Radioactive Waste
Management

NDA Report no. DSSC/321/01

Geological Disposal

Generic Post-closure Safety Assessment

December 2016

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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 a 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 a 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

This Post-closure Safety Assessment (PCSA) presents the results of quantitative assessments of the long-term environmental safety of radioactive waste disposal in a geological disposal facility (GDF). The PCSA supports the Environmental Safety Case (ESC), which presents multiple lines of reasoning (both qualitative and quantitative) with regard to demonstrating the environmental safety of geological disposal.

While a site is being sought for a GDF in the UK, the ESC and the PCSA are necessarily generic, focusing on the assessment of illustrative concepts for radioactive waste disposal in different illustrative geological environments. The PCSA has focused on quantifying how the different barriers of these illustrative disposal concepts act together to provide long-term containment of radionuclides and non-radiological species. The assessment approach described in this PCSA and the illustrative results provide the quantitative understanding that will underpin the future development of a site-specific ESC.

The models developed for the generic PCSA are relatively simple, but of sufficient detail to facilitate understanding of the roles that different barriers play in providing post-closure environmental safety. Once potential disposal sites have been identified, site-specific information will be gathered as part of a site characterisation programme that will then underpin more detailed performance assessment modelling.

The quantitative analysis presented in the generic PCSA has involved the use of insight models and total system models. Insight models have been used to develop understanding of GDF performance at a high level, focusing on evaluating the effects of radioactive decay and ingrowth and the radionuclide environmental safety functions provided by each component of the barrier system. Probabilistic total system models provide a more detailed evaluation of radionuclide migration along groundwater pathways to the biosphere for illustrative disposal concepts. These calculations identify key radionuclides contributing to possible radiological risk.

The generic PCSA also includes:

- analysis of the generation and impacts of radionuclides in the gas phase
- discussion of why inadvertent human intrusion is considered unlikely to occur
- assessment of the potential impacts of non-radiological species on the environmental safety of geological disposal
- analysis of the potential for nuclear criticality to affect the performance of the GDF

Once a location for the GDF has been identified, it will be possible to develop a site-specific ESC based on knowledge of the geological environment and details of a suitable GDF design. As part of the site characterisation, information will be gathered that will include a detailed understanding of the hydrogeological and geochemical systems at the site. This information and supporting data, together with a description of the GDF's engineered barrier system, will be used as the basis for producing a site-specific PCSA that assesses system evolution and the migration behaviour of radionuclides and non-radiological species as part of the demonstration of environmental safety.

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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] approach 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.

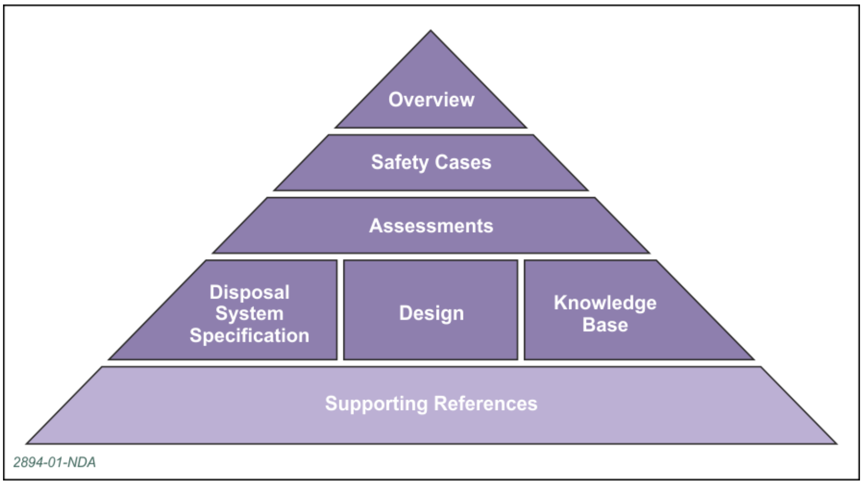
High level information on the inventory for disposal, the illustrative disposal concepts and other aspects of the disposal system is collated in a technical background document (the Technical Background) [3] that supports this generic Disposal System Safety Case.

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 Post-closure Safety Assessment

This document is the Post-closure Safety Assessment (PCSA) of the generic DSSC, which, together with the Operational Environmental Safety Assessment (OESA) [4], underpins the Environmental Safety Case (ESC) [5]. This generic PCSA updates the 2010 PCSA [6] that was published as part of the 2010 generic DSSC. A key driver for updating the DSSC (including the PCSA) now is the availability of an updated inventory for disposal [7]. In addition, this issue of the generic PCSA includes the following developments:

- **A more balanced consideration of illustrative disposal concepts in different geological environments**.

  Radionuclide transport calculations have been undertaken for some disposal concepts in order to illustrate the safety functions provided by the engineered and geological barrier system. These illustrative calculations support the generic ESC, which provides a discussion of the principles that underpin the long-term environmental safety of the GDF. That is, the generic ESC describes how different components of the GDF's engineered and natural barrier system contribute to safety for disposal concepts designed for different types of waste and geological environment, including a consideration of the wider geological environment (and not only the host rock). This approach has been developed in response to comments on the 2010 generic ESC from regulators and others [8; 9].

- **Reference to the developments that have been made in disposal system specifications [10; 11], GDF design [12] and the overall knowledge base since 2010**.

  Advances include new waste packaging and disposal concept development work, research on barrier system performance and disposal system evolution, developments in understanding the post-closure criticality safety of the GDF, and developments in safety assessment modelling. Some of this research has been led by RWM's integrated project teams (IPTs) that have focused on improving understanding in key areas of waste management and geological disposal.

1.3 Objective

The purpose of the generic PCSA is to support the generic ESC, which explains how long-term environmental safety of geological disposal can be achieved. The PCSA provides illustrative calculations of how radionuclides will behave under potential disposal conditions and will be contained by the multiple barriers of the GDF. Broadly, the PCSA:

- presents quantitative analysis that communicates and conveys confidence that the long-term environmental safety of the GDF can be demonstrated
- supports a demonstration of sufficient competence, understanding and ability to produce an environmental safety case in line with regulatory expectations when a suitable disposal site is found

The primary audience of this report are the regulators. The audience is also expected to include academics, learned societies and stakeholders such as the Committee on Radioactive Waste Management (CoRWM) and Non-Governmental Organisations (NGOs). The reports have been written for an audience with a scientific or technical background and with some knowledge of the context of geological disposal.

1.4 Scope

The PCSA:

- presents models and calculations of radionuclide release from waste packages and long-term migration in groundwater under disposal conditions, based on RWM's generic illustrative disposal concepts
- describes a methodology for the assessment of the hazard presented by non-radiological species in the GDF, based on RWM's recent work in this area
- provides a high-level discussion of the effects of gas generation and migration in the GDF, including illustrative calculations of gas behaviour

The quantitative part of a safety assessment is often referred to as a performance assessment for a disposal facility. At this generic stage of the radioactive waste disposal programme there is no information about the geology and hydrogeology of a potential disposal site, and disposal facility designs are only conceptual. Therefore, it is not possible to conduct a full performance assessment of the GDF. Instead, the main purpose of producing this PCSA now is to demonstrate how a post-closure safety assessment would be carried out when a GDF site is identified. The PCSA does include quantitative components based on the assessment of illustrative concepts for the disposal of radioactive waste in different illustrative geological environments. The quantitative components of the PCSA are included for two reasons:

- to illustrate the sensitivity of different performance measures of environmental safety to the properties of a disposal site and concept
- to provide a quantitative benchmark for continuing to give packaging advice to waste producers through the Disposability Assessment process, which endorses proposed waste packages by the issue of Letters of Compliance (LoCs)

In addition, a disposal facility for solid radioactive waste must meet the requirements set out in the environment agencies' Guidance on Requirements for Authorisation (GRA) [13] to show that people and the environment (including non-human biota) are protected from the hazards associated with the geological disposal of radioactive waste. RWM collates all requirements on the disposal system (including regulatory requirements such as those identified in the GRA) in the Disposal System Specification (DSS).

1.5 Document structure

The generic PCSA is structured as follows:

- Section 2 provides an introduction to the PCSA. It describes how the PCSA relates to the other reports in the generic DSSC suite of documents. The section introduces the 'insight modelling' and total system modelling approaches to post-closure safety assessment. An approach to considering the environmental safety functions provided by the barrier components of the GDF as part of the waste package Disposability Assessment process is also introduced.
- Section 3 describes the approach to model development taken in this PCSA, including model development, data qualification, the treatment of uncertainty, scenario development and the modelling undertaken in this PCSA.
- Section 4 provides a detailed discussion of RWM's understanding of post-closure safety for the GDF, focusing on insights gained from simple evaluations of the effects of radioactive decay and the environmental safety functions provided by different components of the barrier system.
- Section 5 presents the results of detailed total system modelling calculations for illustrative disposal concepts, focusing on analysis of radionuclide transport in groundwater.
- Section 6 presents a discussion on radionuclide transport in gas and illustrative calculations of gas generation and migration.
- Section 7 presents a discussion on how the potential for human intrusion into the GDF and its impacts would be assessed at a potential disposal site.
- Section 8 provides an evaluation of the potential effects of post-closure nuclear criticality on the performance of the GDF.
- Section 9 presents RWM's approach to the assessment of non-radiological hazards in the waste and engineered barrier system.

- Section 10 provides a summary and key messages from the PCSA.
- Appendix A presents a test example of how consideration of barrier system environmental safety functions could be considered in the waste package Disposability Assessment process.
- Appendix B includes the Nuclear Energy Agency (NEA) feature event and process (FEP) list [14] and an indication of where each of the FEPs has been considered in the suite of reports that comprise the generic DSSC.

2 Assessing the Post-closure Safety of the GDF

Post-closure safety assessment requires demonstration of a clear understanding of the disposal system and its evolution. This must include understanding of both the expected evolution of the disposal system (the base scenario) and the impacts of future events that might disrupt the expected performance of the system (variant scenarios) [13, §7.2.8]. Owing to the long timescales (hundreds of thousands of years) that are relevant to post-closure safety, there are considerable uncertainties in how the disposal system might evolve. These uncertainties need to be analysed as part of the PCSA.

As described in the Technical Background [3], a disposal system comprises a series of barriers that isolate and contain the wastes. These barriers will provide environmental safety functions that will be effective over different timescales and that work together to ensure the long-term safety of the GDF. Included within this generic DSSC suite of documents are research status reports that discuss in detail the behaviour and evolution of different types of wasteform and engineered and natural barriers in the GDF:

- the Waste Package Evolution Status Report [15] provides details of the expected evolution of waste packages under potential disposal conditions, focusing on the behaviour of different wasteforms and container materials
- the Engineered Barrier System Status Report [16] discusses different barrier materials and their expected evolution after GDF closure
- the Behaviour of Radionuclides and Non-radiological Species in Groundwater Status Report [17] provides details of the processes that affect radionuclides and non-radiological species, focusing on their potential migration behaviour once exposed to groundwater
- the Gas Status Report [18] discusses the generation and behaviour of radionuclides in the gas phase and the effects of bulk gas generation on barrier performance
- the role of the geological environment and the potential hydrogeological, geochemical and mechanical conditions to which wastes and barrier systems could be exposed are discussed in the Geosphere Status Report [19]
- RWM's approach to representing the biosphere in safety assessments is described in the Biosphere Status Report [20]
- the Criticality Safety Status Report [21] discusses how the safe disposal of wastes that contain fissile material is ensured through the controls placed on waste package contents and the safety functions provided by the barrier system

In the context of the post-closure safety of the GDF, an environmental safety function can be defined as [3]:

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

Hence, in the context of post-closure safety, safety functions are provided by the natural and engineered barriers of a given disposal concept. An environmental safety function is often provided by a physical or chemical property or process that contributes to safety.

RWM's understanding of how environmental safety functions associated with each component of a multi-barrier disposal system contribute to the overall environmental safety of the GDF is set out in the Section 3 of the generic ESC, which includes the definition of a general set of environmental safety functions that could be provided by different barrier system components. These general environmental safety functions are listed in Table 1.

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 1. Sections 4 to 9 of the generic ESC, discuss the environmental safety functions provided by the barrier systems of the illustrative disposal concepts selected by RWM for different geological environments.

An assessment of the post-closure safety of the GDF includes calculations (typically using computer codes) to evaluate the behaviour of radionuclides and non-radiological species in the GDF. The calculations are underpinned by mathematical models and data that describe how the environmental safety functions provided by particular barrier systems influence the behaviour of radionuclides and non-radiological species in the GDF environment. Assessment models are also developed to understand the effects of unlikely but potentially disruptive events and processes (such as human intrusion, large seismic events and criticality events) on the performance of the GDF. RWM uses a number of computational approaches to undertake post-closure safety assessments as noted in Sections 2.1 and 2.2.

Table 1 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.

Note that, the assessment approach is consistent with the relevant requirements of the environment agencies' GRA [13]. A discussion of how the different requirements of the GRA are considered and addressed, as far as is possible at the generic stage of GDF development, is provided in Appendix A of the ESC, with reference to sections of the 2010 generic ESC [22] where more detailed information regarding RWM's approach to meeting particular GRA requirements is available.

Section 2.3 discusses how the approach to considering barrier environmental safety functions and assessing post closure safety is used as part of RWM's Disposability Assessment process.

2.1 Insight understanding

An overall simplified understanding of the performance of the GDF may be gained through consideration of the physical and chemical processes that govern the migration of radionuclides or non-radiological species at a high-level. RWM calls this 'insight understanding'. A detailed post-closure performance assessment for a GDF, such as would be necessary for a licence application for a disposal facility, can only be made following site characterisation. Insight understanding allows RWM to gain a broad understanding of disposal system behaviour, for example to inform the development of appropriate disposal concepts for different generic rock types. Insight calculations, such as those presented in Section 4, build on this broad understanding by quantifying the relative effects of significant processes so that the key controls on GDF performance can be determined.

2.2 Total system modelling

Even at the generic stage of GDF development, more complex total system models can be used to undertake illustrative calculations of radionuclide fluxes through barriers and the potential risks associated with any exposure to radionuclides that might migrate from the GDF to the surface environment. The total system models are probabilistic in nature in that they allow representation of uncertainties in disposal system behaviour through specification of probability distribution functions for uncertain parameter values.

The outputs from total system models can be compared to the risk guidance level (RGL) as defined by Requirement R6 of the GRA, which states that after the period of authorisation, the assessed radiological risk from a disposal facility to a person representative of those at greatest risk should be consistent with a risk guidance level of 10^{-6} per year (that is, 1 in a million per year) [13]. The GRA's risk guidance level is consistent with advice given in the Health and Safety Executive's (HSE's) 'Reducing Risks Protecting People' document on risk assessment and risk management [23], which states that '…an individual risk of death of one in a million per annum for both workers and the public corresponds to a very low level of risk and should be used as a guideline for the boundary between the broadly acceptable and tolerable regions'.

Section 3 describes the process of total system model development. The application of total system models to the assessment of radionuclide transport via the groundwater pathway for the illustrative generic disposal concepts being considered in the DSSC is presented in Section 5.

2.3 Application of post-closure safety analysis to the Disposability Assessment process

As discussed in the ESC, RWM has an important role to support waste producers through assessment of waste packaging proposals before waste packages are manufactured. This role is maintained through application of RWM's Disposability Assessment (Letter of

Compliance) Process. '*Waste packages and the assessment of their disposability*' [24] provides more detailed information on the Disposability Assessment process.

The assessment approach taken in this generic PCSA and the generic ESC has provided an opportunity for the post-closure performance assessment (PCPA) methodology that forms part of the Disposability Assessment process to be updated. The procedure for undertaking a PCPA as part of the Disposability Assessment process is currently documented in RWM's management system [25]. The current benchmark for safety assessment in this process is RWM's 2010 generic DSSC. With the update to the 2010 generic DSSC documents and in producing this document, the benchmark for disposability assessments will be moved to the more recent reports. This document details how this update will change the process of undertaking a PCPA, and this will also be reflected in the procedures held in RWM's management system.

In particular, when undertaking a PCPA, RWM will refer to the environmental safety functions provided by the proposed waste package and will assess how the waste package could influence the environmental safety functions provided by other waste packages or components of a multi-barrier disposal system. The generic environmental safety functions for each type of barrier component and understanding of the features, events and processes (FEPs) that could affect them under GDF conditions, as described in the ESC [5, §3], will provide the basis for such an assessment. This assessment process allows:

- confidence to be built in understanding the evolution of the GDF and associated uncertainties
- gaps in knowledge relating to waste package behaviour and interactions with GDF barrier components to be identified
- a basis to be formed on which to offer recommendations regarding the potential disposability of the waste package

A 'post-closure safety tool' will be developed for use in PCPAs, that will facilitate understanding of the generic environmental safety functions discussed in the ESC and the FEPs that could affect them [5, §3]. In applying this post-closure safety tool to a PCPA, the following steps will be taken:

- identify the environmental safety functions relevant to the proposed waste package and disposal concept from the generic list
- consider whether these safety functions are compatible with each other and are sufficient, in combination, to provide an acceptable assurance of post-closure safety
- consider, as part of an optimisation process [13], whether additional environmental safety functions should be provided by the waste package and/or engineered barrier system in order to reduce the risk associated with disposal of the waste

An initial PCPA will consist of a reasoned, qualitative analysis of the environmental safety functions provided by the proposed waste package against the generic environmental safety functions identified for waste packages in the ESC [5, §3]. For packaging proposals where the environmental safety functions are well understood and consistent with those of previously accepted packages, this qualitative evaluation may be sufficient. However, if there are concerns about the adequacy of the environmental safety functions provided by the waste package or its effects on other waste packages or barrier components, then it may be appropriate to supplement understanding of system evolution by undertaking numerical evaluations to demonstrate specific aspects of post-closure performance. The form of the numerical evaluation will depend on the environmental safety function(s) being challenged, but could involve the use of the above-noted insight or total system models.

The outcome of a PCPA may lead to certain requirements (in terms of post-closure safety) being placed on the disposal system. For example, a disposability assessment for waste packages that contained a specific fuel type led to a requirement relating to how waste packages of that fuel type should be stacked with other waste packages in order to provide sufficient post-closure criticality safety margins. Such requirements are recorded in the special emplacements register [12, Appendix G]. There may also be certain outcomes of a disposability assessment that require the scope of, and arguments presented in, the generic PCSA to be updated. For example, such an update may be required if a new packaging material is proposed that has not previously been assessed in the generic PCSA.

Appendix A provides a worked example of a PCPA as part of a disposability assessment for a particular packaging proposal. It discusses the waste package in the context of each of the components of the disposal system, the associated generic environmental safety functions and the FEPs that could affect them.

3 Approach to Model Development

The internationally approved approach to model development for GDF post-closure safety assessments is based on the identification of FEPs that define a GDF and could affect its performance [26]. The Nuclear Energy Agency (NEA) FEP list [14] has been used in support of the DSSC FEP analysis; an indication of where each of the NEA FEPs has been considered in the reports which comprise the DSSC is presented in Appendix B . The FEPs identified in the DSSC are used as the basis for defining different scenarios that describe how conditions in the GDF could evolve, and for developing conceptual and mathematical models of system evolution based on consideration of these scenarios. This model development process is discussed in more detail in RWM's framework for application of modelling in GDF assessments [27]. Definitions of various modelling terms used in the PCSA are provided in Box 1.

