radionuclides in groundwater

The quantitative assessments have focused on evaluation of the behaviour of radionuclides released from degrading waste packages in groundwater in the long term after disposal. In particular, the environmental safety functions provided by the different components of the multi-barrier system have been evaluated in terms of how they contain radionuclides and thus support achievement of the environmental safety states discussed in Section 2.4.4. At this generic stage of GDF development, the assessments can only be considered as illustrations of the post-closure performance of a disposal facility, and are inevitably based on many assumptions about disposal concepts and how conditions in the disposal facility will evolve in the long term after closure. In particular, key assumptions have been made about:

- the engineered barrier systems of illustrative concepts for HHGW and LHGW disposal in different geological environments and the radionuclide containment functions that they provide
- the hydrogeological and hydrogeochemical characteristics of the geological environments, particularly with respect to how radionuclides diffuse or are advected and dispersed along prescribed transport pathways from the assumed location of the GDF to the accessible environment, and the radionuclide retention properties of the rocks along the transport paths
- the ways in which humans could be exposed to radioactivity following radionuclide migration from the GDF to the biosphere

Based on consideration of how conditions will evolve over a 300,000 year post-closure period, key environmental safety arguments and findings for each illustrative disposal concept with regard to the release of radionuclides into groundwater are as follows:

- **HHGW disposal in higher strength rock**

  The copper container assumed in this concept is expected to provide complete radionuclide containment during the assessment period. If there is early loss of the containment function provided by the container, then the stability of the wasteform limits radionuclide releases into groundwater, although there is an instant release fraction of radionuclides associated with spent fuel that is mobilised after container breach.

  The key radionuclides with regard to calculated radiological risk associated with HHGW disposal on the assessment timescale are I-129 and Cl-36. These radionuclides have long half-lives and they are not retarded significantly as they diffuse and are advected along the transport pathways. However, the calculated mean risk via an assumed marine pathway following radionuclide release from a single breached HHGW container is very low, being less than 10^{-12}/year in the assessment period. Even if a PEG is assumed to use water extracted from an aquifer contaminated by radionuclides from the waste package, the calculated mean risk will be low (much lower than the risk guidance level), although this depends on assumptions about the well's location and use, and the groundwater flow rate in the aquifer (which affects the extent to which the contaminated water is diluted).

  On the basis of the assessment calculations, the illustrative concept is robust to the unexpected early failure of several thousand HHGW packages, but it will be important to demonstrate confidence in the long-term containment function provided by the container.

  On much longer timescales than considered in the assessment, radiological risk may become dominated by actinides and their daughters (for example, Ra-226) as they migrate to the accessible environment, but this will depend on the extent to which these radionuclides are retarded in the host rock and cover rocks by processes such as diffusion from hydraulically conductive fractures into the rock matrix and associated sorption on the rock surfaces (described conceptually as rock matrix diffusion).

- **LHGW disposal in higher strength rock**

  The period of containment of LHGW in its package after GDF closure may be no more than hundreds to thousands of years. However, the high pH conditions induced by the cementitious backfill assumed in this illustrative concept will ensure that the solubility of many radionuclides is low and that they are released only slowly from the wasteform into groundwater.

  Key radionuclides with regard to calculated radiological risk associated with LHGW disposal on the assessment timescale are Cl-36 and I-129. If rock matrix diffusion in the host rock is excluded, risks from radionuclides such as Ra-226 and U-233 gradually become significant. However, the calculated mean risk via an assumed marine pathway for each type of LHGW is very low; for example the mean risk associated with UILW/ULLW disposal is less than 10^{-9}/year. The calculated mean risk is greater if exposure occurs via a well pathway; for the assumed aquifer flow rate and well location and use, the calculated radiological risk (primarily from I-129 and Cl-36) is consistent with, or lower than, the risk guidance level depending on the type of LHGW being considered. Therefore, based on these simple illustrative calculations and associated assumptions, the LHGW disposal concept satisfies environmental safety requirements associated with the release of radionuclides in groundwater and potential exposure to humans.

- **HHGW disposal in lower strength sedimentary rock**

  The period of containment provided by the carbon steel containers assumed in this disposal concept is expected to be much shorter (of the order tens of thousands of years) than that provided by the copper containers in the higher strength rock disposal concept for HHGW. However, again, the stability of the wasteform will limit radionuclide releases into groundwater after container breach, except for the instant release fraction of radionuclides associated with spent fuel.

  The 50-metre-thick host rock above the GDF has an important role in retarding the transport of radionuclides after container breach in this illustrative disposal concept. Only the most mobile and long-lived radionuclides diffuse through to the cover rocks on a timescale of 300,000 years, with I-129 and Cl-36 dominating contributions to the radionuclide activity flux for spent fuel wasteforms.

  In the illustrative example, the radionuclide travel time through to the biosphere is long. The calculated mean risk via both the terrestrial pathway and the well pathway on a timescale of 300,000 years is substantially less than 10^{-12}/year for each type of HHGW. In this respect, post-closure environmental safety requirements are met by this illustrative disposal concept for HHGW.

- **LHGW disposal in lower strength sedimentary rock**

  As in the illustrative concept for LHGW in higher strength rock, the period of containment provided by the waste package is relatively short, but high pH conditions induced by the cementitious backfill will ensure that the solubility of many radionuclides is low. However, in this illustrative disposal concept, radionuclide transport through the engineered barrier system and host rock is by slow diffusion rather than more rapid advection. Only the most mobile and long-lived radionuclides diffuse through to the cover rocks on a timescale of 300,000 years.