It is important that conceptual models reflect the available data and understanding of the physical, chemical, and biological processes that could affect the geological disposal system. Conceptual model assumptions should be consistent with one another and with existing information within the context of the given modelling purpose. RWM's approach to modelling is described in Section 3.1 and the qualification of data for use in the models is discussed in Section 3.2. RWM's approach to the treatment of uncertainty is discussed in Section 3.3, including the development of different plausible scenarios through FEP analysis in order to address uncertainties in the evolution of the GDF (Section 3.3.1). The modelling approach taken for this PCSA in support of the generic ESC is described in Section 3.4.

Box 1. Modelling terms

A conceptual model, as defined by the International Atomic Energy Agency (IAEA) [28, p.122], is:

> *"A set of qualitative assumptions used to describe a system (or part thereof). These assumptions would normally cover, as a minimum, the geometry and dimensionality of the system, initial and boundary conditions, time dependence, and the nature of the relevant physical, chemical and biological processes and phenomena."*

A mathematical model is [27, §2.3]:

> *"…a mathematical representation of a system or entity that describes those characteristics of the system considered to be important or relevant"*

A scenario is a specific description of the possible evolution of conditions in the disposal system. The base scenario discussed in this report is the scenario that describes the features of the disposal system at closure and the events and processes that define how the disposal system is expected to evolve. The base scenario is sometimes referred to as the 'normal evolution' scenario. Deviations from the base scenario, caused by potentially disruptive FEPs that may or may not occur are considered as variant scenarios.

3.1 Model development

In order to understand the significance of the different FEPs relevant to each scenario, it is generally necessary to develop and use a variety of models that describe systems at different scales and at different levels of detail. In particular, in support of a site-specific ESC, a hierarchy of models would be developed in order to evaluate and understand how systems evolve and how environmental safety is achieved for a particular disposal concept. That is, models would be developed and applied:

- at the detailed process level, for example, to understand radionuclide transport behaviour in fractured rock or to evaluate gas generation reactions
- at the barrier component level, for example, to understand hydrological or geochemical conditions in the geological environment or to study potential exposure pathways in the biosphere
- at the total system level, to evaluate how radionuclides or non-radiological species are contained by a multi-barrier system and how containment is influenced by processes such as decay and ingrowth of radionuclides and advection, diffusion and sorption along transport paths, and to understand the impacts of any contaminant migration to the biosphere

At each model level, conceptual understanding of FEPs and FEP interactions are first expressed in terms of descriptive conceptual models and these are then expressed in terms of mathematical equations that are solved using numerical methods implemented in computer codes. This modelling approach was described in more detail in the 2010 generic ESC [22, Figure 3.8].

RWM's current understanding of FEPs and system evolution for illustrative disposal concepts is documented in the various research status reports that support the generic DSSC. In some cases, this FEP understanding has been supported by process or barrier component modelling analyses. The models that will be needed to support an assessment of the environmental safety of the GDF at a particular site (as illustrated within the model hierarchy) will be implemented and iterated as necessary as detailed information about the site and disposal concept becomes available. This approach is discussed in more detail in the generic ESC [5, §2.4.1].

As noted in Section 2, RWM's assessment approach involves simple analytical insight models to provide an understanding of disposal system behaviour at a relatively high level and more detailed probabilistic total system modelling to evaluate radionuclide fluxes through barriers and the potential risks associated with any exposure to radionuclides that might reach the biosphere. Both approaches have been used in this generic PCSA to provide illustrative calculations of the environmental safety of geological disposal. The application of insight modelling is presented in Section 4 and the results of total system modelling are presented in Section 5.

The models are underpinned by an understanding of the environmental safety functions provided by the barrier components of different illustrative disposal concepts for different types of waste. This system understanding has been derived from the information presented in the research status reports and from the specification of illustrative geological environments to enable a system-wide assessment to be undertaken. A key objective of these calculations at the generic stage is to demonstrate that RWM has the capability and understanding to develop the total system models that would be required for a site-specific ESC. When a disposal site is identified, and site-specific and concept-specific understanding develops, total system modelling will be supported by detailed models that consider key chemical, mechanical, hydrological, thermal, radiological and biological processes and couplings between them.

3.2 Model, data and parameter qualification

The validity of modelling depends on the quality, validity and appropriate use of the models, the validity (and appropriate use) of the parameter values (including uncertainty ranges) used in the modelling and the data from which these values have been derived. Models, data and model parameter values need to be fit for purpose, and RWM's data and model procedures [25] require that the purpose of the calculations, the conditions being modelled and the potential risks associated with the use of the model outputs are all considered.

RWM's modelling capability is developed and maintained in line with model development procedures and defined roles and responsibilities [29]. This ensures that models are implemented correctly in computer codes and tested. The parameter values used in model calculations are recorded on data definition forms (DDFs) that document the provenance of data on which the parameter values are based and any associated limitations or quality issues. All data for use in the generic DSSC are provided via DDFs and each DDF is approved by an appropriately qualified data owner. The DDFs are stored in RWM's document management system.

At the generic stage of the siting programme, comprehensive data sets of the type that would be required to assess a specific disposal site are, of course, not available. Instead, in many instances, in order to undertake generic assessments of illustrative disposal concepts, it has been necessary to derive parameter values based on information available from disposal concept development overseas (for example, information on radionuclide behaviour under different GDF conditions) or based on expert understanding of specific processes (for example, on hydrogeological conditions in different illustrative geological environments). However, RWM ensures that these parameter values are fit-for-purpose and are suitably recorded on DDFs. The Data Report [30] provides information of the specific data and parameter values used in the generic DSSC assessments, including the illustrative assessments reported in this PCSA.

3.3 Treatment of uncertainty

RWM undertook a study of recent GDF post-closure safety cases that have been reported by overseas radioactive waste management organisations [31] and included consideration of how uncertainty was addressed in the safety cases [31, §7.3]. The study found that, given the long timescales addressed within a post-closure safety case, it is inevitable that there are many uncertainties in GDF performance, even for relatively advanced safety cases. However, these uncertainties can be managed as part of the safety assessment undertaken. The GRA [13, §7.3.10] highlights the need for all important uncertainties to be accounted for in an environmental safety case, with such uncertainties being included on a register of uncertainties:

> *"…[a GDF implementer should take] adequate account of all uncertainties that have a significant effect on the environmental safety case. This will mean establishing and maintaining a register of significant uncertainties…"*

Maintaining a register of significant uncertainties will support prioritisation of the GDF research programme, by ensuring that research is focused on reducing the uncertainties that have the greatest impact on confidence in the safety case. This prioritisation process enables a needs-driven approach to GDF research. RWM's prioritisation principles in support of a needs-driven research programme are discussed in the Science and Technology Plan [32]. Of course, the safety case will need to explain why any uncertainties not recorded in the register are judged to be insignificant, which will require reasoned arguments and/or sensitivity analyses. Most of the uncertainties associated with the data and parameter values used in the illustrative calculations presented in this PCSA have been documented in the Data Report [30].

The GRA [13, §7.3.10] also notes the need for a demonstration of:

> *"…a clear forward strategy for managing each significant uncertainty, based on considering, for example, whether the uncertainty can be avoided, mitigated or reduced, and how reliably it can be quantified."*

It may not be possible to quantify all uncertainties associated with how conditions in the GDF will evolve over the long periods of time that must be considered in an ESC, as recognised in the GRA [13, §6.3.22]:

> *”After the period of authorisation, the evolution of the disposal system (i.e. the disposal facility in its geological setting) becomes increasingly uncertain with time. An important distinction can be made between two types of uncertainties: those that can reliably be quantified and those that cannot.”*

RWM has developed an approach to managing uncertainty that includes ‘designing out’ significant uncertainties as the design of RWM’s preferred disposal concept is optimised (that is, through the selection of barrier materials and specification of requirements on them) and treating uncertainty over future states of the disposal system through the development of scenarios. RWM’s approach to identifying and assessing scenarios is discussed in Section 3.3.1 and is consistent with the approach to treating uncertainties described in the GRA [13, §6.3.22-6.3.28] and illustrated in Figure 2 [13, Figure 6.3].

In particular, RWM’s strategy for maintaining and developing the ESC [5, §2.1] requires a demonstration that any outstanding uncertainties are appropriately managed so that there is confidence in overall environmental safety. At each stage of ESC development, RWM will identify outstanding uncertainties and adopt an appropriate approach to their treatment, noting that:

- **It is neither possible nor necessary to eliminate all uncertainties**.

  A system should be demonstrated to be robust, including when uncertainties are taken into account.

- **The types and extent of uncertainty are expected to change as the GDF implementation programme progresses**.

  For instance, uncertainties associated with the properties of the geological environment at a potential GDF location will be identified and evaluated as the site characterisation process progresses. At the current generic stage, such uncertainties are large and are evaluated through illustrative examples that are representative of the range of geological environments across the UK.

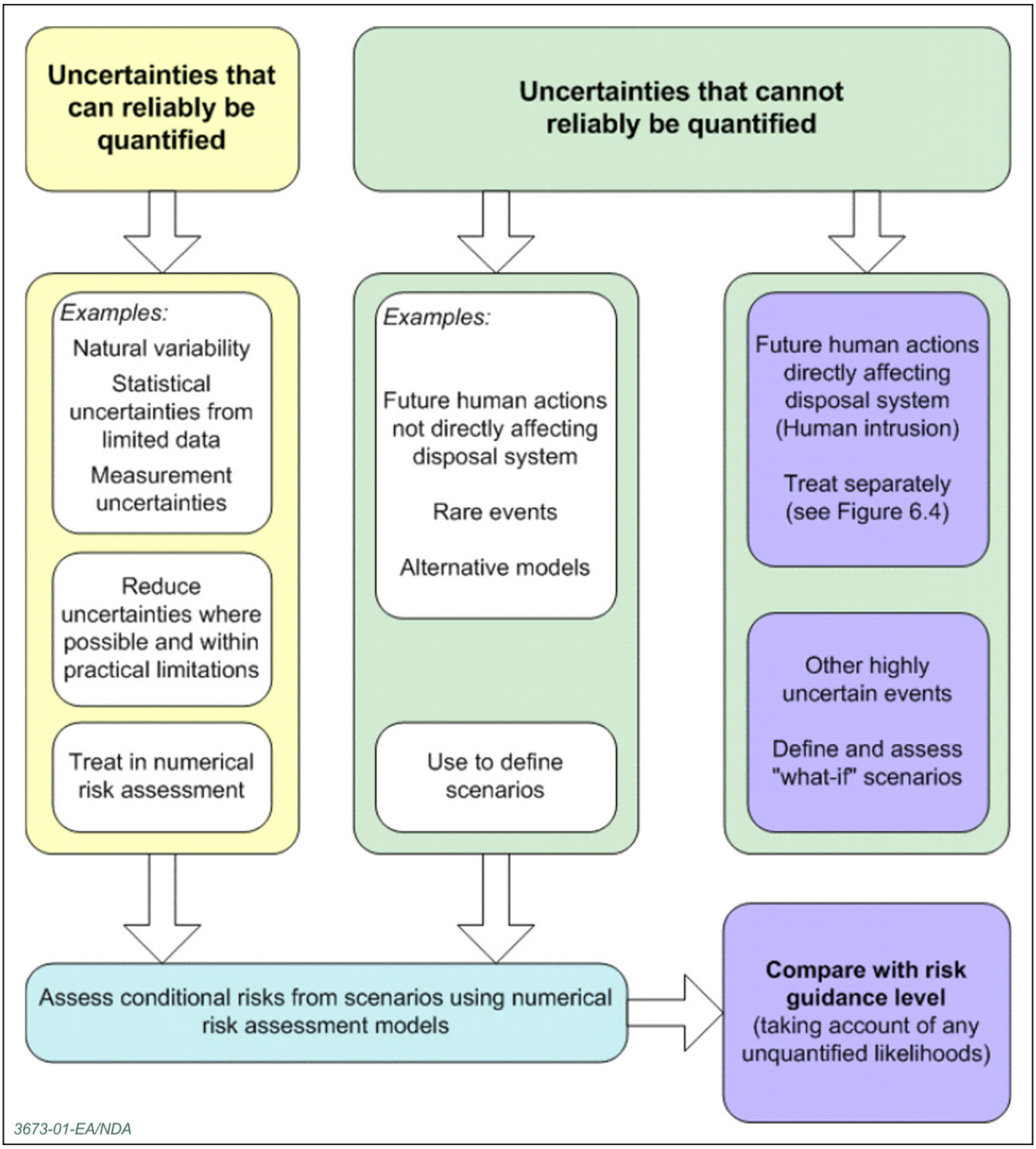
- **Where outstanding uncertainties can be quantified they will be explicitly included in ESC calculations (for example, via appropriate parameter ranges).**

  The results of such calculations are presented in this PCSA. 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**.

That is, multiple lines of reasoning can be used that include qualitative evidence, such as provided by natural and archaeological analogues of material behaviour [33].

Figure 2 **Approach to the treatment of uncertainties as presented in the GRA [13, Figure 6.3] (with reference to Figure 6.4 of the GRA).**



In a geological disposal system both at a generic and a site-specific stage there are a number of different areas in which uncertainty may affect how the performance of the GDF is assessed:

- **Uncertainty over future states of the disposal system.**

  It is not known for certain how a GDF (and the surrounding environment) will evolve over long timescales. Therefore a performance assessment needs to consider a range of different scenarios for future evolution.

- **Data uncertainty**.

  It is likely that, even when information about a specific site is available, the set of data required to evaluate the parameters relevant to a GDF performance assessment will be incomplete or may be inaccurate, leading to parameter value uncertainty. In principle uncertainty in some parameters can be reduced by making more measurements (in the case of properties of the rock at a potential site) or by carrying out more laboratory experiments (in the case of chemical parameters such as solubility). However, uncertainty in some parameters cannot be reduced readily. For example, there may be limited potential to reduce uncertainty in understanding how the chemical conditions at a disposal site might develop in the distant future, when the effects of factors such as climate change could be important. Also, some processes of potential importance to GDF performance, such as container corrosion and chemical alteration in barrier materials, act so slowly that it is difficult to measure them. Acceleration techniques can be used in some cases, but extrapolation to expected conditions introduces other uncertainties. Furthermore, some parameters required for a performance assessment will be associated with properties that are not only uncertain, but are also spatially variable (for example rock permeability). It will not be practicable or possible to make sufficient measurements to enable such variability to be characterised without uncertainties remaining.

- **Model uncertainty**.

  Whilst RWM believes that most processes can be well understood at an appropriate level of detail, understanding of some FEPs relevant to a GDF performance assessment and how they are inter-related may be limited, resulting in uncertainty in the selection and formulation of conceptual models. For example, a model may fit observed data, but if the processes have not been understood and represented properly then the model could be misleading, especially when undertaking calculations for situations outside the range of the observations. To ensure that processes are adequately understood and represented, RWM has developed an approach to model development underpinned by FEP analysis, which is described in Section 3.1. RWM aims to avoid making modelling assumptions. The aim is that models are based on process understanding and any uncertainties are represented explicitly (for example, by probabilistic modelling). However, where there are significant uncertainties, particularly if those uncertainties cannot be quantified, a model may require assumptions and any such assumptions are made on a cautious basis. For example, radionuclide transfer through a barrier may be modelled in a simplified way if there is uncertainty in the structure of the transport pathway and the transport processes occurring. In this case the barrier's containment function is under-estimated rather than over-estimated and, as a result, calculated performance measures such as radiological risk are over-estimated.

- **Uncertainty about human behaviour**.

  Human actions can have a significant impact on the performance and impacts of the disposal system. For example, in the future people may drill for water extraction or excavate in the region of the GDF. Human activity may also change the landscape around a GDF and changes in habits may affect the impacts of the GDF on future generations. Uncertainty about human activity is addressed through consideration of different potentially exposed groups that have stylised behaviour in terms of how they interact with the environment. The potential impacts of such interactions are evaluated in terms of radiological dose and risk. Uncertainties associated with the potential effects of human intrusion into a GDF are addressed through the specification and assessment of variant scenarios.

3.3.1 Scenario development

When a specific site is identified for a GDF, RWM will apply a systematic approach to identifying relevant site-specific scenarios for assessment as part of a site-specific ESC.

The approach will be similar to that taken in the development of scenarios for the generic ESC. RWM's approach to scenario development is described at the beginning of this section (see Box 1 for a definition of terms) and is similar to approaches adopted by other radioactive waste management organisations around the world [34, §5]. That is, a base scenario and a number of variant scenarios that define potential evolutions of the GDF are identified based on an analysis of all FEPs relevant to the performance of the GDF, as described in the ESC [5, §3.3]. The scenarios are described by conceptual models that are assessed qualitatively and/or quantitatively. Mathematical models and computer codes are developed where needed for the quantitative assessment of the scenarios, as discussed in Section 3.1.

Even the most thorough FEP analysis will not entirely eliminate uncertainties about whether FEPs have been represented appropriately in performance assessment models. That is, there will always be some residual uncertainty about whether the FEPs or FEP interactions have been represented correctly for the specific conditions of a given assessment. As noted above, RWM takes a broadly cautious approach to model uncertainty, in which, for example, the radiological risks arising from the GDF are over-estimated rather than under-estimated.

For this generic safety assessment, in the absence of knowledge about the geology at a potential site, and given that a preferred concept has yet to be established, RWM has made a number of assumptions about the scenarios to be considered for illustrative disposal concepts in different illustrative geological environments. Discussion of the scenarios identified for consideration for each illustrative example is presented in the ESC [5, §4-9]. Discussion of the specific assumptions that have been made in support of the illustrative calculations presented in this report is provided in the underpinning Post-Closure Performance Modelling Report [35] and the Data Report [30]. The results of the generic scenario assessment are presented in Section 5. In future site-specific assessments, a site-specific FEP analysis will be undertaken that considers the detailed characteristics and understanding of the site and disposal concept to define the base scenario and relevant variant scenarios.

3.3.2 Methods for treating uncertainty

RWM has previously published a framework for application of modelling to support assessments of geological disposal [27]. This approach notes that in broad terms there are two different approaches to developing a model; 'top-down', and 'bottom-up'. In the 'bottom-up' approach, the development of the model starts at a detailed level, for example by considering individual FEPs and building a model based on these FEPs and their interactions. In such an approach, a detailed treatment of uncertainty may not be practicable. Instead, specific assumptions may be made about parameter values, such that the analysis is deterministic; that is a single result is calculated for a specific set of model input assumptions. This approach may be used for detailed modelling of particular processes or specific components of a barrier system.

The 'top-down' approach starts with the focus on what is required to be calculated (for example radiological risk). The modeller identifies what information is required to perform the calculation and builds a model that abstracts the required information. (Where available, outputs from bottom-up process models may provide inputs to the derivation of parameters and the characterisation of uncertainty for top-down models.) Top-down models are typically developed in an iterative manner, with detail being added as necessary. This approach focuses only on what is known to be important to the model output, which would be determined through identification and understanding of relevant FEPs. Uncertainties are represented explicitly, so that such models are generally probabilistic; that is, the models may be run many times, giving different realisations for different combinations of randomly sampled input values (see Section 3.3.3). Models developed using this approach aim to provide a total system-level understanding.