  The calculated mean risk via the terrestrial and well pathways on a timescale of 300,000 years is substantially less than 10^{-12}/year. Again, post-closure environmental safety requirements are met by this illustrative disposal concept for LHGW.

- **HHGW disposal in evaporite rock**

  The host rock provides the main environmental safety function with regard to radionuclide containment for the concept for the disposal of HHGW in evaporite. Evaporites are generally dry and, as such, there is little potential for radionuclides to become mobilised in groundwater under expected conditions, even if the waste containers are breached after disposal. Also, rock creep will encapsulate the wastes after disposal, closing any potential transport pathways in the disposal system.

  However, the environmental safety functions provided by the tunnel and shaft seal system are key to the safety of this disposal concept. The barrier function of the host rock could be by-passed if the shaft seals do not fulfil their environmental safety functions and pathways for groundwater flow and radionuclide transport develop through them. The potential for and consequences of such scenarios would require assessment in a site-specific ESC.

- **LHGW disposal in evaporite rock**

  The safety arguments for LHGW disposal in evaporite are similar to those for HHGW disposal. Again, there is little potential for the transport of radionuclides in groundwater under expected disposal conditions, but the environmental safety functions provided by the tunnel and shaft seal system are key to the safety of the disposal concept.

Uncertainties in the radioactive waste disposal inventory have been explored qualitatively, based on consideration of alternative scenarios for radioactive waste arisings. The assessment conclusions are not particularly sensitive to the inventory scenarios, except when considering the scenario involving an upper inventory, but only for calculations in which a well pathway is assumed to be present and the calculated mean risk could exceed the risk guidance level [20].

In summary, this generic ESC has documented how total system models of radionuclide behaviour in a disposal system have been developed and can be applied to support demonstrations of the environmental safety of geological disposal in the context of GRA requirements relating to radiological risk and arguments relating to the containment of radionuclides in the engineered and geological barriers of a multi-barrier disposal system.

The risk assessment has demonstrated consistency with the risk guidance level as required by the GRA [20] and has highlighted the model components that dominate risk and parameters to which risk is sensitive. In some cases, where a well exposure pathway has been assumed to be present and cautious assumptions are made about radionuclide transport through the host rock, the calculated mean risk is slightly above the risk guidance level. However, the risk guidance level is cautiously low [20, § 6.3.19] and is intended to indicate the standard of environmental safety that is being sought [20, § 6.3.11]. There is not an absolute requirement for the risk guidance level to be met [20, § 6.3.11]. For a real site, the environmental regulators will make judgments about whether the demonstrated degree of consistency with risk guidance level is sufficient [20, § 6.3.32], taking account of the uncertainties that have been included in the risk assessment. RWM considers that the approach taken and risk assessment results presented in this generic ESC illustrate how a sufficient degree of consistency with the risk guidance level can be demonstrated (even if the risk guidance level is exceeded for some scenarios) based on a cautious treatment of uncertainties. The results of the assessment also enable future research to focus on addressing key uncertainties. Further, for a real site, the process of disposal concept optimisation will aim to ensure that wastes are disposed of in a way that ensures risks are ALARA, consistent with the requirements of the GRA [20, § 4.4.1].

The probabilistic calculations have focused on an assessment period of 300,000 years after GDF closure, which is considered to be sufficient to give an indication of the barriers that are likely to be of most importance to GDF performance on the timescales over which some large-scale natural processes could occur. In future site-specific ESCs, calculations will be included to evaluate the impacts of natural processes on the safety functions provided by key barriers, based on specific descriptions of possible long-term environmental conditions. That is, assessments of GDF performance over timescales in excess of a few hundred thousand years will be based on stylised deterministic calculations involving different assumptions about how natural processes, such as tectonism (including earthquakes), subsidence, uplift and erosion, permafrost development and periods of glaciation could affect conditions in the biosphere and geological environment. Such assessments will build on RWM's initial research to consider the effects of natural transient processes on groundwater flow and radionuclide transport [54].

Also, a site-specific ESC will include a more comprehensive assessment of variant scenarios of system evolution than considered here. The assessment of variant scenarios in this generic ESC has focused on scenarios relating to the environmental safety functions provided by the waste packages. A site-specific ESC will include identification and assessment of variant scenarios relating to the performance of the full system of engineered and geological barrier components, based on suitable data on facility design and site characteristics, which will be assessed as 'what-if' scenarios. In addition, a site-specific ESC will include a more detailed and formal analysis of the sensitivity of environmental safety arguments to important parameters relating to the evaluation of risk.

RWM is undertaking research to develop methodologies for assessing such scenarios and undertaking sensitivity analysis. For example, methodologies for addressing variant scenarios involving shaft seal failure in disposal concepts in evaporite rocks and its impacts on environmental safety are being considered. Also, gas generation associated with waste degradation reactions in some waste packages could result in the development of high pressures that could disrupt an engineered and natural barrier system through induced fracturing and could affect the movement of radionuclides in groundwater. As discussed in Section 10.9, under alternative inventory Scenario 2, direct disposal of Magnox spent fuel could result in significant hydrogen generation as a result of fuel corrosion after container breach and water ingress, which could affect the barrier system. Variant scenarios involving radionuclide transport in a period of high gas pressure and increased host rock permeability as a result of pressure-induced fracturing will be considered for disposal concepts in lower strength sedimentary rock and may also be relevant to disposal concepts in evaporite under circumstances where brine enters the disposal facility.

To some extent, the generic ESC has considered the effects of potential operational phase faults on post-closure behaviour. For example, the effects of errors in bentonite buffer emplacement have been considered in the assessment of the concept for HHGW disposal in higher strength rock. However, future work will involve assessment of the range of potential operational phase faults [26] for different disposal concepts to determine if they could impact post-closure performance.

10.10.2 Assessment of radionuclides in gas

The assessment of the impacts of radionuclides released from degrading waste packages in the gas phase has focused on the consideration of gas generation and migration processes for the illustrative concepts for HHGW and LHGW disposal in different geological environments. The main radioactive gas requiring consideration in a GDF post-closure safety assessment is C-14. Any carbon dioxide (and the C-14 it contains) is likely to react with cementitious materials if present in the barrier system and, thus, will not be released into the host rock as a free gas. If long-lived radionuclides in the uranium series migrate to and accumulate in the near-surface environment, then Rn-222 ingrowth may also be significant in terms of potential radiological risk, depending on exposure pathways. The generation of radioactive gases is less of a concern for HHGW, although small amounts of radioactive gases may be generated from defective or degrading spent fuel pins after container breach.

As the gas phase migrates through the geological environment, it will come into contact with groundwater and some or all of the gas will dissolve into the groundwater. Gas transfer through the geological environment of a disposal facility will be specific to the characteristics of the disposal site and the design of the GDF. Calculations of the radiological risk arising from any C-14 in methane that reaches the biosphere depend on assumptions made about the area over which the gas is released and potential human exposure pathways. Such issues have been considered as part of RWM's research into C-14 behaviour [15; 16] and calculations of radiological risk have shown that the risk guidance level is not exceeded provided the proportion of C-14 released from reactive metals is limited and any gas that does migrate to the biosphere is released over an area roughly equivalent to the GDF footprint or larger. The methodology developed as part of RWM's research into C-14 behaviour has enhanced RWM's knowledge base on gas generation and its impacts, which will support the waste packaging assessment process.

10.10.3 Assessment of human intrusion

The discussion of human intrusion in this generic ESC has focused on RWM's involvement in work to identify measures to reduce the likelihood and consequences of inadvertent human intrusion into a GDF, as part of the overall GDF optimisation process. Stylised human intrusion calculations have not been undertaken, because they would not be relevant to any GDF optimisation considerations. The GRA requirement to evaluate the potential consequences of human intrusion will be addressed in a site-specific ESC when relevant site characterisation data are available.

10.10.4 Assessment of post-closure criticality

RWM's research on the likelihood and consequences of criticality has demonstrated that that post-closure criticality following the geological disposal of HHGW and LHGW is not a significant concern. This includes analysis of what-if criticality scenarios that has found that a hypothetical criticality event would not affect the environmental safety of the GDF. Therefore, RWM's work on criticality safety reported in this generic ESC gives confidence that the GRA requirements relating to criticality safety will be met for a real GDF.

10.10.5 Assessment of impacts on non-human biota

RWM has undertaken a preliminary assessment of the potential radiological impacts of the GDF on wildlife and the results indicate that the impacts are likely to be low.

10.10.6 Assessment of non-radiological contaminants

RWM is undertaking work in the area of non-radiological contaminant assessment in the context of the need to meet the requirements of the Groundwater Daughter Directive. Beryllium, cadmium, chromium, lead and uranium have been identified as priorities for human health risk assessment based on their presence in the radioactive waste inventory and toxicological properties.

10.10.7 Implications for waste package disposability assessments

As discussed in Section 2.5, RWM's waste package Disposability Assessment process is being revised to ensure consistency with the generic ESC's approach to assessing the environmental safety functions provided by the GDF's barrier system components. The revised approach will include checking that the FEPs associated with the characteristics and post-closure performance of the proposed waste package are consistent with the assumptions made about wastes and waste packaging in this generic ESC and are compatible with post-closure requirements for environmental safety. That is, the FEP analysis will determine whether the proposed wasteform and container provide appropriate environmental safety functions, consistent with those assumed for the waste packages considered in the generic ESC, and are compatible with other components of the GDF's multi-barrier system. The analysis will be undertaken in the context of the environmental safety arguments set out for the illustrative disposal concepts considered in this generic ESC. The environmental safety function influence diagrams discussed in Section 3.2 (and the software implementation of them) will be useful in ensure a comprehensive approach to assessments.

Where judged necessary, qualitative or quantitative analysis of FEPs may be undertaken, for example to estimate the extent of post-closure thermal, mechanical or chemical perturbations associated with the proposed waste package in order that judgments can be made about its impacts on overall disposal system evolution and barrier performance. Judgments about the acceptability of waste package properties such as voidage, gas generation potential and non-radiological contaminants are generally qualitative, based on checking for consistency with RWM's current assumptions and analysis of these FEPs.

If the proposed waste packages are judged to be in some way inconsistent with the waste packages and environmental safety arguments presented in the generic ESC, then a more detailed quantitative assessment of the impacts of the proposed waste packages may be required. For example, the total system model used in the generic ESC could be used to evaluate the impacts of the proposed waste package on calculated mean radiological risk via the groundwater pathway. As RWM develops more detailed quantitative methods for assessing waste package disposability against other properties, these methods could be used in disposability assessments. However, it is not expected that many disposability assessments would require such detailed calculations to be undertaken.

The generic PCSA [5, §2.3 and Appendix A1] provides further information on this revised approach to waste package disposability assessments.