The previous subsection explained how uncertainty about the evolution of conditions in the GDF can be addressed through FEP analysis and scenario development. For a defined scenario, however, data uncertainty and model uncertainty need to be managed. Strategies for handling such uncertainties tend to fall into the following broad categories:

1. Demonstrating that the uncertainty is irrelevant. That is, showing that the environmental safety of the GDF is not sensitive to uncertainty in a particular process.
2. Addressing the uncertainty explicitly by for example using probabilistic techniques.
3. Bounding the uncertainty where it is possible to identify bounding values and showing that calculations for the bounding case result in acceptable environmental safety.
4. Ruling out the uncertain process or event, usually on the grounds of its very low probability of occurrence, or because other consequences (were the uncertain event to happen) would far outweigh concerns over the performance of the GDF (for example a large direct meteorite strike could affect the performance of the GDF, but would most likely have far greater detrimental impacts on the surface environment than the disturbed GDF).
5. Agreeing a stylised approach for handling an uncertainty (for example, in the description of a biosphere or when assessing human intrusion), as described in the GRA [13, §7.3.18].

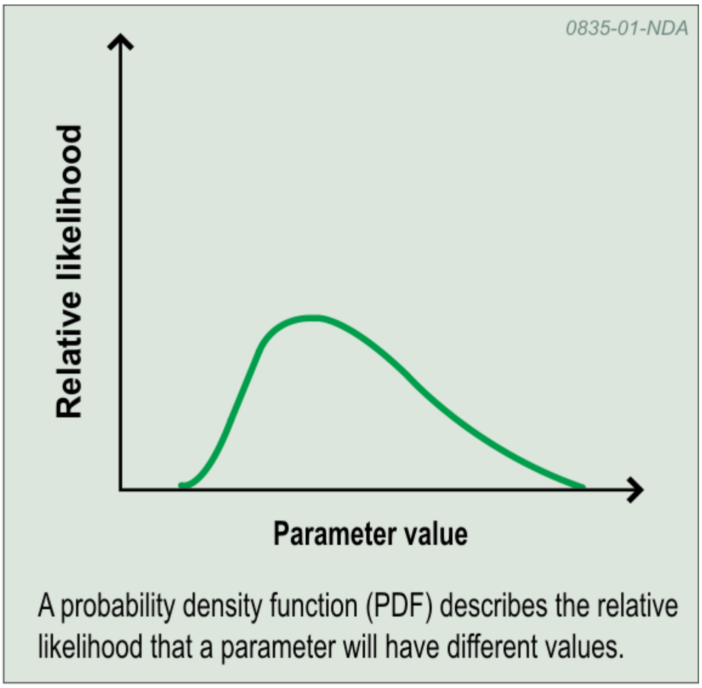
The preferred treatment of particular uncertainties will depend on the context of the assessment and the stage in the process of developing a GDF. At this generic stage, RWM has adopted a combined probabilistic and deterministic approach to treating uncertainties in order to assess the potential long-term impacts of radionuclides released from waste packages in the GDF and migrating in groundwater. That is, uncertainties about engineered barrier system performance and radionuclide behaviour have been treated probabilistically, but a deterministic approach has been taken to defining the structure of radionuclide transport pathways from the disposal facility to the biosphere for GDFs in illustrative geological environments, as discussed in Section 5. The next subsection gives details of the probabilistic element of the modelling approach.

3.3.3 Probabilistic safety assessment

Uncertainties in data can be quantified in terms of probability density functions (PDFs) that give the relative likelihood of different parameter values as illustrated in Figure 3. The links between measured data and the PDFs assigned to parameter values used in total system models can potentially be quite complex. The PDFs can be based solely on measured values, or, more usually (in the radioactive waste community), are generated by a process in which measured values are supplemented by the judgement of suitably qualified and experienced experts on the basis of various research data, and can take into account any scarcity of data, uncertainty or bias from measurements [36]. Thus, expert judgement ensures that the measured data are interpreted in the context of the situation that is to be modelled and the way it is to be modelled.

With the uncertainty quantified as PDFs, a probabilistic assessment can be carried out using a Monte Carlo approach. In such an approach, a computer model is run many times (each run is called a realisation) with different sets of parameter values. In each realisation, the values of the parameters are chosen at random from the PDFs representing the range of possible values. This is known as a ‘probabilistic safety assessment’, or PSA, approach. It ensures that a variety of possible parameter values is considered from across the ranges specified within a performance assessment. Statistical analysis of the results of a PSA can be used to explore the sensitivity of performance measures such as radiological risk to the uncertain model parameters.

Figure 3 **Schematic illustration of a probability density function**



A probability density function (PDF) describes the relative likelihood that a parameter will have different values.

The PSA approach is consistent with current regulatory guidance in the UK [13, §6.3.21]. The calculation of the expectation value of risk (obtained by averaging the calculated risk from each PSA realisation at any time and identifying the peak of these calculated mean risks over time) can be used for comparison with the risk guidance level [13, §6.3.10]. It can also be used to inform the GDF developer/operator about how models and research should be developed, by highlighting the model parameters that dominate calculated risk and the parameters to which risk is sensitive. To ensure that sufficient combinations are computed to have confidence in the average risk value, it may be necessary to run models many thousands of times or more.

RWM recognises that measures of risk other than the expectation value could also be used. For example, other statistical measures and figures showing the distribution of the calculated peak risk, or scatter plots showing how the peak risks from individual realisations depend on the values of key input parameters could be presented. When more information about particular sites is available, RWM will use appropriate measures, demonstrating why the chosen measures are a reasonable choice. RWM will also present information about the sensitivity of the chosen measures to important parameter values in order to understand factors controlling the safety of the GDF and hence appropriately direct RWM's research programme.

3.4 Key assumptions underpinning the PCSA models

Prior to the identification of a disposal site, RWM has identified a range of illustrative geological environments as a basis for developing, designing and assessing illustrative disposal concepts for different categories of waste. Descriptions of these illustrative 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 [19, §5.3.1 to §5.3.6].

In order to undertake a quantitative assessment of the performance of the GDF it is necessary to develop the high-level descriptions of the geological environments to a more detailed level at which potential pathways for radionuclide transport are characterised. RWM has developed hydrogeological and geochemical descriptions of specific illustrative geological environments for performance assessment calculations, based on the views of suitably qualified experts. The resultant realistic but hypothetical environments represent illustrations of geological environments with properties that are within the range known to exist in the UK but do not have any relation to any specific sites. This is RWM's preferred approach at the generic stage of the GDF programme. Once sites have been identified for consideration for a GDF, site-specific information will be gathered to develop site descriptive models that will then underpin the performance assessment modelling.

Any descriptions of potential pathways for the transport of radionuclides or non-radiological species should only be seen as simple deterministic illustrations of the potential characteristics of the GDF. In particular, the detailed transport pathway descriptions developed for this post-closure analysis assume that diffusion pathways or hydraulic head gradients and connected pathways will exist for the eventual transport of radionuclides or non-radiological species to the surface environment. In reality, a 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 to the surface environment for the actual GDF. The illustrations of potential flow and transport pathways for different geological environments that have been developed for this PCSA are presented in Section 5. These deterministic illustrations have enabled simple descriptions of transport paths to be developed for representation in total system models.

Note that the illustrative geological environments present hydrogeological and hydrogeochemical conditions as steady state. However, various natural processes could affect groundwater flow movement and groundwater geochemistry and hence change the migration behaviour of radionuclides or non-radiological species and the performance of the GDF over long timescales. For example, the performance of the GDF could be affected by processes related to climate change (such as glaciation), seismic activity and erosion. Given these uncertainties in system behaviour, the probabilistic analysis has been limited to the period for which there is good understanding of the expected evolution of the geological environment (that is a period of no more than a few hundred thousand years). The GRA [13, §7.3.28] supports this approach, stating that:

> *"We recognise that models used to support the environmental safety case will often be used to provide projections over time periods far exceeding any period for which the models have been tested against observations. Modelling projections of this nature cannot be regarded as predictions, but as assessments provided to support judgements about environmental safety. Quantitative modelling projections should not be made for times so far into the future that uncertainties make the modelling results lose any meaning."*

The descriptions of the groundwater flow and potential transport pathways, and the simplifying assumptions about system evolution, have enabled total system models of radionuclide transport to be developed for the generic PCSA in support of the generic ESC. Key features of the total system models are:

- representations of the release of radionuclides from waste packages that have been breached at some time after disposal, with radionuclide concentrations solubility limited where appropriate
- evaluation of radioactive decay and ingrowth

- one-dimensional transport along pathways of prescribed length through the host rock and cover rocks; transport is by advection or diffusion, depending on the hydrological characteristics of each rock formation
- retardation by sorption along the transport paths
- evaluation of radiological risks via different exposure pathways

These total system models have been implemented using GoldSim [37; 38] and the details are presented in the Post-Closure Performance Modelling Report [35].

4 Developing Insights into GDF Performance

High-level insights into the performance of the GDF can be developed by considering the nature of the wastes and the environmental safety functions provided by the engineered barrier system and the geological barrier between the wastes and surface environment. In Sections 4.1 and 4.2, these components and the key processes that control radionuclide behaviour through them are discussed qualitatively. Section 4.3 provides a demonstration of how this insight understanding can be quantified; calculations to support understanding of the importance of radionuclide decay and ingrowth and the transport of radionuclides in groundwater in different geological environments (advection-dominated and diffusion-dominated systems) are presented.

4.1 Understanding wasteform and container performance

Developing insights into radionuclide behaviour in the GDF begins with consideration of the inventory for disposal and recognition that its radiological hazard will generally reduce over time as radionuclides decay. Box 2 describes the radioactive decay process.

The radiological hazard presented by different wastes is strongly dependent on the specific radionuclides present and their activities. Thus, the time over which radionuclide decay has occurred is an important factor in defining the hazard (that is, the number of half-lives that have elapsed for each radionuclide present). However, many radionuclides likely to be present in wastes do not generally decay directly to stable species; instead they form part of a decay chain (see Box 2). Hence, radioactive daughter isotopes of certain radionuclides will ingrow, and the mass of such isotopes may increase with time, until they too decay. If the half-life of a daughter is significantly smaller than that of the parent, then, with time, the radionuclides tend to secular equilibrium, where the activities of parent and daughter are the same. The conditions under which secular equilibrium is achieved are described in Box 3.

The process of radioactive decay is well understood, with the half-lives and decay chains (and branching ratios) of most radionuclides being well-characterised. This means that the mass of any particular radionuclide at any given time can be calculated given knowledge of its initial mass (that is the inventory for disposal), its half-life and the relevant decay chain. The effects of radioactive decay on the inventory are evaluated in Section 4.3.1.

In addition to differing isotopic compositions, different waste streams have different physical and chemical compositions. Such differences may represent important considerations in disposal concept development and post-closure performance assessment. For example, under disposal conditions, certain types of organic material present in some wastes may degrade to acids that affect the chemistry of the groundwater. This can then affect how quickly a radionuclide or contaminant dissolves or migrates in the groundwater.

Box 2. Radioactive decay and ingrowth

All radioactive substances decay. In some instances, the radionuclide decays directly to a stable, non-radioactive isotope. In other cases, a chain of radioactive ‘daughter’[2] nuclides is produced before a stable isotope is formed. It is important to take account of decay and ingrowth of daughters when assessing the safety of the GDF. For example, the ingrowth of Ra-226 as a product of the U-238 decay chain can be important in assessments of the safety of geological disposal [17, §2.1].

Radioactive decay is an intrinsic property of each radionuclide, characterised by the property that the probability of a given atom decaying is fixed and independent of time. The total number of decays of that radionuclide $N(t)$ is then proportional to the number of such atoms present so that

$$\frac{dN}{dt} = -\lambda N$$

where the constant of proportionality λ (1/s) is referred to as the radionuclide’s decay constant. If the nuclide is no longer being generated, and the number of such atoms present at $t = 0$ is N_0 then this equation may be integrated to give

$$N(t) = N_0 e^{-\lambda t}.$$

From this solution the time $t_{1/2}$ (s) taken for the number of such atoms to half, ie for

$$\frac{N\left(t + t_{1/2}\right)}{N(t)} = \frac{1}{2}$$

is fixed and given by

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

$t_{1/2}$ is referred to as the half-life of the radionuclide. Radionuclide half-lives range from fractions of a second to billions of years. For example, tritium (H-3) has a half-life of around 12 years, whilst U-238 has a half-life of around 4.5 billion years.

The hazard presented by a radionuclide relates to its activity and the type of radiation emitted. In terms of the activity A, which is the number of disintegrations that a quantity of the radionuclide undergoes per second (Bq):

$$A = \lambda N$$

where N is the number of atoms of the radionuclide present.

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[2] While the term ‘progeny’ is more technically accurate, the term ‘daughter’ is more commonly used and widely understood, hence it is used in this report.

Box 3. Secular equilibrium

As noted in Box 2, when a parent radionuclide decays it may produce one or more daughter nuclides that are not themselves stable. In this case, if the half-life of the daughter is significantly smaller than that of the parent, then, with time, the nuclides tend to a so-called ‘secular equilibrium’ where the concentration of parent and daughter approach a fixed ratio. To see this, suppose that the parent lies at the top of a decay chain and is no longer being generated; if its decay constant is λ_p and the number of atoms initially present N_{p_0}, then the number remaining after a time t is given by

$$N_p(t) = N_{p_0} e^{-\lambda_p t}.$$

The number of daughter nuclides present $N_d(t)$ will then depend upon the rate of decay of the parent together with the rate at which it itself decays, according to

$$\frac{dN_d}{dt} = -\frac{dN_p}{dt} - \lambda_d N_d = \lambda_p N_{p_0} e^{-\lambda_p t} - \lambda_d N_d$$

where λ_d is the decay constant of the daughter and it is assumed that daughter radionuclides are produced only from that parent (and with a stoichiometry of one). This equation may be integrated through the use of the integrating factor $e^{\lambda_d t}$ to produce

$$N_d(t) = \frac{\lambda_p N_{p_0}}{\lambda_d - \lambda_p} e^{-\lambda_p t} + c e^{-\lambda_d t},$$

where c is a constant of integration, determined through the requirement that the number of daughter nuclides is initially zero, $N_d(0) = 0$. This gives finally

$$N_d(t) = \frac{\lambda_p N_{p_0}}{\lambda_d - \lambda_p} \left(e^{-\lambda_p t} - e^{-\lambda_d t} \right).$$

The ratio $N_d(t)/N_p(t)$ is then seen to satisfy

$$\frac{N_d(t)}{N_p(t)} = \frac{\lambda_p}{\lambda_d - \lambda_p} \left(1 - e^{(\lambda_p - \lambda_d)t} \right)$$

and hence if $\lambda_d \gg \lambda_p$

$$\lim_{t \to \infty} \frac{N_d(t)}{N_p(t)} = \frac{\lambda_p}{\lambda_d - \lambda_p}.$$

The time taken to reach secular equilibrium is typically of the order of 5 to10 daughter half-lives.

For the purposes of gaining insights into the significance of the physical and chemical compositions of wastes, it is helpful to divide the various wasteforms into four categories:

- unencapsulated/unimmobilised wastes that would be placed in highly durable containers
- cementitious wasteforms, which are generally alkaline and porous, and quickly saturate if exposed to groundwater
- polymer or resin wasteforms, which are generally relatively impermeable, but may slowly degrade under disposal conditions
- synthetic rock, ceramic or vitrified wasteforms that are chemically highly stable and are expected to immobilise wastes for very long periods of time with very slow leach rates when exposed to groundwater

Waste containers may be grouped according to the level[3] and duration of containment they provide. For example:

- thin walled stainless steel waste drums could remain intact for very long periods of time after closure of the GDF (much more than 1,000 years), although this depends on site-specific hydrological, geochemical and mechanical conditions [15, §12.2.1]
- thick-walled carbon steel and cast iron containers are expected to be highly durable, remaining intact for a long period after GDF closure (more than 1,000 years), although, again, their durability will depend on the environmental conditions at a specific site [15, §12.2.2]
- copper disposal containers, which will be surrounded by a protective bentonite buffer once emplaced in the GDF, may provide containment for more than 100,000 years [15, §11.2.1]

The time taken for radionuclides to enter a mobile phase depends on how quickly groundwater reaches the wasteform and the quality of the wasteform. A long period of containment will ensure substantial decay of many radionuclides in the waste packages. Once exposed to groundwater, high quality wasteforms, such as those discussed above, will dissolve slowly, potentially over hundreds of thousands of years, limiting the concentrations of radionuclides released from the wasteform. The concentration of a radionuclide in groundwater may also be limited by the maximum amount of the radionuclide that can dissolve in the groundwater under disposal conditions (the solubility limit). The quantity of mobile radionuclides will therefore be limited by the rate of dissolution of the wasteform, the solubility of those radionuclides in the associated groundwater, and the rate at which mobile radionuclides are transported away from the wasteform in groundwater. The solubility limit effectively acts as a cap on the dissolved concentration of a radionuclide, and thus limits transport in groundwater. For example, radionuclides such as uranium and plutonium are likely to be solubility limited under disposal conditions, whereas chlorine and iodine will effectively have unlimited solubility [30; 17, §2.6].

Another significant property of a waste package is the amount of gas, if any, it may generate through chemical reactions and radiolysis. Some radionuclides (for example C-14) may be transported away from the disposal facility in the gas phase, and bulk gas generation (predominantly hydrogen from corrosion reactions) could pressurise parts of the engineered barrier system (EBS) if there is resistance to gas transfer. Simple physical laws (such as, Henry's law – see Box 4) can be used to estimate how much of the gas dissolves in groundwater as it migrates through the barrier system. Section 6 presents some illustrative calculations of gas generation and migration from different types of waste in different geological environments.

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[3] LHGW containers (such as thin walled stainless steel containers) will generally be vented, whilst HHGW containers (such as copper and carbon steel containers) would not be vented. The vents in LHGW containers provide openings for the release of gases generated within the waste package, but in a saturated disposal environment the vents may allow groundwater ingress before the container is breached in the long term as a result of degradation processes (such as corrosion). The presence of the vent in this type of package makes it unlikely for them to provide complete containment of the radionuclides during the post-closure phase, even if the package functionality is preserved for long times: after backfilling, the GDF will become resaturated with groundwater and transport of radionuclides through the vent is likely to occur slowly [14, Box 21].

Box 4. Henry's Law

Henry's Law states that, at a constant temperature, the amount of a given gas dissolved in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid [18, §3.3.3]. In a mixture of ideal gases, each gas has a partial pressure, which is the pressure that the gas would have if it alone occupied the volume. The total pressure of the mixture of gases is the sum of the partial pressures of each individual gas in the mixture.

Henry's Law is strictly valid only for ideal gases and dilute porewaters in the GDF environment. For real gases the fugacity (a function of temperature, pressure and composition of the solution) should be used instead of the partial pressure. Thus, the Henry's Law 'constant' depends on the gas, the composition of the liquid and the temperature. However, Henry's Law is adequate for describing the solubility of most of the gases of interest in low ionic strength waters [18, §3.3.3].

In the post-closure period, the safety significance of different waste conditioning and packaging options largely depends on the characteristics of the engineered barrier system and the geological environment, and any pathways by which radionuclides could migrate to the accessible environment, as discussed in the next section.

4.2 Understanding barrier system performance

For waste to present a hazard (in terms of its radiological content) in the post-closure period, radionuclides must be released from waste packages, migrate through the engineered barriers and find a pathway through the geological environment to the biosphere. The following potential radionuclide transport pathways require consideration:

- the groundwater pathway
- the gas pathway

In addition, assuming loss of knowledge of the GDF's location at some time in the future, the potential for inadvertent human intrusion into the GDF also requires consideration, as this could provide a further route for transport of radionuclides into the biosphere.

The groundwater and gas pathways are not independent, as gases are able to dissolve in groundwater at sufficiently high partial pressure (see Box 4) and are able to reform following migration to locations in the system where the partial pressure reduces (for example, nearer the ground-surface where fluid pressures are lower). Further, radionuclide migration largely depends on the site-specific properties of the geological environment (for example, rock permeability, fracture properties, heterogeneity), as discussed in Section 6. Therefore, no simple insight models have been developed for this PCSA for gas migration.

Significant insight can be obtained into how radionuclides could migrate via the groundwater pathway through a high level 'semi-quantitative' analysis of migration processes. There are two fundamental processes that lead to the movement of radionuclides in a groundwater-saturated environment, namely advective transport and diffusive transport, which are considered in turn.

Advective transport occurs when the radionuclides transfer to a mobile form, for example by dissolving in groundwater or by attaching to mobile colloids, and then migrating via the bulk motion of the groundwater. This advective transfer process may be visualised by considering how a spot of ink would be carried by water when dropped into a flowing stream.

The rate of radionuclide migration depends on the groundwater flow velocity (as well as the concentration of the mobile radionuclide in the groundwater and the rates of radionuclide decay and ingrowth). Any groundwater flow in the GDF will be driven primarily by hydraulic head gradients, although thermal and salinity gradients may also result in groundwater movement. A low groundwater flow velocity (or the absence of groundwater) is desirable for post-closure safety.

The structure of any connected porosity and/or fracture network present in the engineered and natural barriers surrounding the waste packages will also be important in determining the direction and rate of groundwater flow, and thus any radionuclide transport pathways. Typically, groundwater flow in a porous medium is approximated by Darcy's Law (Box 5), although the presence of an interconnected fracture network may have a dominant effect on flow conditions.

Diffusive transport of radionuclides occurs when the waste dissolves in groundwater and the mobile radionuclides travel from an area of high radionuclide concentration to an area of lower concentration due to the random motion of molecules or particles. This diffusion process may be visualised by considering the behaviour of a spot of ink when dropped into a glass of water. The rate of radionuclide migration depends on the concentration gradient according to Fick's first law (see Box 6).

Once mobile, any advected radionuclides have a tendency to disperse as they migrate [17, §2.13]. This results from the groundwater taking an indirect path through the connected pores or fractures of the material (as shown in Figure 4) and results in a spread of radionuclides laterally to the flow direction. Radionuclide spreading will also occur along the length of a transport pathway because of variability in groundwater velocity as well as heterogeneity along the pathway. These spreading effects are known as transverse and longitudinal hydrodynamic dispersion respectively.

As radionuclides migrate they may sorb to wasteform materials, engineered barriers and rock [17, §2.5]. The quantity that sorbs depends on the concentration of the radionuclide in the surrounding groundwater and the radionuclide-barrier interaction properties. A common model used to represent this interaction is the linear equilibrium sorption model (see Box 7) which is a reversible process in which the concentration of radionuclides sorbed to rock depends linearly on the local concentration in groundwater at that point.

Sorption has the effect of delaying radionuclide migration and this delay is represented by a retardation factor. The higher the retardation factor, the slower the migration of radionuclides away from the disposal system. Radionuclides such as uranium and plutonium will sorb strongly to most rocks, but others, such as chlorine and iodine, have little or no potential for sorption [30; 17, §2.5].

Processes such as sorption and solubility limitation reduce the rate at which mobile radionuclides migrate along groundwater transport pathways and provide more time for radionuclides to decay. Processes such as diffusion and longitudinal and lateral dispersion help to dilute radionuclides and thereby limit their concentrations in groundwater.

In general, both advective and diffusive mass transfer processes will be present in the geological environment, but in practice it is common for one to dominate. Sedimentary rocks such as clays generally have a relatively high, but unconnected, porosity, and therefore are of low permeability and resist flow for usual pressure gradients. Thus, diffusive processes tend to provide the primary migration mechanisms in clays. Higher strength rocks are more likely to have a connected porosity, with groundwater able to flow through fracture networks. Whether advective transport is important in such environments depends on whether sufficient pressure gradients are present to drive bulk flow of groundwater.

Box 5. Darcy's Law

The first experimental study of groundwater flow was performed by Henry Darcy [39]. He found that one-dimensional flow of water through a pipe filled with sand was proportional to the cross sectional area and the hydraulic head loss along the pipe and inversely proportional to the flow length. Darcy's law can be expressed as:

$$Q = -KA\nabla h$$

where

Q = volumetric discharge (m^3/s)

K = hydraulic conductivity (m/s)

A = cross-sectional area (m^2)

∇h= gradient of hydraulic head (-)

This equation can also be expressed in terms of specific discharge, or Darcy velocity, q (m/s), as follows:

$$q = \frac{Q}{A} = -K\nabla h$$

Box 6. Fick's first law

A solute in water will move from an area of greater solute concentration towards an area where it is less concentrated. This process is known as diffusion [39]. Diffusion will occur as long as a concentration gradient exists, even if the fluid is not moving. The mass of solute diffusing (the diffusive flux) is proportional to the concentration gradient, which can be expressed according to Fick's first law of diffusion:

$$F = -D_d\nabla C$$

and this is related to the solute concentration according to Fick's second law of diffusion:

$$\frac{\partial C}{\partial t} = -\nabla \cdot F$$

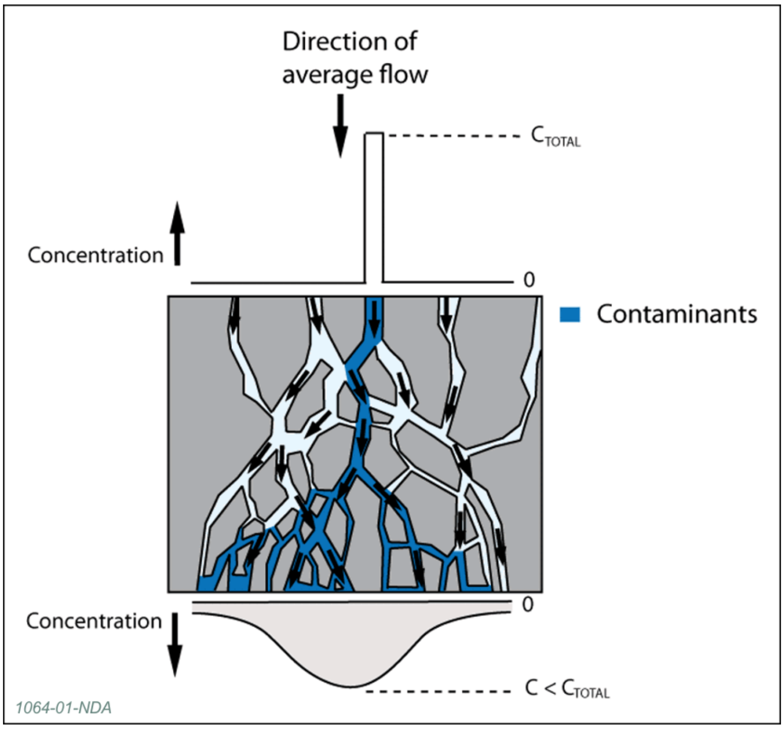
where

F = mass flux of solute (kg/m^2s)

D_d = diffusion coefficient (m^2/s)

C = solute concentration (kg/m^3)

Figure 4 **Illustration of the process of hydrodynamic dispersion [17, Fig. 18]**



Box 7. Linear equilibrium sorption

If there is a linear relationship between the amount of a solute sorbed onto a solid and the concentration of the solute, the resulting linear sorption isotherm is described by the equation [39]

$$C^{*} = K_d C$$

where

C^{*} = mass of solute sorbed per dry unit weight of solid (kg/kg)

C = concentration of solute in solution in equilibrium with the mass of solute sorbed onto the solid (kg/m^3)

K_d = the distribution coefficient (m^3/kg)

Whether advection or diffusion dominates can be determined by consideration of the Péclet number, which represents the ratio of the advective transport rate to the diffusive transport rate (see Box 8). Section 4.3.2 presents high-level insight calculations for radionuclide migration in an environment in which the Péclet number is high (that is, transport dominated by advection). Section 4.3.3 presents an insight calculation for radionuclide migration in an environment where the Péclet number is low (that is, transport is dominated by diffusion).

Box 8. Péclet number

A Péclet number is a dimensionless number that relates the effectiveness of mass transport by advection to the effectiveness of mass transport by diffusion [39]. Péclet numbers have the general form

$$v_x d / D_d$$

where

v_x= fluid velocity (m/s)

d = characteristic transport length (m)

D_d = the diffusion coefficient (m^2/s)

4.3 Insight calculations

In this section, insight calculations are presented to support understanding of:

- the effects of radionuclide decay and ingrowth on total radionuclide activity
- the migration of radionuclides through an advection-dominated geological environment
- the migration of radionuclides through a diffusion-dominated geological environment

4.3.1 Effect of radionuclide decay

Useful insight into the nature of the UK's radioactive waste and the hazard it presents may be obtained by examining how its total activity changes with time. Each type of waste contains many radionuclides, the half-lives (and thus the activities) of which vary over many orders of magnitude (see Box 2 and [30]). As radionuclides in the waste decay and generate daughter radionuclides, the radionuclide composition and the total activity of the waste change. 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 daughter radionuclides up to that time. As the total activity of the waste and the composition of the component radionuclides changes, the radioactive hazard it poses changes, generally reducing with time[4]. This radioactive hazard can be assessed in the context of the environmental safety functions provided by the multiple barriers of the GDF over different timescales, to give insights into the environmental safety of the GDF. In Section 5, the safety function provided by each barrier of a disposal concept is assessed by evaluating how the activity fluxes of radionuclides change through progressive GDF barriers.

Individual waste streams within the 2013 Derived Inventory [7] are grouped according to their origin (for example, High Level Waste, new build spent fuel and highly enriched uranium). When considering post-closure safety it is useful to split the waste groups into two classes, namely HHGW and LHGW, because they have distinct packaging and disposal concepts. The HHGW and LHGW groups are listed in Table 2. Figure 5 shows how the total activities of the various HHGW groups vary over a period of one million years after GDF closure. Figure 6 shows the total activity evolution of LHGW groups over a similar period.

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[4] In some cases the hazard may increase in time when the radionuclides decay to certain daughter radionuclides.

Table 2 Derived Inventory waste groups

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

Figure 5 Effects of radioactive decay on the total activity of HHGW groups listed in Table 2; the combined total activity of all LHGW and HHGW is also shown

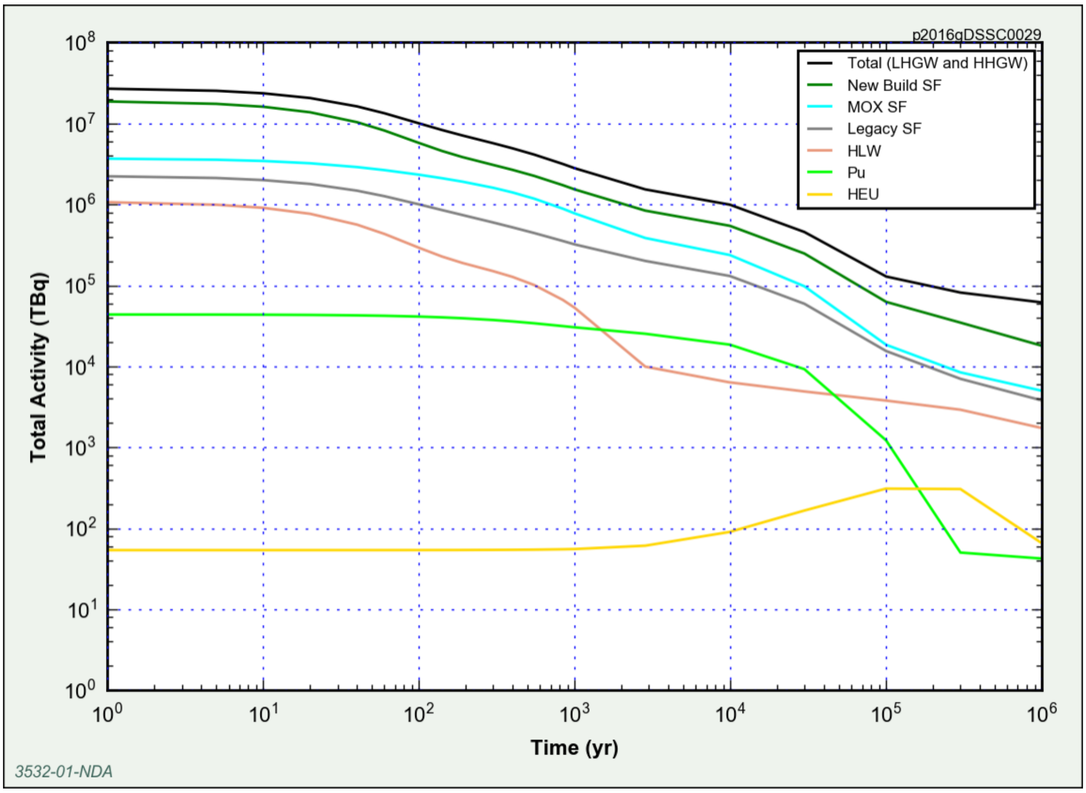


Figure 6 Effects of radioactive decay on the total activity of LHGW groups listed in Table 2; the combined total activity of all LHGW and HHGW is also shown

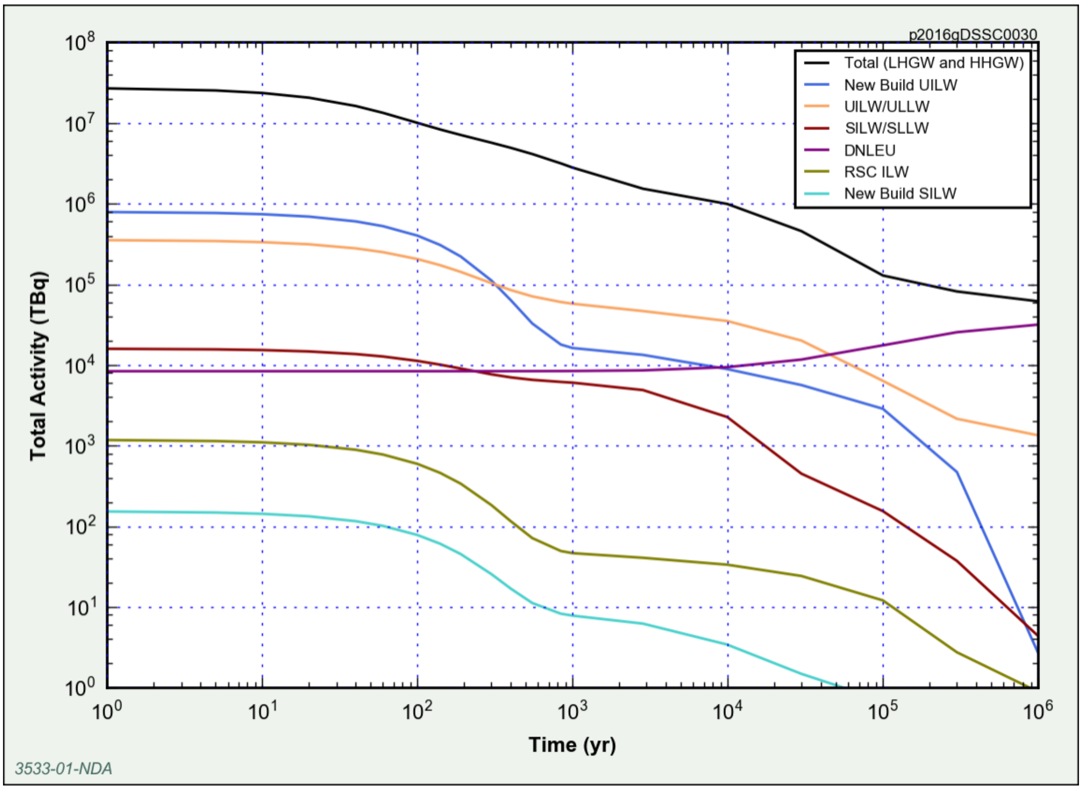


Table 3 summarises the effects of radioactive decay and ingrowth on total radionuclide activity at different times after GDF closure as a percentage of the activity that was present at the assumed time of GDF closure (2200). The following insights may be drawn:

- over a 100 year period after closure, during which a GDF site is likely to remain under institutional control, the total activity of LHGW and HHGW is reduced by over 60%
- over a 1,000 year period, which is the minimum timescale over which a thin-walled stainless steel ILW drum is expected to provide containment, LHGW activity is reduced by over 90%
- over a 10,000 year period, HHGW activity, which dominates total activity, is reduced by over 96%
- over a 100,000 year period, which is the timescale over which a copper container is expected to provide containment according to the illustrative concept for HHGW in higher strength rock, HHGW activity is reduced by over 99.5%
- the change in total activity after 100,000 years is small and the activity of LHGW increases slightly and eventually begins to dominate as higher activity daughters of long-lived uranium isotopes in DNLEU are ingrown and eventually reach equilibrium with their parents; note that 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

In summary, most of the radionuclides in the inventory for disposal will decay within the waste containers, so that the activity of any radionuclides released from degraded waste packages will be low. This highlights the importance of the environmental safety functions provided by the waste containers and the engineered barrier systems that protect them. The total activity of the waste will change little in the period beyond 100,000 years. However, as discussed in Section 4.2, processes such as sorption, diffusion and dispersion will act to limit the concentrations of any radionuclides that might migrate to the biosphere. These factors combine to ensure that the environmental safety of geological disposal is maintained in the long term.

Table 3 Percentage of radionuclide activity remaining in LHGW and HHGW as a function of time after assumed GDF closure

Period after GDF closure [years]	Remaining activity as a percentage of activity at the time of GDF closure		
	LHGW	HHGW	LHGW and HHGW
100	53.5%	36.1%	36.8%
1,000	7.5%	10.4%	10.3%
10,000	4.7%	3.6%	3.6%
100,000	2.3%	0.4%	0.5%
1,000,000	2.8%	0.1%	0.2%

4.3.2 Migration of radionuclides through an advection-dominated geological environment

The peak radiological risk arising from the migration of radionuclides via the groundwater pathway in an advection-dominated geological environment can be estimated using a simple one-dimensional insight model of radionuclide transport in a porous medium, as described in Box 9.

A simple slow leaching model may be used to represent radionuclide release from a disposal region, where the radionuclide flux from the disposal region is proportional to the inventory remaining in the disposal region. The underlying conceptual model of the source term is one of radionuclides fully dissolved in pore water (that is, not subject to any solubility limitation) and evenly distributed throughout the disposal region. These source term assumptions are not realistic for a GDF, but they allow a simplistic evaluation of radionuclide transport. Using the insight model presented in Box 9 and Box 10, the peak radiological risk for a radionuclide (n) depends on:

- the initial inventory (M_0^n) of each radionuclide (n) in the disposal region and its rate of decay (λ_n)
- the amount of each radionuclide leaving the disposal region and the extent of spreading of the source term (σ_s^2), which depends on:
    - the specific discharge of groundwater through the disposal region (q)
    - the cross-sectional area of the disposal region (A)
    - the volume of the disposal region (V)
    - the accessible porosity within the disposal region (ϕ_n^V)
    - the density of materials in the disposal region (ρ^V)
    - sorption to materials in the disposal region (for example, backfill) $(K_{d,n}^V)$
- the extent of spreading of radionuclides through the geological barrier $(\sigma_{g,i}^2)$, which depends on:
    - the path length through the geological barrier (L)
    - the time for groundwater to travel across the geological barrier (T_i)
    - dispersion in the geological barrier (α_L)
    - retardation in the geological barrier (R_n)
- the biosphere factor (B_n)

The dependence of the peak radiological risk on the above quantities is set out in Box 10.