11 Summary and Key Messages

11.1 Summary

This generic ESC explains how the geological disposal of the UK's higher activity radioactive wastes can be accomplished in a way that ensures environmental safety at the time of disposal and in the long term after wastes have been emplaced and the disposal facility has been closed. Underpinning the ESC are:

- A safety concept that is based on ensuring that the long-term safety requirements for the GDF, as defined in RWM's generic Disposal System Specification, are met.
- A demonstration of how environmental safety, and the fundamental safety objective of the environmental regulators' GRA, can be achieved by implementing disposal concepts that are based on systems of multiple engineered and natural barriers that provide multiple safety functions. These barriers are designed to ensure that the wastes are isolated and contained for the long term after disposal by passive means.
- A waste package Disposability Assessment process that aims to ensure that waste packaging concepts and waste packages being produced in support of ongoing waste management, clean-up and decommissioning activities will meet GDF post-closure performance requirements.
- An understanding of expected barrier performance and how conditions in a disposal system will evolve, based on research findings presented in RWM's knowledge base, including the suite of research status reports, which reflect learning from UK research as well as work reported internationally.
- A consideration of the radiological and non-radiological hazards presented by the wastes and how the environmental safety of a GDF can be demonstrated with respect to these hazards in the context of the requirements of the GRA.
- An approach to safety assessment based on multiple lines of reasoning, involving both qualitative and quantitative analysis. Total system modelling has been used to develop an understanding of how different components of the engineered and natural barrier system contribute to environmental safety. Qualitative analyses have included the use of archaeological and natural analogues of material behaviour.

At the current time, no site is available for a GDF in the UK and therefore this ESC is necessarily generic. That is, illustrative concepts have been identified for the disposal of higher activity waste (HHGW and LHGW) in three generic rock types (higher strength rocks, lower strength sedimentary rocks and evaporites). The high-level generic safety arguments presented in this ESC for these illustrative disposal concepts provide the understanding that will underpin the future development of a site-specific ESC. In particular, at each stage of the development and design of the GDF, demonstration of the post-closure safety of a disposal concept will be founded on an understanding of the environmental safety functions that will be provided by the specific engineered barriers defined for a particular combination of host rock and wasteform and the natural barriers provided by the geological environment.

The GDF needs to provide long-term isolation and containment of the wastes. A stable geological environment and well-constructed plugs and seals will ensure waste isolation for a long period for any disposal concept. The containment function may be provided in turn by the container, wasteform, buffer/backfill and geological barrier as conditions in the disposal facility evolve. These barriers work to contain any contaminants that may be released from the slowly degrading waste packages by delaying their migration through the barrier system. Eventually, conditions may arise in which small concentrations of contaminants migrate to the surface environment, although whether such pathways exist will depend on the hydrogeological characteristics of a specific disposal site.

The demonstration of how the GDF provides environmental safety requires an understanding of how conditions in the GDF will evolve over hundreds of thousands of years or more. In this generic ESC, this understanding has been achieved through:

- consideration of the FEPs that affect the environmental safety functions provided by the barrier components of the illustrative disposal concepts identified for each combination of waste group and geological environment
- assessment of the expected evolution (or base scenario) of each disposal concept to show how the disposal facility will be expected to meet environmental safety requirements; the behaviour of contaminants in groundwater and in the gas phase has been considered
- assessment of a number of variant scenarios based on the consideration of FEPs that, although considered unlikely to occur, could disrupt the performance of the GDF, and showing how the GDF will be robust to such disruptions

The assessment approach followed in this ESC is proportionate to the current state of the GDF programme in the UK. In particular, the approach to assessing the geological barrier is based on illustrations of potential geological environments for the GDF founded on expert knowledge of hydrogeological and geochemical systems. The models developed for the generic ESC are relatively simple, but of sufficient detail to facilitate understanding of the roles different barriers play in providing post-closure environmental safety. Also, the analysis of variant scenarios has focused on those scenarios involving disruption to buffer and container performance. Variant scenarios involving factors associated with disruption to the geological barrier would be assessed in detail at a site-specific stage, when suitable data on facility design and site characteristics are available.

The approach taken in this generic ESC to assessing the environmental safety functions provided by a GDF's barrier system components is being implemented in a revised waste package Disposability Assessment process. The revised approach will continue to ensure that waste packages are compatible with post-closure requirements for environmental safety, as considered in this generic ESC.

The development of this generic ESC, including qualitative and quantitative disposal system environmental safety assessment methods, has enabled RWM to further develop its capability in demonstrating the environmental safety of geological disposal. This includes developments in RWM's capability to undertake probabilistic total system modelling and in RWM's understanding of the environmental safety functions provided by the components of multi-barrier geological disposal systems. The development of influence diagrams for each environmental safety function of the barrier components, and the incorporation of the diagrams and associated technical discussions into computer software that will enable automated interrogation of the environmental safety functions provided by GDF barriers, will support further understanding and communication of the safety case.

Quality assurance of data has been a key process in developing the ESC. In particular, the assessments have drawn on RWM's new data management framework for recording information used in its GDF research, development and design work. The framework provides a structure that ensures a transparent and reliable approach to data management and use. This approach builds confidence that the data are fit for purpose and traceable. This system will provide a structure for acquiring and storing new information in the future, ensuring clarity and consistency in a database that can be readily scrutinised.

11.2 Future development of the ESC

Once a location for the GDF has been identified, it will be possible to develop a site-specific ESC that is based on an actual GDF design and knowledge of the geological environment. The site-specific ESC will be developed in parallel with development of the generic ESC, and will be refined as the disposal facility development programme proceeds. The generic ESC will be maintained until there is sufficient confidence in the site-specific ESC that the generic ESC is judged no longer to be required.