Examining the equation in Box 10, it can be seen that peak radiological risk is low if there is:

- a long retarded travel time in the geological barrier relative to the rate of radionuclide decay (represented by a large value for the dimensionless parameter $\lambda_n R_{n,i} T_i$), which implies a long groundwater travel time to the biosphere for long-lived radionuclides
- significant longitudinal dispersion (represented by the dimensionless parameter $a_{L,i}/L_i$) along the transport path through the geological barrier (which spreads the radionuclide plume and reduces the peak flux)
- slow leaching of radionuclides from the disposal region relative to the rate of radionuclide decay (represented by a small value of the dimensionless parameter $qA/\lambda_n V$), which indicates the importance of a low rate of water flow through the host rock and disposal region when considering the risks associated with long-lived radionuclides

Box 9. Insight model for radionuclide advection

Assuming a homogeneous porous medium with one-dimensional advection, longitudinal dispersion, linear reversible sorption and radionuclide decay (but not ingrowth), the porewater concentration $c_n(x,t)$ of an isotope n at position x and time t is given by [40]

$$R_n \frac{\partial c_n}{\partial t} = D_n \frac{\partial^2 c_n}{\partial x^2} - v \frac{\partial c_n}{\partial x} - \lambda_n R_n c_n \tag{1}$$

where λ_n is the decay constant and

$$R_n \equiv 1 + \frac{\rho K_{d,n}}{\phi_n}$$

is the retardation factor for species n, ρ is the density of the rock, ϕ_n is the accessible porosity of the rock to radionuclide n, v is the groundwater velocity and

$$D_n \equiv D_n^{\text{eff}} + a_L v$$

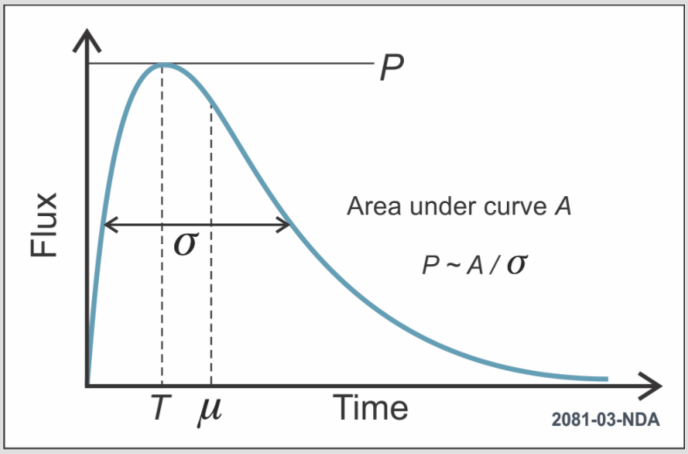
where D_n^{eff} is the effective diffusivity and a_L is the longitudinal dispersion coefficient. Neglecting solubility limitation, the advection-dispersion equation may be solved using a Laplace transform when coupled to a suitable model for radionuclide release from a disposal region at $x = 0$, $t = 0$ and a boundary condition.

The radiological risk to a member of an exposed group in the biosphere assumed to be at some location downstream from the source term may be calculated through the use of equilibrium biosphere factors that relate radionuclide fluxes to radiological doses. That is, the radiological risk from radionuclide n may be written as

$$r B_n F_n$$

where r is the dose to risk conversion factor, B_n is the biosphere radionuclide flux to dose conversion factor and F_n is the peak flux of radionuclide n entering the biosphere.

The peak radionuclide flux may be estimated through the use of a simple approximation to the shape of a radionuclide breakthrough curve (that is, the curve showing the time of travel across a geological barrier). As indicated in the figure below, for a radionuclide plume migrating from the geological environment to the biosphere, the peak radionuclide flux P at time T may be approximated by SA/σ where A is the area under the curve, σ is a measure of the width of the curve, usually given by the standard deviation (μ is the breakthrough time of the mean of the radionuclide flux), and S is a scaling factor of order unity [41] used to improve the approximation.



For the solution to equation (1) above, both A and σ may be calculated in Laplace space and hence used to determine P.

Box 10. Solution of the insight model for advection

For the slow leaching model, it may be shown that the peak risk for an inventory containing radionuclide n (for which there is no ingrowth from the decay of other radionuclides) travelling across a geological barrier defined by k distinct stratigraphic units is

$$R_{peak,n} = \frac{rB_n S M_0^n \lambda_n}{\sqrt{\sigma_{s,n}^2 + \sum_{i=1}^{k} \sigma_{g,n,i}^2}} \prod_{i=1}^{k} e^{\frac{1-\psi_{n,i}(0)}{2} \frac{L_i}{a_{L,i}}} \tag{2}$$

where

$$\sigma_{s,n}^2 = \left(\frac{1}{1 + k_n/\lambda_n}\right)^2$$

and

$$\sigma_{g,n,i}^2 = \frac{2\left(\lambda_n R_{n,i} T_i\right)^2}{\psi_{n,i}^3(0)} \frac{a_{L,i}}{L_i}$$

with

$$\psi_{n,i}(0) = \sqrt{1 + \frac{4(\lambda_n R_{n,i} T_i) a_{L,i}}{L_i}}$$

and

$$\frac{k_n}{\lambda_n} \equiv \frac{qA}{(\phi_n^V + \rho^V K_{d,n}^V)\lambda_n V}$$

where T_i is the time for groundwater to travel across the geological barrier (given by L_i/v_i with L_i the thickness of geological barrier i and v_i the groundwater speed within it).

The symbol Π is used to indicate products of terms as the coefficient is varied between its limits, so that $\prod_{i=1}^{k} a_i = a_1 \times a_2 \times \ldots \times a_k$ and the symbol Σ is used to indicate sums of terms. These terms appear as a result of the representation of the output of one geological unit as the input to the next.

The functions $\sigma_{s,n}^2$ and $\sigma_{g,n,i}^2$ are referred to as the source term and geosphere spreading time, respectively. Increases in the values of either of these terms (as a result of, for example, greater retardation or a reduction in groundwater velocity) imply reduced peak risk.

It is also evident from the equation in Box 10 that the calculated peak radiological risk increases linearly with:

- the initial radionuclide inventory M_0^n
- the biosphere radionuclide flux to dose conversion factor B_n

The insight radionuclide advection model described above has two significant limitations:

1. The neglect of radionuclide ingrowth, which means that the model is unsuitable for evaluating peak radiological risk for any radionuclides for which significant ingrowth occurs on the timescale of radionuclide migration through the geological barrier.
2. Neglect of solubility limitation leads to an over-estimation of the migration of those radionuclides that would be solubility limited under disposal conditions. Any

solubility limitation will occur in the EBS of a disposal system where the concentration is greatest.

4.3.3 Migration of radionuclides through a diffusion-dominated geological environment

This section describes the use of an approximate analytic solution to the diffusion equation to explore the time taken for radionuclides to diffuse through different thicknesses of low-permeability rock (where advection is insignificant). This solution to the diffusion equation provides insights into the safety functions provided by a low-permeability rock such as a lower strength sedimentary rock.

If a disposal region is sufficiently elongated that one-dimensional diffusion from the disposal region across a plane into the neighbouring rock may be assumed, then the concentration of a substance in porewater can be calculated as shown in Box 11. Using the expression for diffusive radionuclide transport in Box 11, the time for a radionuclide to break through a geological barrier by diffusion can be estimated as a function of barrier thickness.

For example, for a relatively mobile species assumed to be diffusing through a clay layer with effective diffusion coefficient:

$$D_n \sim 10^{-10}\ \mathrm{m}^2/s,$$

the radionuclide breakthrough time varies with the thickness of the clay layer as shown in Figure 7. In this figure, estimated breakthrough times are evaluated as times at which the radionuclide concentration at a distance L from the source reaches 0.01%, 0.1% and 1% of the source concentration. It is seen that it would take a radionuclide around 100,000 years to diffuse through a clay layer with a thickness of around 100 metres (neglecting factors such as radioactive decay and sorption). As described earlier, after such a period only around 0.5% of the initial radioactivity would remain. Thus, for a GDF located at the centre of a clay host rock (noting that diffusion would occur both upward and downward from the GDF), a 200-metre-thick clay layer would be expected to provide containment for more than 100,000 years after closure.

Box 11. Diffusive breakthrough model

The porewater concentration $c_n(x,t)$ of a substance is given by the diffusion equation [39]

$$\frac{\partial c_n}{\partial t} = D_n \frac{\partial^2 c_n}{\partial x^2}$$

where decay has been neglected for radioactive species and D_n is the effective diffusion coefficient, which includes the effect of tortuosity in a porous medium.

The concentration c_n may be determined by solving the above equation with a fixed concentration boundary condition $c_{n,0}$ in the disposal region and with the concentration tending to zero at large distances from the source term. These are both conservative assumptions, because in reality the radionuclide concentration in a disposal region will reduce as radionuclides migrate away from it (although the radionuclide concentration may be solubility limited initially). The solution to the diffusion equation is given by

$$c_n(x,t) = c_{n,0}\mathrm{erfc}\sqrt{\frac{x^2}{4D_n t}}$$

where erfc is the complementary error function $(1 - \mathrm{erf}(x))$. The error function is a well understood integral which may be evaluated numerically. This solution indicates that the front of a radionuclide plume travels with time according to the relation

$$x \sim \sqrt{4D_n t}$$

implying that the radionuclide travel time over a given distance is of the form

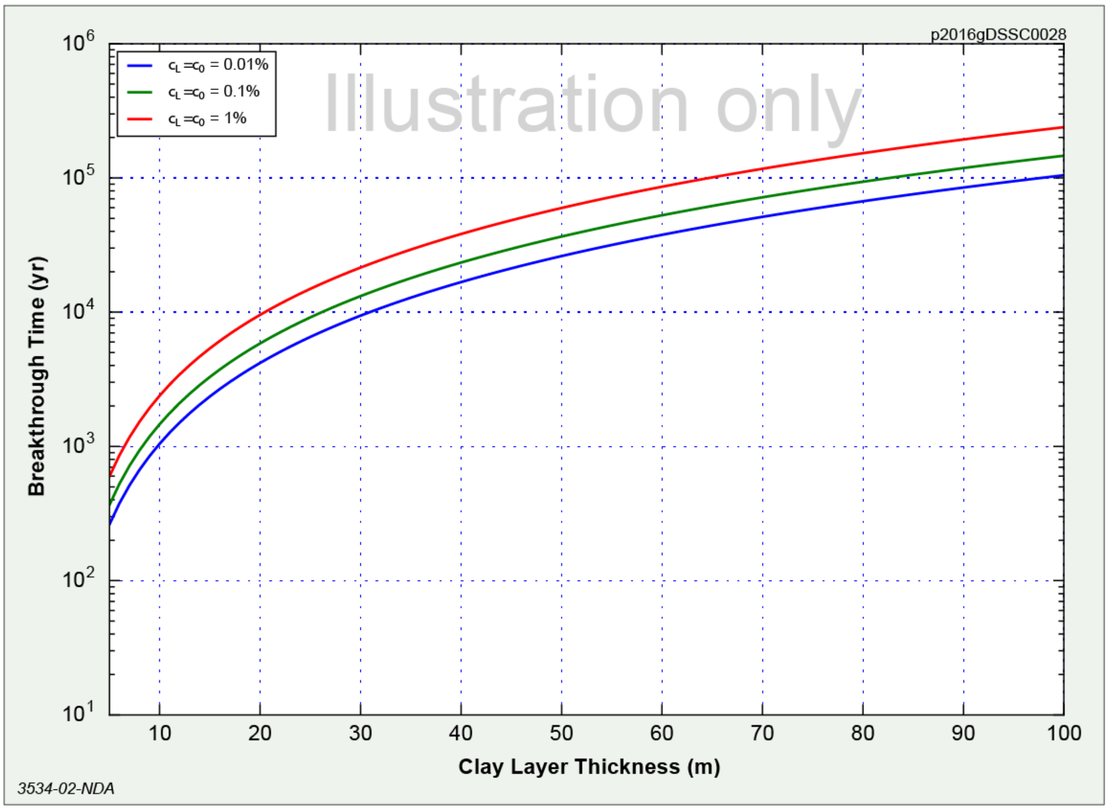
$$t \sim \frac{x^2}{4D_n}$$

Hence the diffusion time varies as the square of the diffusion distance. If the time for a radionuclide plume to pass through a diffusive medium of thickness L is defined as the time at which $c_n(L,t)/c_{n,0}$ first reaches a specified value, then the breakthrough time varies with L according to

$$t = \frac{L^2}{4D_n}\left[\frac{1}{\mathrm{inverf}\left(1 - \frac{c_n}{c_{n,o}}\right)}\right]^2$$

This expression is a pessimistic representation of radionuclide diffusion through rock because it neglects radioactive decay, sorption and the effects of diffusion in three dimensions. The expression also excludes the period of containment provided by the engineered barrier system and other factors such as the time taken for the host rock and EBS to re-saturate after GDF closure.

Figure 7 **Radionuclide breakthrough time by diffusion through clay as a function of clay layer thickness (excluding the effects of radionuclide decay and sorption)**



4.4 Summary

An understanding of the processes that affect how radionuclides behave under potential disposal conditions enables insights to be developed into the way in which environmental safety arguments can be qualified and quantified for a multi-barrier disposal concept. It is important to remember that a GDF may not necessarily be saturated, in which case detailed modelling of transport in groundwater would not be required. For example a facility constructed within an evaporite host rock may be dry so that a groundwater transport pathway will not exist.

The presence of a durable container and a robust wasteform can delay the formation of mobile radionuclide phases (whether via the groundwater or the gas pathway), potentially allowing substantial decay of radionuclides in the waste packages. The permeability distribution and hydraulic head gradients in the geological environment determine how any radionuclides released from waste packages could migrate. Physical processes such as solubility limitation, sorption, diffusion and dispersion act to control radionuclide transport rates and concentrations. Evaluations of these processes have been presented using simple models in order to build a greater understanding of radionuclide behaviour in the GDF.

With the exception of decay and ingrowth, the radionuclide behaviour processes discussed in this section are equally applicable to the behaviour of non-radiological species, and the methods used to evaluate radionuclide behaviour can also be used to evaluate the behaviour of non-radiological species.

Note also that the various radionuclide transport processes discussed in this section are represented in the detailed probabilistic total system models that have been developed for assessing GDF performance for disposal concepts in different illustrative geological environments. The results of the more detailed calculations for the groundwater pathway are presented in Section 5.

5 Radiological Assessment of the Groundwater Pathway

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 that individuals, society and the environment are protected against radiological and non-radiological hazards in the long term. This requires a detailed understanding of the way the various barriers of the disposal system work together to isolate and contain the wastes as conditions evolve after GDF closure. That is, an understanding of how radionuclides and potential non-radiological contaminants are released from waste packages (in groundwater and gas) and transported through the barrier system is required.

This section presents the results of detailed total system modelling of radionuclide migration along groundwater pathways for disposal concepts defined for specific illustrative geological environments. Illustrative calculations of disposal system performance have been undertaken using these models in order to evaluate radionuclide fluxes through barriers and the potential risks associated with any exposure to radionuclides that might migrate to the surface environment in the long term. The models enable illustrative estimates of the radiological risks associated with geological disposal to be compared with the regulatory risk guidance level (see Section 2.2). The calculations provide a means of identifying the key radionuclides contributing to the calculated radiological risk and provide quantitative support for the safety arguments presented in the ESC [5].

As discussed in Section 3.4, RWM has developed hydrogeological and geochemical descriptions of specific illustrative geological environments for performance assessment calculations. These descriptions have been developed in order to enable assessment calculations to be undertaken prior to the availability of a detailed understanding of a specific disposal site. The detailed descriptions of groundwater pathways along which radionuclides may migrate from the GDF have been developed for illustrative disposal concepts in higher strength rock and lower strength sedimentary rock, but are not required for the illustrative disposal concepts in evaporite rock because such host rocks do not include groundwater transport pathways [19, §3.1.1].

As noted in Section 3.4, the deterministic descriptions of potential radionuclide transport pathways should only be seen as illustrations of the potential characteristics of the GDF in these types of geological environment. The transport pathways have been defined as a means of undertaking calculations to provide an indication of the environmental safety functions provided by a geological barrier and to identify the relative contributors (in terms of waste groups and radionuclides) to calculated radiological risk. The definition of transport pathways also provides a means of demonstrating how quantitative assessments could be undertaken to support a post-closure safety case in the future when disposal sites become available.

This total system modelling (TSM) approach represents a progression from that taken in the 2010 PCSA [6, §5.2], where advective transport pathways in the geological environment were characterised by a small number of key parameters that focused on the assessment of the GDF in higher strength rock. However, although the approach taken in this generic PCSA 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 similar to that adopted in the 2010 PCSA calculations.

5.1 Illustrative geological environment for higher strength rock

The illustrative geological environment assumed for these TSM calculations is shown in Figure 8; it represents an example of a higher strength host rock overlain by a higher-permeability sedimentary rock [19, §5.3.2]. The GDF is located 650 metres below ground level (BGL) within a higher strength host rock defined as a very low grade metasediment[5]; a component of the GDF assumed to represent a radionuclide release region is indicated in Figure 8; but the actual GDF is of greater lateral extent than illustrated. The metasediments are assumed to be metamudstones (mudstones with a slatey cleavage) [19, §3.1.3]. The metamudstone dips towards the coast and overlying the GDF is 350 metres thick (from the assumed location of radionuclide release from the GDF to the top of the metamudstone host rock), the upper 20 metres of which is weathered. The overlying cover rocks consist of fine-to-coarse grained sandstone containing localised silt and clay layers; the cover rocks are 300 metres thick above the GDF. Superficial deposits are present at surface in the low-lying areas below 70 metres AOD (above ordnance datum), comprising silt with sand and gravel lenses.

For such a geological environment, the sandstone is assumed to have been deposited within a sedimentary basin with an extensional boundary fault present at the basin margin (as indicated in [19, Figure 27]). The boundary fault is not illustrated on the cross-section shown in Figure 8, and is not considered within the parameterisation of the conceptual model. Whilst this is an over-simplification of the geological environment, it reduces the need to make further assumptions regarding groundwater flow and radionuclide migration. The influence of the fault is, however, indicated by the thickening of the sandstone and the down slope on the upper surface of the metamudstone in an eastwards direction along the line of section.

Conditions in the illustrative geological environment have been assumed to remain stable for the 300,000 year assessment period, as discussed in the following sub-sections.