Understanding of the geological environment at the GDF site will be obtained through a site characterisation process. RWM's approach to site characterisation is described in a Site Characterisation Status Report [65], which includes discussion of the types of information required and describes potential data acquisition. Site characterisation will involve the development of site descriptive models that summarise the state of knowledge of the site (such as understanding of the hydrogeological and geochemical systems). The site descriptive model and its supporting data, together with a description of the GDF's EBS, will be used as the basis for analysing system evolution and contaminant migration as part of the demonstration of environmental safety presented in ESCs.

The safety arguments and analyses presented in the ESC will continue to be developed in an iterative manner, building on developments in the RWM knowledge base, inventory understanding, the Disposal System Specification, disposal concepts and disposal system designs. This iterative approach leads to a needs-driven, prioritised Science and Technology Plan [13] that captures the requirements for future research and development to support the ESC. This generic ESC has focused on documenting understanding of the environmental safety functions provided by the different barriers of illustrative GDFs and, in particular, the radionuclide containment functions that the barriers fulfil. It is important that RWM's knowledge base continues to be developed in these areas. Some key topics where further research on barrier system behaviour will be beneficial to the development of future ESCs are as follows:

- Regions of high voidage, such as in some types of waste package, could lead to collapse of the waste stack as conditions in the disposal facility evolve, potentially disrupting engineered and geological barrier performance. However, filling void spaces in waste packages has associated operational risks and cost. Therefore, research is necessary to understand the impacts of voidage on the evolution of conditions in a disposal facility and, in particular, on the environmental safety functions provided by the barrier system. Such research will build on RWM's recent work on identification of screening levels against which tolerability to voidage in waste packages can be judged [67], and will support waste package disposability assessments to help ensure risks from the overall disposal process are ALARP.

- Gas generation associated with waste degradation reactions in some waste packages could result in the development of high pressures that could disrupt an engineered and natural barrier system through induced fracturing. Also, radionuclides such a C-14 could be generated in the gas phase, which could affect the radiological risk associated with disposal. Further research is necessary, building on the results of RWM's recent integrated project on C-14 behaviour [15; 16], to understand these processes such that waste package screening levels can be developed relating to gas generation that can be used in disposability assessments.

- Research is necessary to evaluate the impacts of non-radiological contaminants in waste, packaging materials and materials used in GDF construction, which may be harmful to humans and to the wider environment, including non-human biota. A methodology is needed for judging the disposability of waste packages that include non-radiological contaminants.

- Understanding how radionuclides migrate through low-permeability fractured rock is important to environmental safety assessments for disposal facilities in higher strength rock. The environmental safety function provided by such rocks will depend on the potential for migrating radionuclides (and non-radiological contaminants) to be retarded in the fractures and in the rock matrix surrounding the fractures. Diffusion and dispersion into micro-fractures and the accessible porosity in the rock matrix will reduce the rate of radionuclide migration, which may be significant for weakly-sorbing radionuclides such as I-129 and Cl-36 that are of significance to calculations of radiological risk. Also, sorption on fracture fill materials or in the rock matrix will significantly reduce the rate of migration of strongly sorbed radionuclides such as uranium. Research is needed to underpin current understanding of the techniques for characterising such retardation processes in fractured rock and the associated conceptual model and parameter uncertainties.
- A methodology needs to be established for evaluating the impacts of natural processes on the safety functions provided by the barrier system of a GDF to support post-closure performance assessments, building on RWM's initial research to consider the effects of natural transient processes on groundwater flow and radionuclide transport [54, 55, 56]. This includes definitions of stylised deterministic scenarios of GDF performance over timescales in excess of a few hundred thousand years based on assumptions about how natural processes, such as earthquakes, subsidence, uplift and erosion, permafrost development and periods of glaciation could affect conditions in the biosphere and geological environment. Also, developing methodologies to assess variant scenarios of disposal system evolution based on consideration of potentially disruptive FEPs will be important in advance of the preparation of site-specific ESCs.

11.3 Key messages

This document provides:

- A discussion of how the long-term environmental safety of geological disposal can be assured through the construction of a disposal facility based on a system of multiple barriers that isolate and contain the wastes such that the long-term safety requirements are met by passive means.
- In the absence of a GDF site, an approach to demonstrating environmental safety based on illustrations of plausible geological environments and descriptions of engineered barrier systems appropriate to the disposal of different types of waste in those environments.
- A demonstration of how the GDF could be developed such that the principles and requirements of the GRA are met, although this generic ESC focuses only on requirements relating to the demonstration of GDF post-closure environmental safety.
- A document for facilitating discussion within RWM of how the barriers of the GDF in different geological environments will contribute to environmental safety at different stages of GDF evolution.
- A high-level discussion of how an ESC supports the provision of waste packaging advice as part of the Disposability Assessment process, with reference to a revised approach to disposability assessment that includes consideration of how a proposed waste package could affect the environmental safety functions provided by the disposal facility that contribute to isolation and containment of the waste; the revised approach is discussed further and exemplified in the PCSA [5].

- A means of highlighting the most important components of the barrier systems in terms of the environmental safety functions they provide in different geological environments and identifying where further research on barrier materials and their behaviour under disposal conditions could reduce uncertainties and enhance the safety arguments made in an ESC.
- A demonstration of RWM's capability to evaluate the environmental safety of geological disposal, including through quantitative assessment of contaminant transport and with reference to natural and anthropogenic analogues of material behaviour.
- The strategy for maintaining and developing the ESC. As information concerning potential GDF sites becomes available, development of a site-specific ESC will commence and will become increasingly detailed as the GDF is developed. The generic ESC will be maintained as the basis for broad-based disposability assessments until such time as there is sufficient confidence in the site-specific ESC. Eventually, a site-specific ESC will support a future application relating to the construction, operation and closure of a facility for the geological disposal of radioactive wastes made under the Environmental Permitting Regulations.