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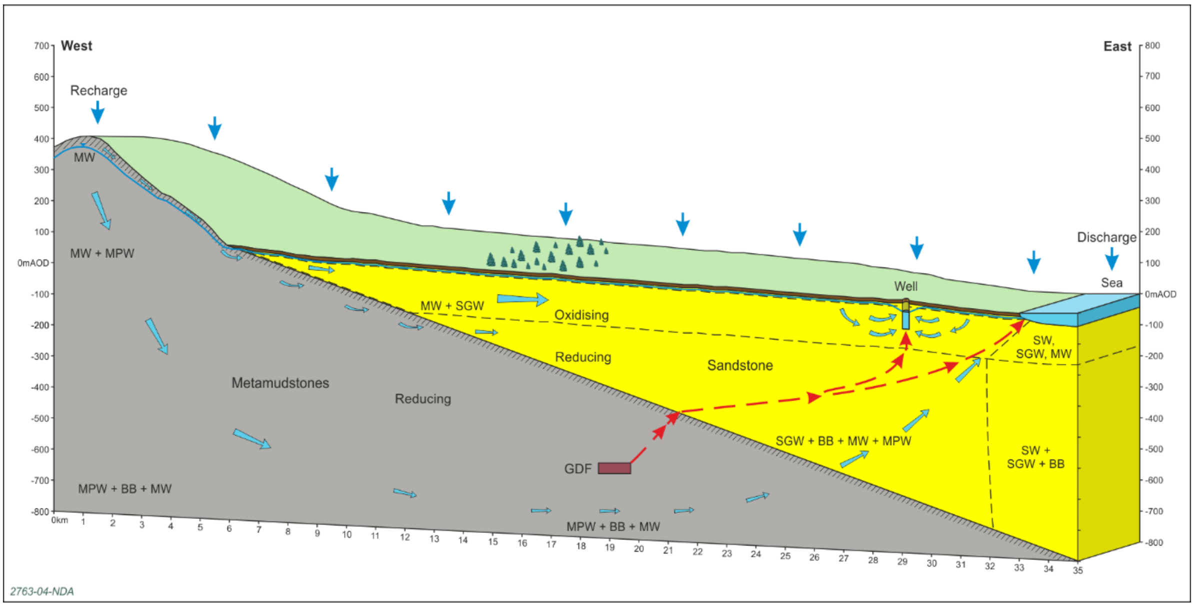
[5] Metasediments are sediments or sedimentary rocks affected by metamorphic processes and have a variety of compositions and properties that depend upon the initial rock properties and the intensity, heat and duration of metamorphic processes.

Figure 8 **Possible groundwater pathway from a GDF to the surface environment where the higher strength host rock is overlain by a sequence of sedimentary formations[6]; a component of the GDF is illustrated – the complete GDF is of greater lateral extent**



5.1.1 Hydrology and hydrogeology

The line of section illustrated in Figure 8 is 35 kilometres long and orientated west to east. From the west, the first 10 kilometres is represented by high ground up to 400 metres AOD. Thereafter the topography slopes gently from 70 metres AOD to 0 metres AOD at the coast. The high ground to the west forms both the surface water and groundwater catchment divide, which constitutes a vertical no-flow boundary in the model.

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 base of the metamudstone rock represents a no-flow boundary in the model (that is, there is no inflow of groundwater to the metamudstone from deeper rocks).

The permeability of the rocks is anisotropic because of the interconnected fractures and bedding plane permeability in the metamudstone and sandstone, as well as intergranular permeability in the sandstone. The permeability of the metamudstones is less than that of the overlying sandstone. Additionally, the overburden weight closes fractures, causing permeability (and groundwater flux) to decrease with depth.

As indicated by the blue line near the ground surface in Figure 8, a shallow water table exists in the outcropping metamudstones in the west and within the superficial deposits and sandstone to the east (which, for simplification are assumed to act as a single aquifer, with no perched groundwater bodies present). The average depth to the groundwater in low lying areas is 4 metres BGL. The water table is deeper (approximately 30 metres) below the high ground formed by the metamudstone in the west (that is, the water table exhibits a subdued form of the topography). Whilst, in reality, groundwater in both the sandstone and mudstones would be confined to some degree and at some locations, estimation of

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

hydraulic gradients along the flow paths has been simplified by assuming unconfined conditions throughout.

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.

5.1.2 Groundwater composition

The composition of groundwater reflects recent precipitation, rock type, the duration of contact between the rock and water (residence time), rock temperature, the existence of water trapped during its formation or during past meteoric or saline recharge, and mixing with groundwater inflowing from other sources.

The groundwater bodies assumed to be present in this illustrative geological environment are indicated by the dashed black lines on Figure 8, although the boundaries shown are more likely to be gradational rather than distinct. The assumed groundwater compositions are summarised below:

- Shallow, near surface groundwater composition across the line of section, irrespective of rock type, will have a composition that is predominantly that of recent precipitation, or meteoric water (MW), modified slightly by chemical reaction with the rock.
- There are assumed to be two hydrochemically-distinct groundwater bodies in the sandstone:
    - Groundwater in the upper 150 metres (‘upper groundwater unit’) is assumed to be oxidising. The salinity is assumed to be intermediate between MW and fresh sandstone groundwater (SGW) and will also reflect the composition of groundwater inflowing from the lower sandstone groundwater body.
    - Groundwater below 150 metres (‘lower groundwater unit’) is assumed to be chemically reducing and likely to be hydraulically confined, but for the purposes of simplification will be considered as being unconfined. It is assumed to have an intermediate salinity, having minor components of basinal brines (BB) and mudrock porewater (MPW) reflecting inflow of groundwater from the metamudstones.
- Towards the coast, both the upper and lower sandstone units are assumed to incorporate a seawater component due to seawater intrusion and fluctuation of the saline/groundwater interface in the past. The saline water/groundwater interface represents a no-flow boundary in the model, with groundwater following the marine flow path discharging at the coast, landward of the interface. The shape of the groundwater/saline water interface represented on Figure 8 reflects the principles of the Ghyben-Herzberg relationship[7] [42, §2.11.2], noting the limitation however that this relationship is true for systems in hydrostatic equilibrium (rather than the hydrodynamic system here, in which groundwater is flowing to the sea).
- Groundwater in the shallower part of the metamudstone beneath its outcrop and the western edge of the sedimentary cover will be predominantly MW with a small

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[7] The Gyhben-Herzberg rule reflects the observation that, for unconfined coastal aquifers, the depth to which fresh water extends below sea level is approximately forty times the height of the water table above sea level [42, §2.11.2].

proportion of MPW, which will increase with depth. Relatively minor flow of this groundwater to greater depth accounts for dilution of pre-existing deeper MPW towards the location of the GDF.

- Groundwater flowing into the GDF from within the metamudstone host rock will have a composition of mudstone pore water. There will be a gradient of salinity through the metamudstone from the GDF location to the boundary with the lower sandstone unit.

The groundwater is stratified according to density, and density increases with depth. The salinity will also increase in the deep sandstone under and seawards of the coast, but in the shallow sandstone, more dilute groundwater will have flushed remnants of ancient basin brines.

5.1.3 Potential transport paths

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 contaminant transport out of the host rock. Potentially, at the GDF location, groundwater movement and contaminant 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 pessimistically that a contaminant transport pathway exists from the GDF to the biosphere. That is, there is an assumed transport pathway through the EBS, host rock and overlying lower sandstone unit to the near-surface in upwelling water. Groundwater flow in the sandstone is via fractures and interconnected intergranular pore spaces [19, §3.1.7].

Radionuclides reaching the near-surface groundwater are transported and diluted in the drainage network, before eventually entering a river and discharging to the sea landward of a saline/groundwater interface. This discharge may be to an estuary, low-lying coastal land (such as salt marshes), as seepage along a cliff face, or as seepage or springs on the beach or foreshore. Where the discharge is through a cliff face or on the beach or foreshore, both tidal water flows and sediment transport will tend to disperse rapidly and dilute the discharge. In the model, a resource area is assumed to become contaminated and radiological risks to potentially exposed groups 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.

The TSM calculations have focused on 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 transport path has been parameterised to support safety assessment modelling according to the distinct hydrogeological, geological and hydrogeochemical conditions indicated in Figure 8 along the transport paths (that is, through the host rock, including the weathered zone, and through the lower and upper sandstone).

Radionuclide transport in the host rock is through fractures. 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 [16, §2.14]. Transport through the overlying sandstones is assumed to be by advection with retardation by sorption in an equivalent porous medium (representing the fractured and porous rock). The effects of longitudinal dispersion along the transport paths are represented. Radionuclide decay and ingrowth are also included in the model.

The biosphere model represents biosphere processes for a series of reference biospheres. An equilibrium approach is used, on the basis that timescales for processes within the biosphere are typically expected to be shorter than those within the geosphere. This approach allows the risk to members of potentially exposed groups to be calculated using simple radionuclide-dependent biosphere dose conversion factors that relate transfer rates of radionuclides to a region of discharge in the accessible environment to effective doses to potentially exposed groups. In the TSM, it is assumed that radionuclides may be released to the biosphere via groundwater discharge to the coast or via a groundwater well receptor (Figure 8). Biosphere dose conversion factors are calculated in biosphere models separate to the TSM [20; 43; 44].

The biosphere model for releases to marine biosphere calculates doses to potentially exposed groups from radionuclide discharges to estuarine, coastal and/or marine biosphere systems [43]. Biosphere dose conversion factors are calculated based on a unit concentration of a radionuclide's activity discharging to the marine environment (H_{mar}, Sv/Bq). The total effective dose to a potentially exposed group (D_{mar}, Sv/yr) from a release r (in Bq/yr) is given by:

$$D_{mar} = H_{mar} r.$$

For the illustration considered here, discharge occurs along a section of coastline. The smallest length of coastline considered in the marine biosphere model is 1 km. Evaluation of this distance is based on consideration of the region that a potentially exposed group might reasonably be expected to occupy on an annual basis. The potential exposure pathways included in the biosphere model are external irradiation, inadvertent inhalation and ingestion of suspended material and spray, inadvertent ingestion of sea water, and ingestion of plants, animal produce, fish and shellfish [43]. The total effective dose is converted to a risk through a dose-to-risk conversion factor.

A terrestrial biosphere model is used to evaluate doses to potentially exposed groups from a plume of radionuclides in groundwater at a well [44]. The model calculates biosphere dose conversion factors based on a unit concentration of a radionuclide's activity in well water (H_{well}, Sv/yr per Bq/m^3). The total effective dose to a potentially exposed group (D_{ter}, Sv/yr) from a release r (in Bq/yr) of a radionuclide into the near-surface is given by:

$$D_{ter} = \frac{H_{well}}{F} r$$

where F is the groundwater flow rate in the aquifer at the well (m^3/yr). The groundwater flow acts as a dilution factor that reduces the doses from unit discharges of activity to the biosphere. For each radionuclide the total dose per unit activity, H_{ter} is multiplied by the releases (Bq/yr) from the transport path that discharges to the aquifer in order to calculate the total terrestrial doses arising for the potentially exposed population.

The flow rate in the aquifer (F) can be calculated according to the following formula:

$$F = XKi$$

where:

X is the vertical cross-section area of the plume at the well (m^2)

K is the hydraulic conductivity of the aquifer (m/yr)

i is the head gradient driving flow through the aquifer (-)

In the biosphere model, evaluation of the well dose conversion factor assumes that water from the well is used for domestic purposes (including drinking) and agricultural purposes (including drinking water for animals and irrigation of crops) [44]. Again, the total effective dose is converted to a risk through a dose-to-risk conversion factor.

Details of the mathematical model underpinning the TSM (and its implementation in GoldSim) are presented in the Post-closure Modelling Report [35, §3.5 and §6].

5.2 HHGW disposal in higher strength rock

5.2.1 Base scenario description

The illustrative disposal concept for HHGW in a higher strength rock involves packaging the wastes within cast iron inserts inside copper containers [5, §4]. Each copper container is surrounded by a bentonite buffer in its emplacement location. Details of the different waste forms are provided in the Waste Package Evolution Status Report [15]. Under expected hydrogeological and geochemical conditions, the general corrosion rate of copper will be so low that the lifetime of a 50 mm thick copper container will be much greater than 100,000 years [15, §4.2.1.1]. As the copper containers are not expected to fail under base scenario conditions until well beyond the timescale for which it is considered appropriate to quantify uncertainties for probabilistic calculations, no total system model calculations have been undertaken for the base scenario. Instead, quantitative analysis for this illustrative disposal concept has focused on a variant scenario in which there is early breach of a copper container as a result of more rapid corrosion than would be expected.

5.2.2 Variant scenario description

The variant scenario involves early container breach as a result of sulphide attack and accelerated copper corrosion. Such a scenario could occur if the bentonite buffer density is too low (for example as a result of failures in material quality control) to ensure that sulphate-reducing bacteria populations are suppressed when the bentonite saturates. This scenario results in the generation of large concentrations of sulphide near the container surface. Container failure times as a result of this process have been estimated to be between 50,000 years and 500,000 years [30]. The likelihood of such container failure occurring has not been estimated. However, a TSM has been developed to evaluate the radiological risk conditional on failure of a single copper container of each type of HHGW in order to illustrate the robustness of the disposal concept to such scenarios [35, §3.4]. The inventory of radionuclides per waste package for each type of HHGW is based on the 2013 Derived Inventory of higher activity wastes and other materials that may require geological disposal [7].

The TSM for this scenario is based on the following conceptual model: once water penetrates the disposal container, the wasteform starts to dissolve and release any radionuclides that have not decayed *in situ*. For spent fuel, the portion of the instant release fraction (that is, radionuclides that have segregated to the grain boundaries and other immediately accessible parts of the fuel) that has not decayed is released rapidly; the spent fuel matrix then dissolves slowly and congruently releases the remaining radionuclides. For HLW, slow dissolution of the glass matrix limits the release rate of any remaining radionuclide inventory. Similarly, ceramic plutonium and HEU wasteforms dissolve and release radionuclides slowly. Radionuclides are released (some limited by their solubility under local geochemical conditions) into and diffuse through the saturated bentonite buffer, before entering the fracture network in the host rock and migrating to the surface environment through the defined pathways in the cover rocks of the illustrative geological environment. The TSM evaluates the resultant radiological doses and risks to potentially exposed groups in the biosphere [35, §3.4].

5.2.3 Results

GoldSim TSM calculations have been undertaken for each HHGW group, except the small inventory of exotic fuels. 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.

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 9 shows the calculated mean of the radionuclide activity fluxes (Bq/yr) entering the host rock for the example involving early failure of a pressurised water reactor (PWR) spent fuel container. Results are shown for a period of three hundred thousand years in order to present an understanding of the behaviour of long-lived radionuclides. As noted in Section 3.4, the conditions in a geological environment may be influenced by external factors such as those relating to climate change on timescales longer than a few hundred thousand years. Such external factors will be considered when assessing the environmental safety of a real site.

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 [30]), which is an activation product that, in these calculations, is assumed to be released 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 [30]), it occurs as a result of the decay of Th-230 (which has a half-life of 7.54×10^4 years [30]) and, unlike Th-230, Ra-226 is only weakly sorbed in the buffer.

Radionuclides that enter the host rock are advected through fractures towards the cover rock. Figure 10 shows the calculated mean radionuclide activity fluxes entering the cover rock for the PWR spent fuel example. In this example, there is no matrix diffusion or sorption of any radionuclides in the fractures. 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) 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 9) because it sorbs strongly to the bentonite as it is generated, where it decays.

Diffusion of radionuclides into, and their sorption in, the host rock matrix was not represented in the calculations discussed above. This represents a cautious approach, because it is likely that many radionuclides would be retarded by such processes in a typical higher strength rock. Therefore, additional calculations have been undertaken in order to provide insights into the potential significance of radionuclide sorption in the rock adjacent to host rock fractures by including a narrow zone (1 mm thick) into which radionuclides can diffuse and sorb. 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 11 (compare with Figure 10). In particular, activity fluxes from Ni-59, Cs-135, Ra-226, Pb-210 and Tc-99 are substantially reduced.

On these illustrations, 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 12. 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. For the well pathway, the main contributors to risk for all realisations are non-sorbing I-129 (half-life of 1.57×10^{7} years [30]) and Cl-36 (half-life of 3.07×10^{5} years [30]). On much longer timescales than shown on Figure 12, the impacts of various long-lived actinides begin to become important (notably, Np-237 and its decay products U-233 and Th-229).

Figure 9 **Mean radionuclide activity flux from bentonite buffer to host rock following failure of a PWR spent fuel container disposed of in higher strength rock**

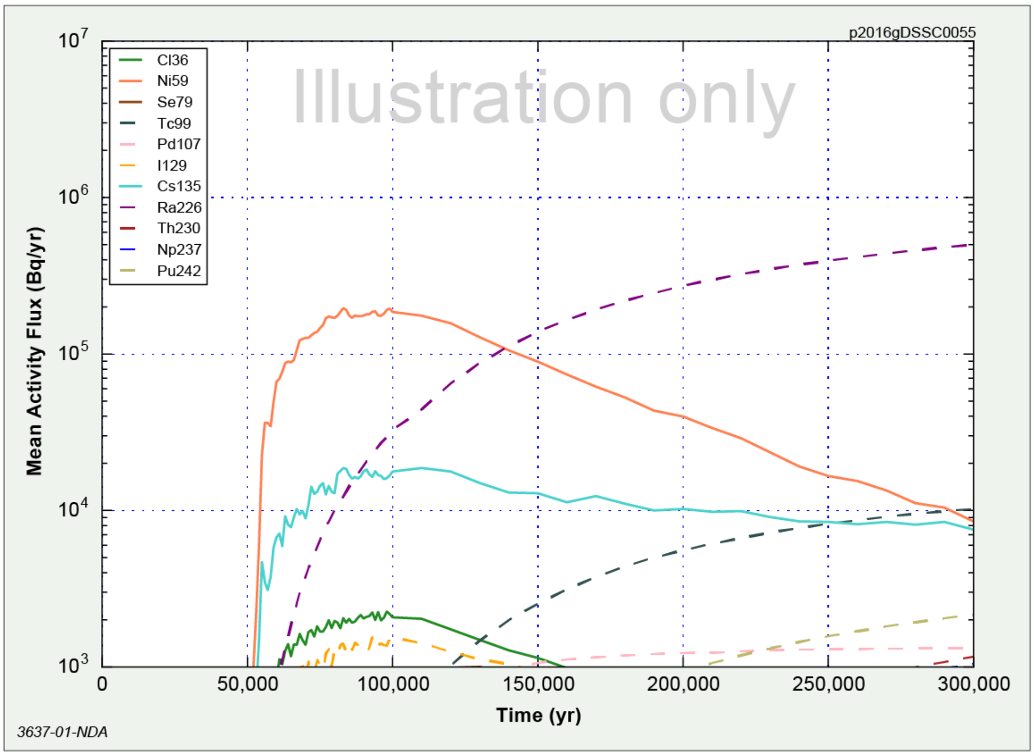


Figure 10 Mean radionuclide activity flux from the host rock to the cover rocks following failure of a PWR spent fuel container disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock

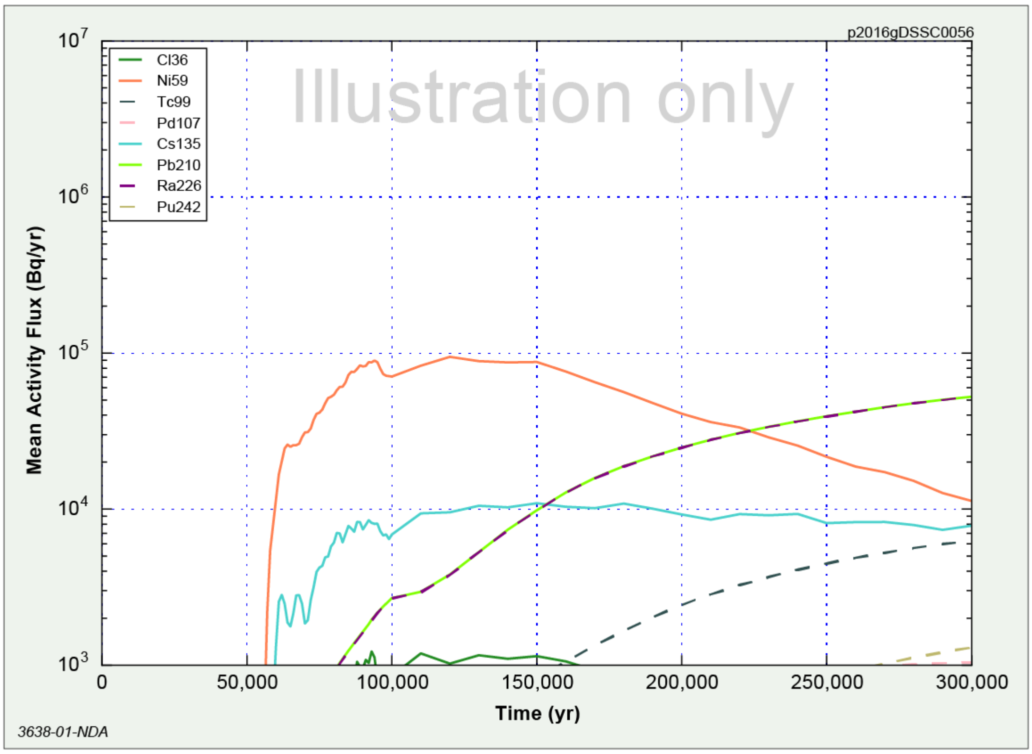


Figure 11 Mean radionuclide activity flux from the host rock to the cover rocks following failure of a PWR spent fuel container disposed of in higher strength rock, with matrix diffusion and radionuclide sorption in the host rock