In providing this information, the generic ESC meets the objectives presented in Section 1.3.

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Glossary

A glossary of terms specific to the generic DSSC can be found in the Technical Background.

Appendix A Meeting the requirements of the GRA

This generic ESC does not address each requirement of the GRA [1] in a systematic fashion, as was done in the 2010 generic ESC [2]. Instead, the safety assessment strategy for this generic ESC focuses on a narrative that presents RWM's understanding of environmental safety in the context of illustrative concepts for radioactive waste disposal in three types of host rock environment. However, the generic ESC and the safety narrative are consistent with the requirements of the GRA. This appendix describes how the different requirements of the GRA are considered and addressed as far as is possible at the generic stage of GDF development.

Figure A1 shows the relationship between the GRA's fundamental protection objective, principles and top-level requirements for solid radioactive waste disposal [1, Figure 3.1]. The following sub-sections discuss how each GRA requirement is considered in the generic ESC, with reference to discussion in the 2010 generic ESC where additional relevant information is available. Sections in this report and the 2010 generic ESC where the requirements of the GRA are discussed are indicated in Table A1.

Requirement R1: Process by agreement

The Environment Agency expects RWM to enter an agreement by which the Environment Agency can provide chargeable advice and assistance after a decision has been made to start a process to select a site for the GDF. This arrangement is termed a "process by agreement" in the GRA and is intended to, for example:

- ensure sufficient attention is focused on regulatory requirements in the early stages of developing a geological disposal facility
- support the Environment Agency's understanding of RWM's proposals for a disposal facility, such that the Environment Agency can make informed comments during the land-use planning process
- through publication of the Environment Agency's advice and comments, support dialogue with stakeholders, such as potential host communities, by aiding understanding of the environmental regulation of a radioactive waste disposal facility.

This process by agreement will continue until the first formal regulatory submission to the environmental regulator, which will be an Initial Site Evaluation (ISE) to obtain the necessary permit for the start of intrusive investigations at a specific site, such as drilling boreholes to investigate the geological formation, as part of a staged authorisation (or permitting) process.

Consistent with the process by agreement, RWM has an ongoing formal arrangement with the Environment Agency that facilitates the Environment Agency's scrutiny of RWM's work. RWM has a similar arrangement with the Office of Nuclear Regulation (ONR). Through these arrangements, the regulators have provided reviews of many topics relating to waste package transport and disposal. The findings of recent joint regulatory reviews (April 2013 to March 2015) have been summarised by the Environment Agency and ONR [3]. The regulators also provided a review of the 2010 generic DSSC. These interactions with the regulators have been considered in RWM's work programme and are reflected in the content and structure of the 2016 generic DSSC. The 2016 generic DSSC, including this generic ESC, will be submitted for review as part of the regulatory scrutiny programme (see Section 2.1 of the main text).

Figure A1 **Relationship between the fundamental protection objective, principles and top-level requirements for solid radioactive waste disposal in the GRA [1, Figure 3.1]; the "period of authorisation" is the same as the period for which an environmental permit is held**

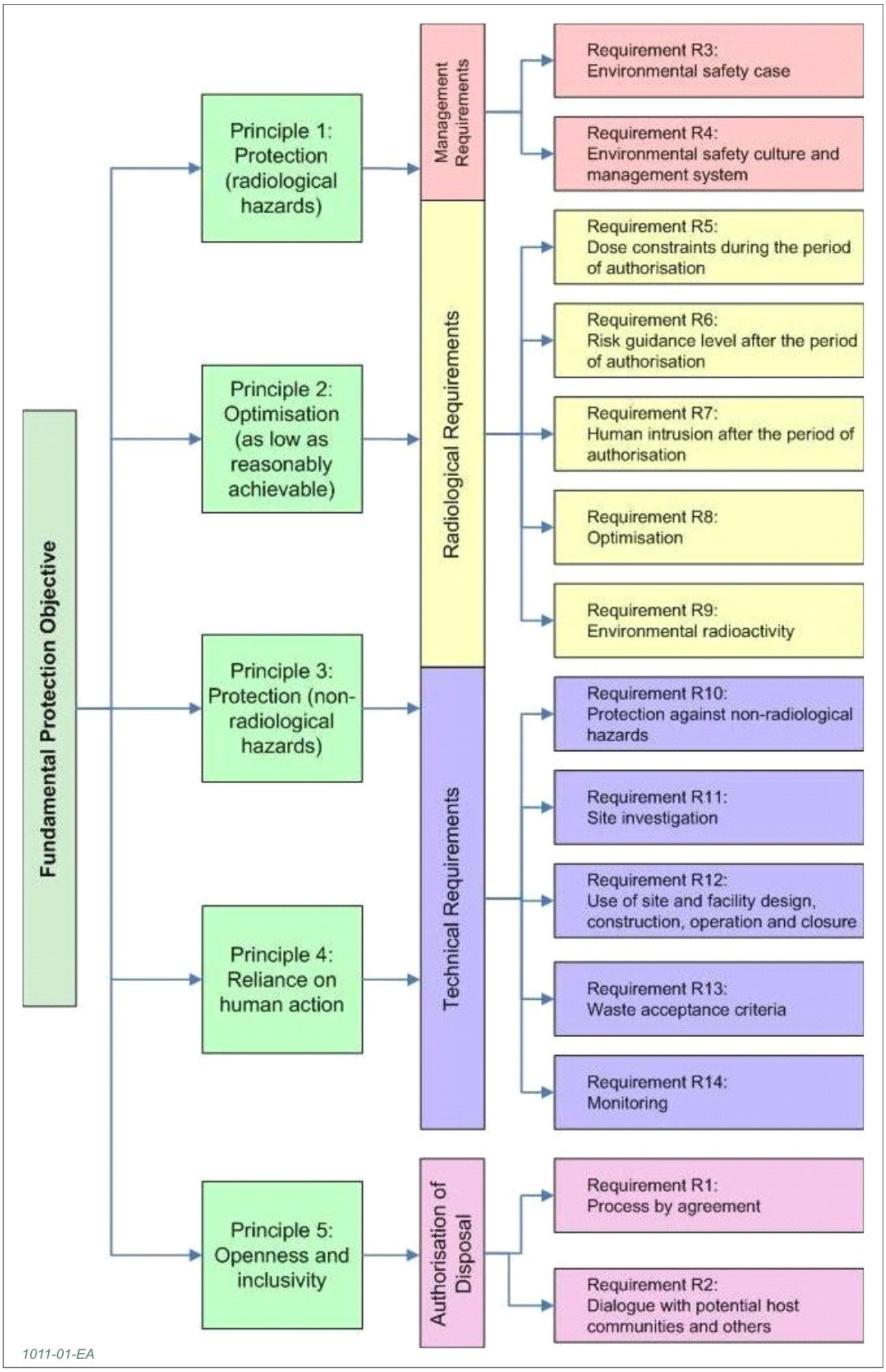

Table A1 Sections in this report and the 2010 generic ESC where the requirements of the GRA are discussed; sections of the 2010 generic ESC are indicated in bold font if they include more detailed discussion of RWM's approach to meeting a particular requirement than is included in this generic ESC[18]

No.	GRA requirement title	Section of this generic ESC in which the approach to meeting the requirement is discussed	Section of the 2010 generic ESC in which the approach to meeting the requirement is discussed
R1	Process by agreement	Section 2.1	Section 2.3
R2	Dialogue with potential host communities and others	Section 2.3	**Section 2.4**
R3	Environmental Safety Case	Section 2 (with entire document comprising the generic approach)	Sections 2.1 and 2.2 (with entire document comprising the generic approach)
R4	Environmental safety culture and management system	Section 2.2	**Section 3.3**
R5	Dose constraint during the period of authorisation	Section 2.6	Section 3.2.1
R6	Risk guidance level after the period of authorisation	Section 2.4.3, 10.3 and 10.4	Section 3.2.2
R7	Human intrusion after the period of authorisation	Section 10.5	Section 3.2.3
R8	Optimisation	Section 2.3	**Section 3.1.2**
R9	Environmental radioactivity	Section 10.7	Section 3.2.4
R10	Protection against non-radiological hazards	Section 10.8	Section 3.2.5
R11	Site investigation	Section 2.4.6	Section 3.1.5
R12	Use of site and facility design, construction, operation and closure	Section 2.3	**Section 3.1.3**
R13	Waste acceptance criteria	Section 2.5	Section 3.1.4
R14	Monitoring	Section 2.6	**Section 3.1.6**

Requirement R2: Dialogue with potential host communities and others

RWM is required to engage in dialogue with the planning authority, potential host communities, other interested parties and the general public on the developing ESC. This generic ESC provides information to all stakeholders on how environmental safety arguments for the GDF are developed, documented and underpinned by an understanding

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[18] Note that the "period of authorisation" is the same as the period for which an environmental permit is held.

of how conditions in the GDF will evolve. It is anticipated that the lines of reasoning presented in this generic ESC for the illustrative disposal concepts will be applicable in the context of a site-specific ESC. Future updates of the ESC will be supported by more extensive programmes of dialogue with potential host communities, once they are participating in the site selection process (see Section 2.3). Potential dialogue processes are noted in the 2010 generic ESC [2, §2.4].

Requirement R3: Environmental Safety Case

This generic ESC demonstrates how the safety objectives defined by the environmental regulators and the IAEA for geological disposal can be met by addressing the regulatory principles and requirements contained in the GRA (as indicated in Figure A1) as far as is possible before a site for the GDF is available. The generic ESC provides an understanding of the long-term environmental safety of geological disposal for a GDF constructed in a range of geological environments based on sound scientific and engineering principles. Section 2.1 explains how an ESC will be maintained and refined as information is obtained on possible sites for the GDF.

Requirement R4: Environmental safety culture and management system

RWM's Management Strategy [4] provides confidence that GDF planning and delivery can be achieved in a coherent, integrated way, with appropriate quality and management accountability and a positive environmental safety culture. The Management Strategy is summarised in Section 2.2; the broader description of the Management Strategy that was presented in the 2010 generic ESC [2, §3.3] is not repeated in this generic ESC.

Requirement R5: Dose constraints during the period of authorisation

The GRA presents source-related and site-related dose constraints on the effective dose from a disposal facility to a representative member of the critical group during the operational and active institutional control phases of the facility. The generic OESA [5] addresses environmental safety during the GDF's operational phase (see Section 2.6).

Requirement R6: Risk guidance level after the period of authorisation

The GRA includes a risk guidance level relating to the assessed radiological risk from a disposal facility to a person representative of those at greatest risk from the presence disposal facility in the long term after facility closure. The risk guidance level represents the assessment standard for natural evolution of the disposal system (not including human intrusion). The strategy taken in this generic ESC for evaluating the post-closure environmental safety of geologic disposal, including assessment of disposal facility against the risk guidance level, is discussed in Section 2.4.3. Calculations quantifying potential radionuclide releases to the accessible environment for different illustrative disposal concepts, and the comparison of associated risks with the regulatory guidelines are presented in Section 10.3. Details of the risk assessment methodology (including total system modelling and the approach to treating uncertainty) and detailed results of risk assessment calculations are presented in the generic PCSA [6].

Requirement R7: Human intrusion after the period of authorisation

The GRA allows the assumption to be made that human intrusion into the GDF after surrender of the environmental permit is highly unlikely to occur, but requires any practical measures that might reduce this likelihood still further to be considered and implemented. The GRA also requires the potential consequences of human intrusion after permit surrender to be assessed, in part to support the facility optimisation process.

Section 10.5 discusses approaches to addressing the issue of potential human intrusion into the GDF after permit surrender, drawing on international experience. Passive controls for reducing the likelihood of intrusion are noted. However, human intrusion calculations have not been presented in this generic ESC, because they could only be based on assumptions about illustrative disposal concepts and would be of little relevance to any disposal facility optimisation process that they would be intended to support.

Requirement R8: Optimisation

Optimisation in the context of geological disposal is concerned with the principle of ensuring that radiation exposures to members of the public, both during the environmental permitting period and afterwards, are ALARA in given circumstances.

As discussed in Section 2.3, as the GDF implementation programme progresses, an iterative design optimisation process will be followed using a site-specific ESC to ensure that any radiological exposures from the GDF are ALARA. However, design optimisation is not appropriate at this generic stage, beyond identifying illustrative geological disposal concept examples relevant to different waste groups and geological environments. RWM's approach to optimisation (and optioneering) is discussed in detail in the 2010 generic ESC [2, §3.1.2]; the discussion is not repeated in this generic ESC.

Requirement R9: Environmental radioactivity

All aspects of the accessible environment should be adequately protected from the radiological effects of a disposal facility. Requirement R9 is concerned with the protection of non-human species and habitats. RWM is in the process of developing an approach to assessing the potential impacts of radioactivity on wildlife, as discussed in Section 10.7.

Requirement R10: Protection against non-radiological hazards

The GRA requires that the GDF provides adequate protection against the non-radiological hazards that might be presented by some wastes, packaging materials and materials used in the construction of the GDF. RWM's work in this area is discussed in Section 10.8, which notes the approach being developed to assess the impacts of non-radiological contaminants in line with the requirements of the Groundwater Daughter Directive.

Requirement R11: Site investigation

As noted in Section 2.4.6, the development of a site-specific ESC will be integrated with a site investigation programme [7]. Site-investigation activities will aim to characterise and understand the geological environment and biosphere. This generic ESC does not include detailed discussion of how such site-investigations will be undertaken.

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

The GRA requires that a disposal site is used and the facility is designed, constructed, operated and capable of closure in a way that avoids unacceptable effects on the performance of the disposal system. The ESC produced in support of the initial site evaluation will demonstrate that any proposed intrusive site investigation will not compromise the integrity of a site to the unacceptable detriment of post-closure safety. Subsequent ESCs will demonstrate that the GDF can be constructed, operated and closed in a manner that ensures environmental safety.

Disposal facility designs are developed such they meet the requirements for the disposal system that are set out in the Disposal System Specification [8; 9]. The technical requirements include the need to consider the impacts of construction materials on the barrier system and interactions between barrier materials. At this generic stage, the designs considered are based on the illustrative disposal concepts that meet the generic technical requirements. The development of the generic GDF options for different waste types in different geological environments is discussed in Section 2.3 and the 2010 generic ESC [2, §3.1.3.2].

Requirement R13: Waste acceptance criteria

Waste acceptance criteria (WAC) need to be established that are consistent with the assumptions made in the ESC. As discussed in Section 2.5, the information necessary to develop WAC is not available at this generic stage. However, in order that wastes can be converted into a safe and disposable form as soon as possible, RWM has produced and maintains generic specifications for waste packaging that define the bounding requirements for waste packages. The Disposability Assessment process determines whether RWM is satisfied that a waste package will be compliant with disposability requirements.

Requirement R14: Monitoring

Site and facility monitoring is required to ensure that the facility is operating within the parameters set out in the ESC, as discussed in Section 2.6. The underground facilities will also be monitored during the operational period such that any emissions of radioactive materials will be detected. Monitoring is discussed in more detail in the 2010 generic ESC [2, §3.1.6].

References for Appendices

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2 NDA, *Geological Disposal: Generic Environmental Safety Case, Main Report* NDA/RWMD/021, December 2010.

3 Environment Agency, *Regulatory Scrutiny of Radioactive Waste Management Limited's Work on Geological Disposal of Radioactive Waste: Biennial Report: April 2013 to March 2015*, Issue 1.0, August 2015.

4 Radioactive Waste Management*, Management System Manual*, RWM01 Revision 11, September 2014 (unpublished).

5 Radioactive Waste Management, *Geological Disposal: Generic Operational Environmental Safety Assessment,* DSSC/315/01, December 2016.

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7 Radioactive Waste Management, *Geological Disposal: Geosphere Status Report,* DSSC/453/01, December 2016.

8 Radioactive Waste Management, *Geological Disposal: Disposal System Specification Part A – High Level Requirements,* DSSC/401/01, December 2016.

9 Radioactive Waste Management, *Geological Disposal: Disposal System Specification Part B: Technical Specification,* DSSC/402/01, December 2016.

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Certificate No LRQ 4008580

Radioactive Waste Management Limited
Building 587
Curie Avenue
Harwell Oxford
Didcot
Oxfordshire OX11 0RH

t +44 (0)1925 802820
f +44 (0)1925 802932
w www.gov.uk/rwm