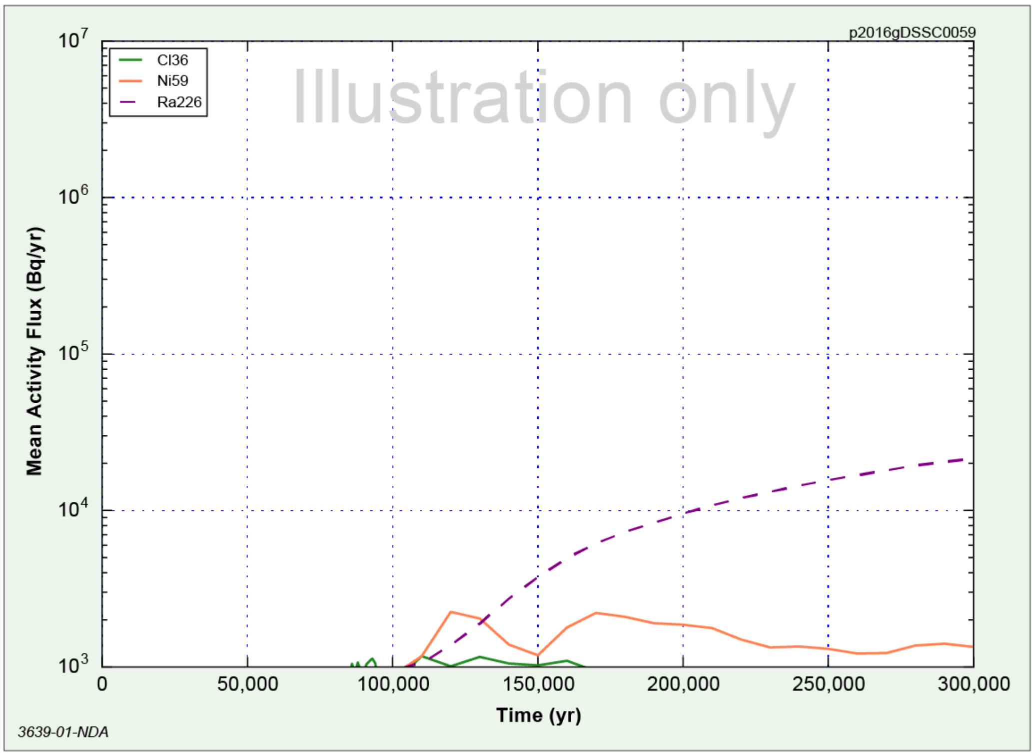


Figure 12 Mean radiological risk (total and significant contributors) via the well pathway following failure of a PWR spent fuel container disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock; the risk guidance level (RGL) and the estimated risk from background level (BL) ionising radiation are also shown

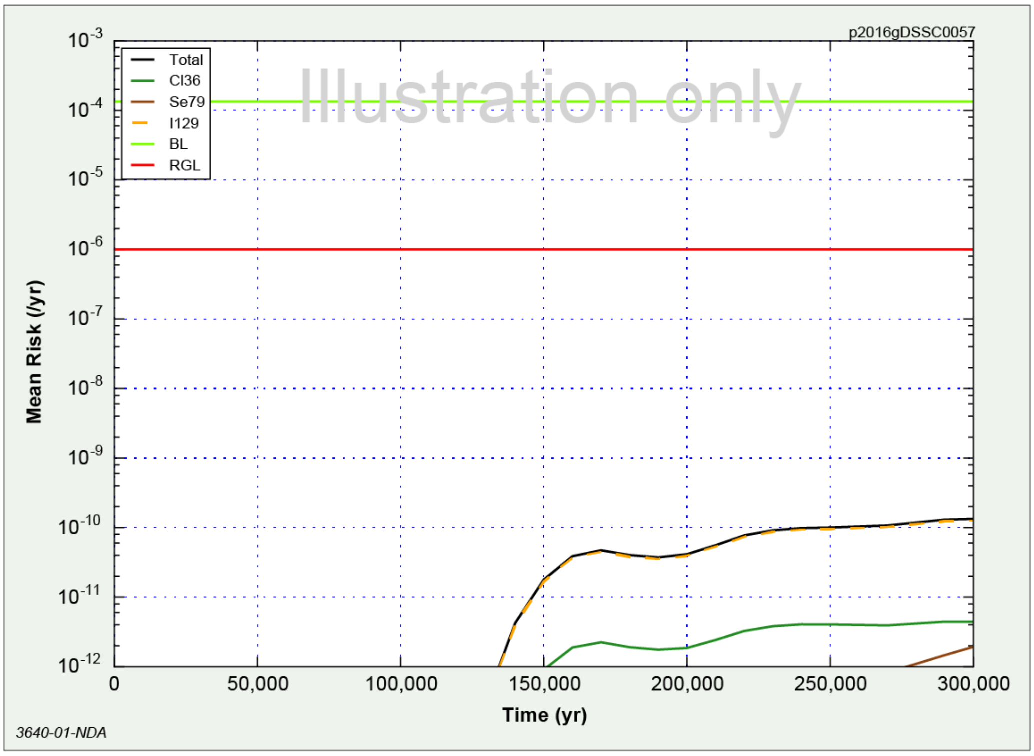
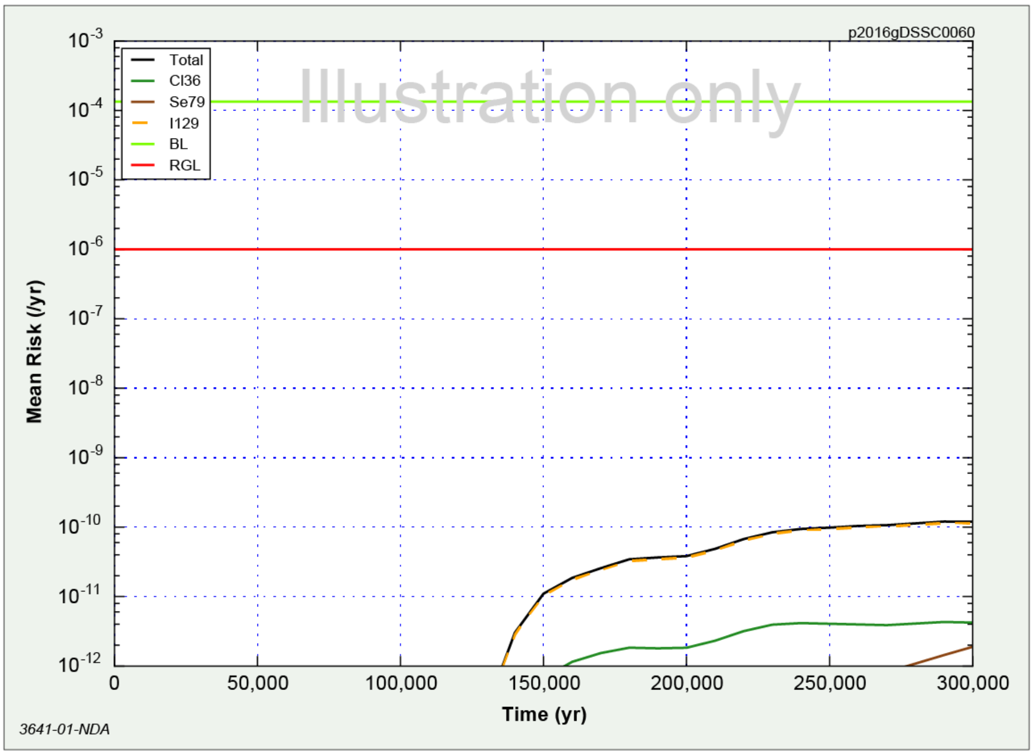


Figure 13 Mean radiological risk (total and significant contributors) via the well pathway following failure of a PWR spent fuel container disposed of in higher strength rock, with matrix diffusion and radionuclide sorption in the host rock



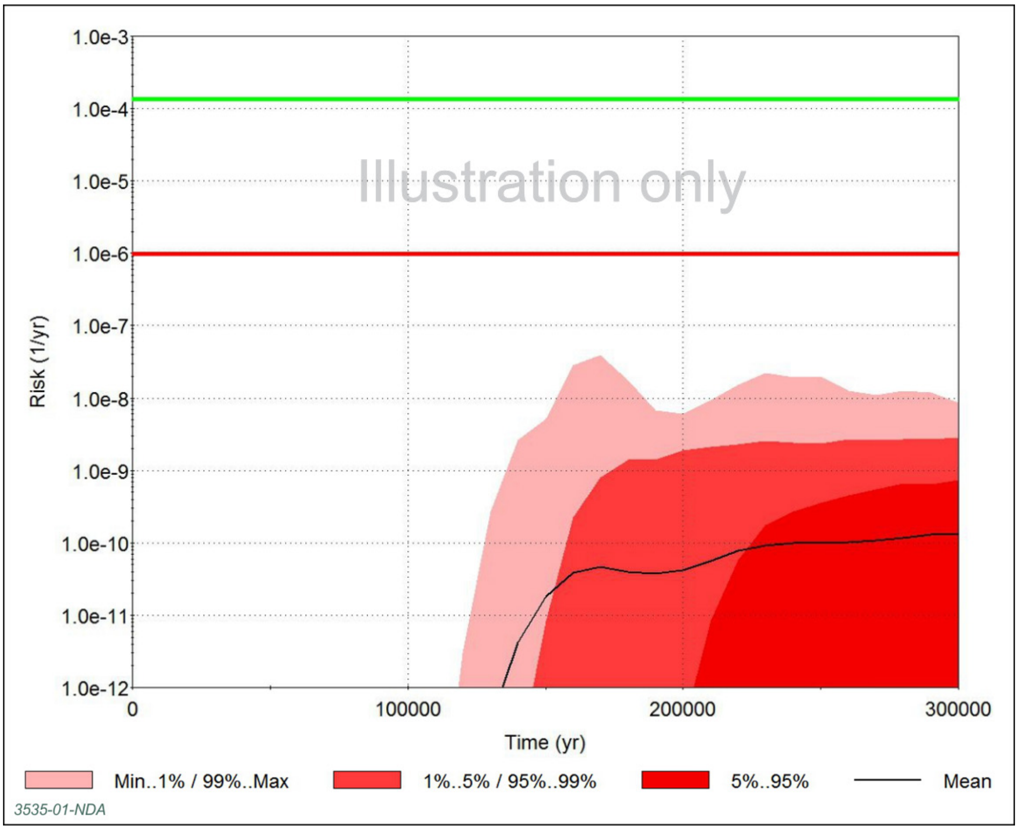
The calculated total mean risk is substantially below the risk guidance level (RGL) of 10^{-6}/yr throughout the assessment period [13, §6.3.10]. The calculated mean risk from the marine pathway is negligible (less than 10^{-12}/yr throughout the assessment period). The calculated mean risk is also substantially lower than the risk associated with radiological dose that might be received from natural background ionising radiation. The average annual dose from natural radiation is about 2.23 mSv [45]. Risk factors for low dose rate exposure have been estimated to be about 0.06 /Sv for the whole population [30]. Therefore, the risk from natural background radiation is about $1.3\text{x}10^{-4}$/yr. This background level (BL) risk is indicated in Figure 12.

The calculated risks from non-sorbing I-129, Cl-36 and Se-79 are little affected by the presence of the matrix diffusion zone in the host rock as shown in Figure 13 (compare with Figure 12). The assumed matrix diffusion zone is too thin to offer any greater potential for such radionuclides to be contained in the host rock. However, on longer timescales than shown in Figure 13, the matrix diffusion zone has an important impact on the behaviour of radionuclides such as U-233 and Th-229, substantially reducing the contributions that they make to calculated risk via the well pathway.

Note that a small number of realisations strongly influence the mean calculated risk on timescales of up to around 200,000 years, as indicated in Figure 14. This figure shows statistical information based on the results of the 2,000 realisations, each involving failure of a single PWR spent fuel container at some time between 50,000 years and 500,000 years after GDF closure for the case in which there is no diffusion or sorption of radionuclides in the host rock. The shading in the figure indicates the demarcation between different percentiles of calculated risk. For example, the region shaded light red indicates the range of the highest 1% of calculated risk values (that is, results above the 99th percentile) for the 2,000 realisations at any given time in the assessment period. The range of the highest 5% of calculated risk values (that is, results above the 95th percentile) and the mean calculated risk at any time are also shown. Having a mean value that is higher than the 95th percentile is a characteristic of a highly skewed distribution of results; in the period up to about 200,000 years, only a small number of realisations contribute significantly to the calculated mean. That is, in a few realisations, a combination of sampled parameter values leads to relatively early container failure and relatively fast transport of high concentrations of long-lived radionuclides, such as I-129 and Cl-36, to the biosphere. Such results are typical of assessments where there are large uncertainties in the values of key parameters (perhaps ranging over many orders of magnitude).

For each realisation, there is a peak in calculated risk primarily associated with exposure to the I-129 and Cl-36 that stem from the instant release fraction of radionuclides, followed by a steady lower level risk associated with exposure to the I-129 and Cl-36 that stems from the slow dissolution of the spent fuel. As a result, the mean calculated risk shows an initial peak at about 170,000 years followed by a small increase associated with the combined effects of exposure to I-129 and Cl-36 from fuel dissolution and the instant release fraction associated with an increasing number of realisations with time.

Figure 14 **Statistics (maximum, 99th percentile, 95th percentile and mean of 2,000 realisations at any time) for calculated total radiological risk 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**



Results for new build spent fuel, MOX spent fuel, AGR spent fuel and metallic spent fuel are similar to those for PWR spent fuel. For example, Figure 15 shows the calculated mean radionuclide activity fluxes entering the cover rock for a calculation in which there is early failure of a new build spent fuel container, with no matrix diffusion or radionuclide sorption in the host rock. Significant isotopes in terms of activity reaching the cover rock are Cs-135, Cl-36, Ni-59 and I-129. Again, Ra-226 and Pb-210 contribute the greatest activity on a timescale of several hundred thousand years. The most significant contributors to calculated risk via the well pathway are indicated in Figure 16 for the new build spent fuel example. The main contributor to risk is I-129. The calculated total mean risk is substantially below the RGL of 10^{-6}/yr throughout the assessment period [13, §6.3.10]. The results for MOX spent fuel are shown in Figure 17 (mean radionuclide activity fluxes entering the host rock) and Figure 18 (mean risk via the well pathway). The calculated total mean risk is similar to that calculated for PWR spent fuel.

The most significant isotope in terms of calculated mean radionuclide activity fluxes entering the cover rock for the example involving early failure of an HLW container is Cs-135, as indicated in Figure 19, but the Cs-135 activity flux will be less if it is assumed to sorb in the host rock. The most significant contributors to calculated risk via the well pathway are indicated in Figure 20. The main contributors to risk are I-129, Cl-36, Cs-135 and Se-79, but the calculated total mean risk is substantially below the RGL of 10^{-6}/yr throughout the assessment period. There is a limited instant release fraction of radionuclides from HLW, but calculations of mean risk are not greatly influenced by such effects.

Figure 15 Mean radionuclide activity flux from the host rock to the cover rocks following failure of a new build reactor spent fuel container disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock

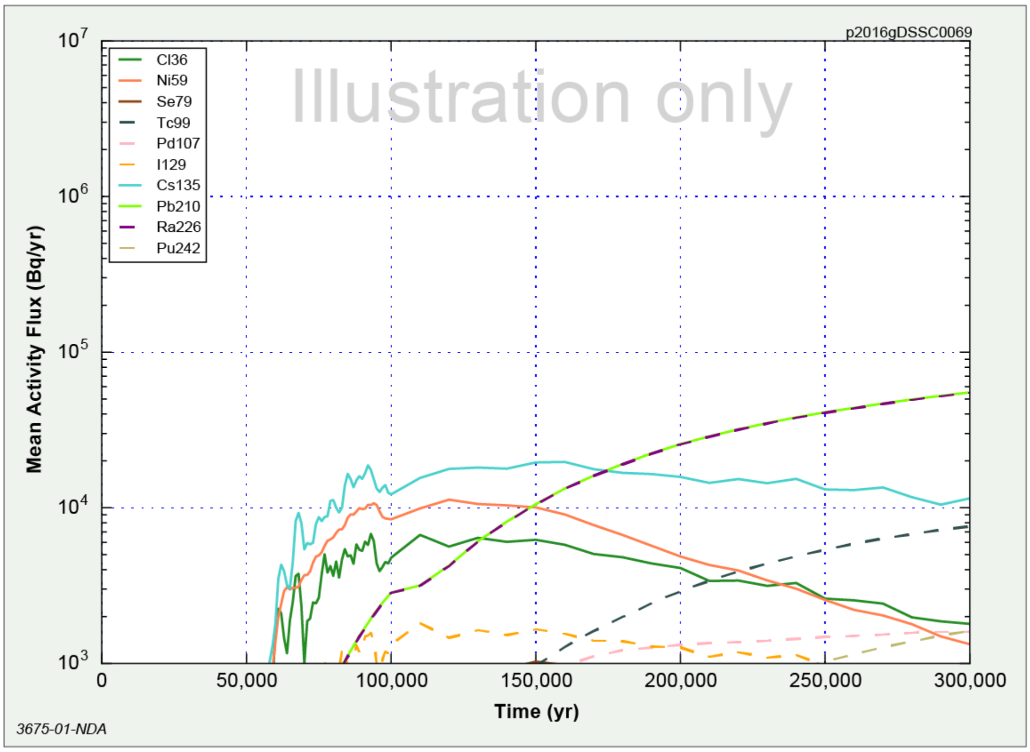


Figure 16 Mean radiological risk (total and significant contributors) via the well pathway following failure of a new build reactor spent fuel container disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock

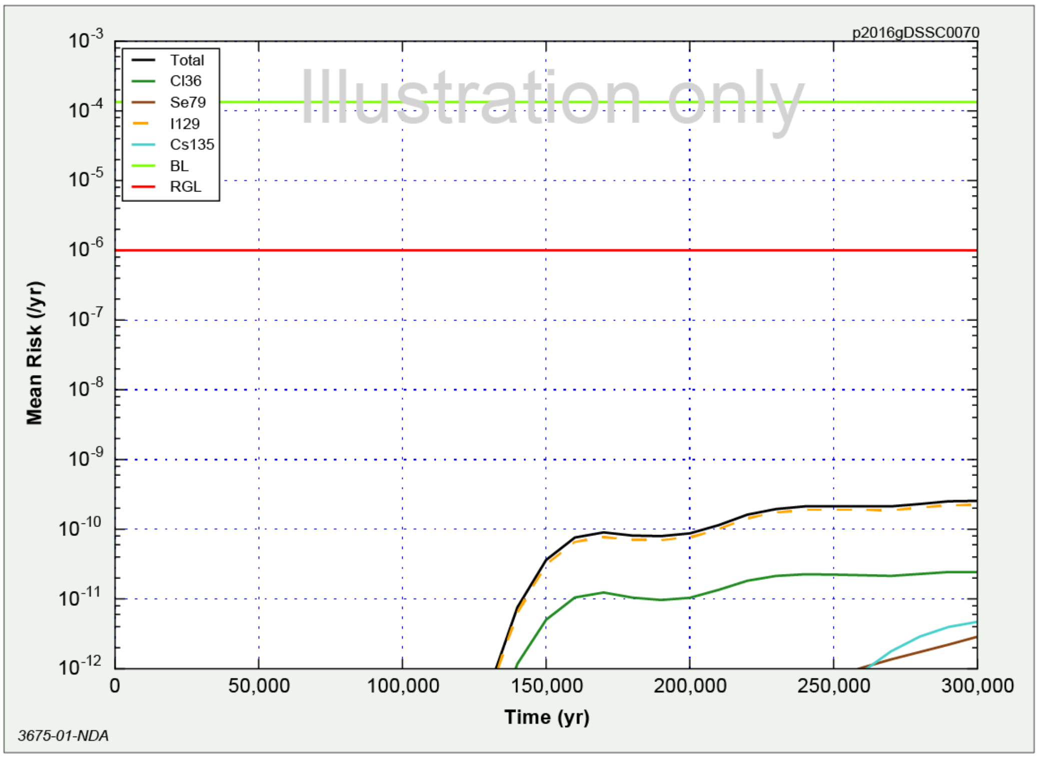


Figure 17 **Mean radionuclide activity flux from the host rock to the cover rocks following failure of a MOX spent fuel container disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock**

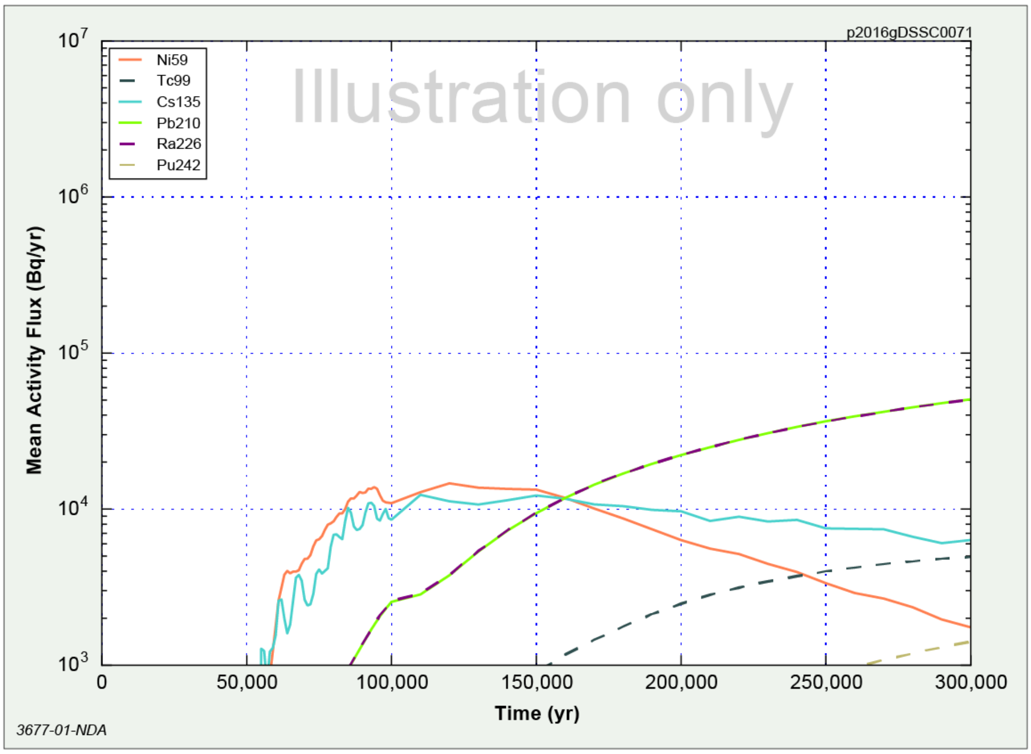


Figure 18 **Mean radiological risk (total and significant contributors) via the well pathway following failure of a MOX spent fuel container disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock**

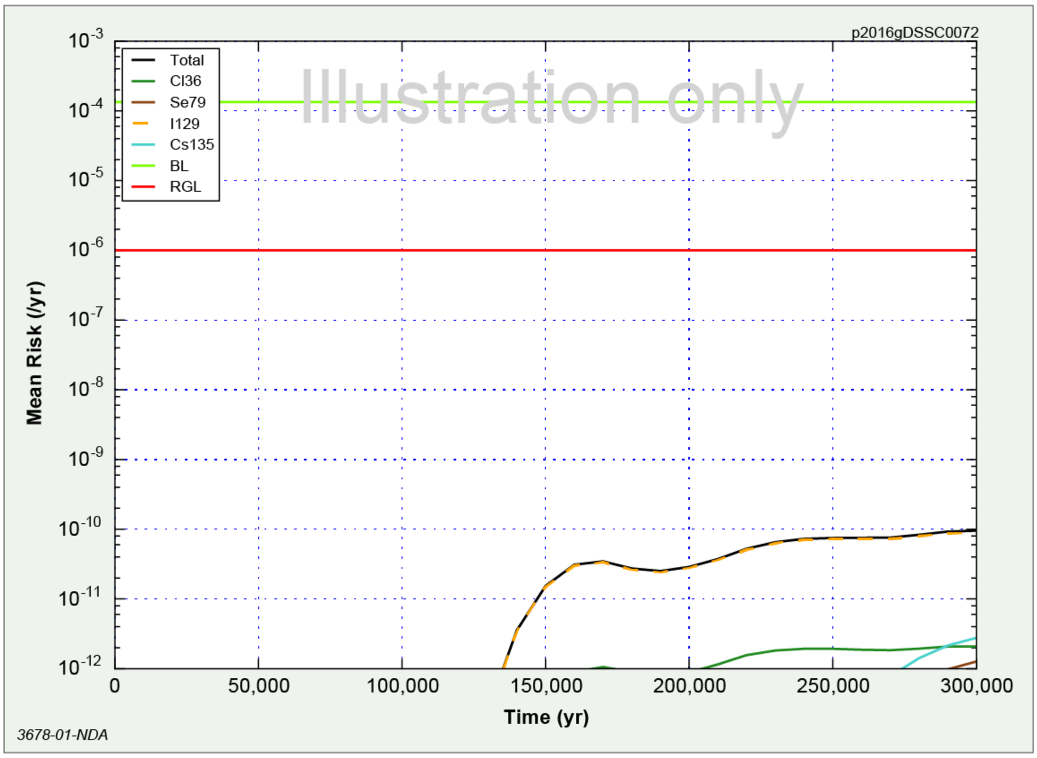


Figure 19 Mean radionuclide activity flux from the host rock to the cover rocks following failure of a HLW container disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock

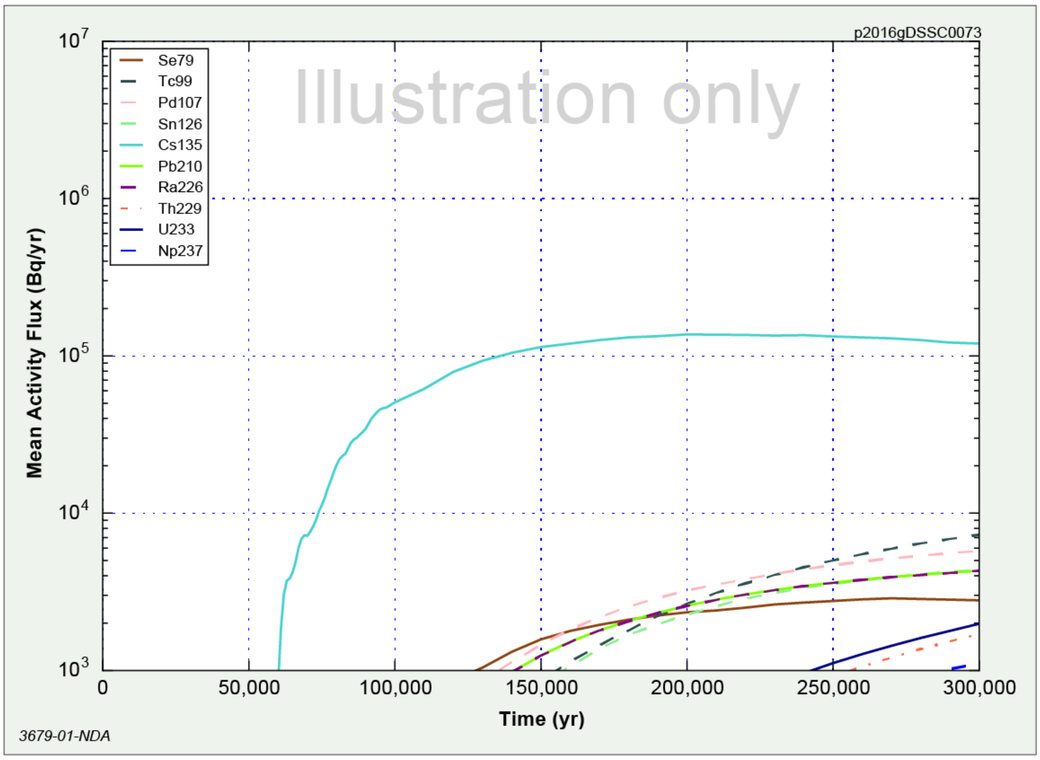
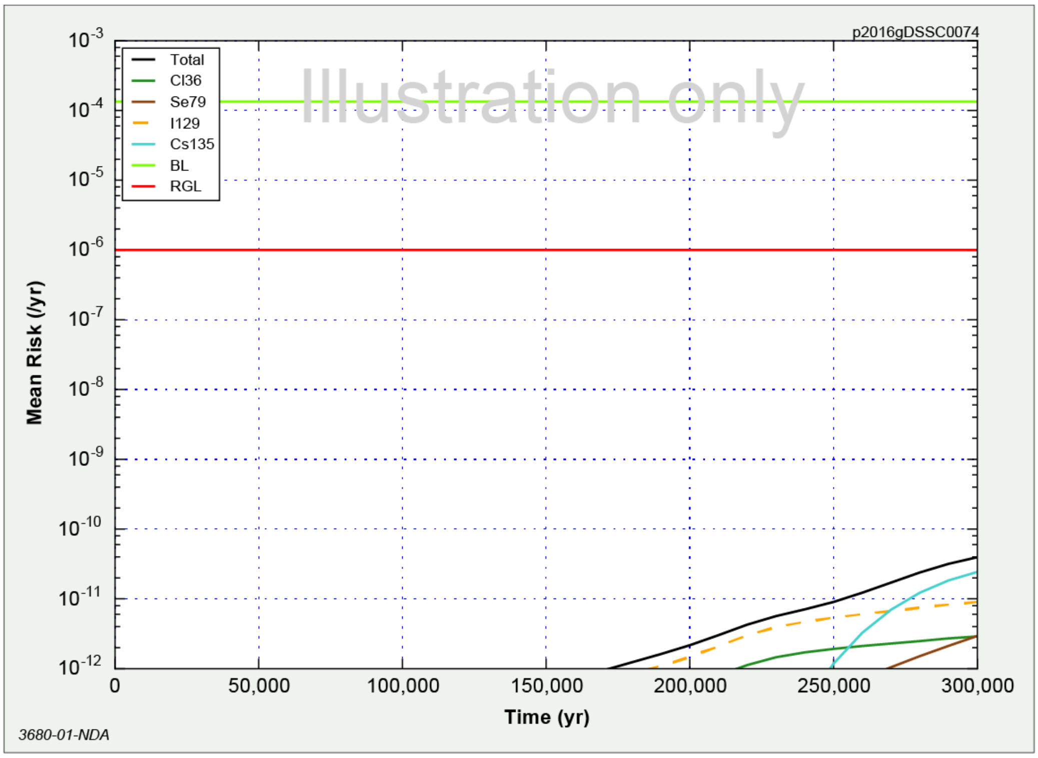


Figure 20 Mean radiological risk (total and significant contributors) via the well pathway following failure of a HLW container disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock



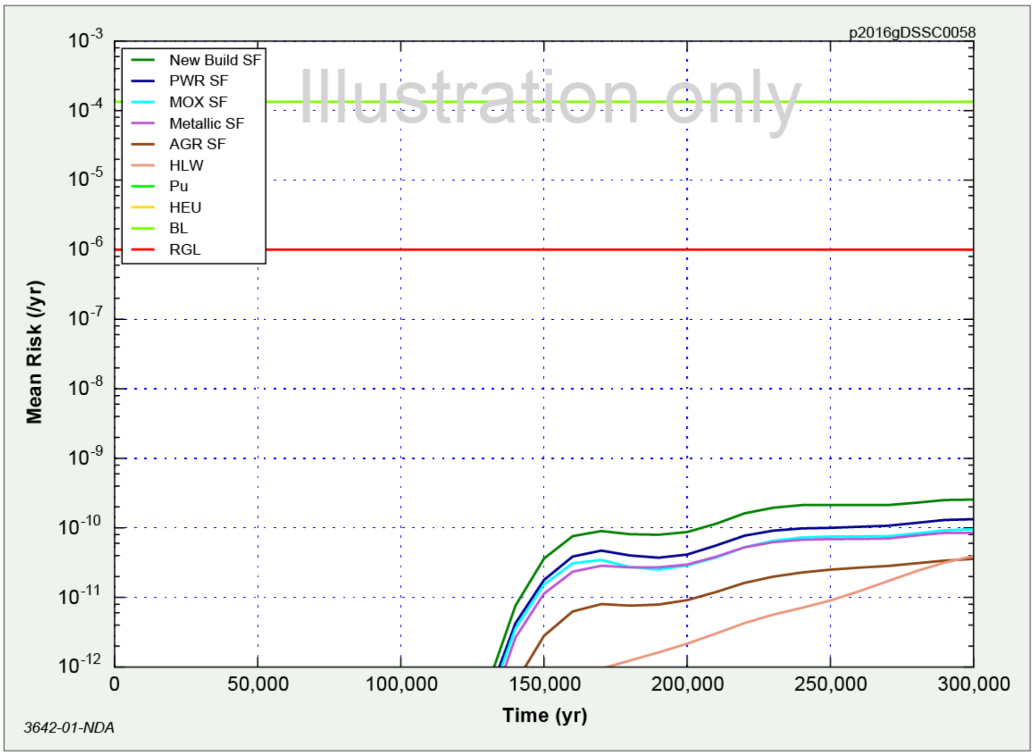
The calculated mean radionuclide activity fluxes entering the cover rock for examples involving early failure of a container of Pu ceramic waste and early failure of a container of HEU ceramic waste are substantially less than 10^3 Bq/yr in the assessment period and the mean risk is less than 10^{-12}/yr in each case. The plutonium wasteform comprises actinides and only a small fraction of fission products and HEU comprises actinides only. Furthermore, the plutonium and HEU ceramic wasteforms degrade slowly. Therefore, the calculated risks from disposal of plutonium and HEU waste packages are only apparent after several hundred thousand years and are associated with long-lived actinides.

The different types of spent fuel show similar characteristic behaviour with regard to the calculated mean risk for the illustrative well pathway, as shown in Figure 21, with the largest calculated risks occurring as a result of exposure to I-129. The highest calculated risks are from a failed new build reactor spent fuel waste package.

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 mechanisms. 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.

If advective transport pathways from the disposal facility to the accessible environment exist, then calculated radiological risks over the assessed timescale following early failure of a spent fuel container are likely to be low. The mobile radionuclide I-129, that forms part of the spent fuel instant release fraction, has the potential to dominate calculated radiological risk, especially when exposure via a well pathway is considered. Thus, understanding I-129 behaviour in each component of the barrier system is important to the demonstration of environmental safety of the illustrative disposal concept. The capacity for the host rock and cover rocks to contain and dilute such radionuclides (for example, by diffusion and dispersion processes), the existence of transport pathways to the biosphere and assumptions about human activity in the biosphere have a strong influence on the potential for such radionuclides to contribute to calculated 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 long-lived actinides for this disposal concept.

Figure 21 **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**



5.3 LHGW disposal in higher strength rock

The concept for the disposal of LHGW in higher strength rock involves emplacing the waste packages in vaults that are backfilled with a cementitious material [3]. For the illustrative disposal 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.

In this concept, the establishment of alkaline and reducing conditions is important for ensuring that the corrosion rates of metal containers are low and that the rate of release of radionuclides from the waste packages and their migration from the vaults are 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 in this environment [5, §10.2.1]. However, after hundreds of thousands of years, it is likely that degradation of the engineered barriers would be such that they would no longer be able fully to perform their original safety functions. Therefore, total system model calculations have been undertaken for the base scenario in order to provide an illustration of the potential risks associated with LHGW disposal on a timescale of 300,000 years after GDF closure.

In addition, a variant scenario has been evaluated in which there is early breach of stainless steel containers as a result of corrosion under oxic and low pH conditions in the presence of groundwater rich in chloride.

5.3.1 Base scenario description

Separate calculations have been undertaken for each type of LHGW. That is separate calculations have been undertaken for vaults containing SILW/SLLW, UILW/ULLW, ILW in robust shielded containers (RSCs), DNLEU, New Build SILW and New Build UILW. In each case, all the vaults that contain a specific type of LHGW were included in the model. The inventory of radionuclides per waste package for each type of LHGW is based on the 2013 Derived Inventory of higher activity wastes and other materials that may require geological disposal [7].

The different types of LHGW are packaged in either stainless steel, carbon steel or concrete containers and these containers have been assumed to degrade and to be breached some time after GDF closure, as follows:

- Stainless steel containers are used for SILW/SLLW, UILW/ULLW and DNLEU. The time for the containers of each waste group to fail has been estimated to be between 1,000 years and 100,000 years [30]. 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 assumed to be between 50 years and 200 years [30]. 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 [30]. Other containers in the waste group are assumed to fail within the subsequent 200 year period.

Once the containers have been breached, radionuclides may be released and advected into the backfill. 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; such vents are included in most LHGW packages to allow gas release.

Radionuclides migrate from the backfill into the fractured host rock under a prescribed hydraulic gradient, before migrating to the surface environment through the cover rocks. The illustrative geological environment (including the hydrogeological and hydrogeochemical conditions) and the biosphere assumed for these calculations is as modelled in the analysis of HHGW disposal in higher strength rock. Again, sensitivity of radionuclide transport to matrix diffusion from fractures in the host rock and retardation by sorption in the host rock matrix has been evaluated. Transport through the overlying sandstones 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. Again, in the TSM, it is assumed that radionuclides may be released to the biosphere via groundwater discharge to the coast or via a groundwater well receptor (Figure 8). Details of the mathematical model underpinning the TSM (and its implementation in GoldSim) are presented in the Post-closure Modelling Report [35, §3.3 and §6].

5.3.2 Results

The calculated mean of the total radionuclide activity fluxes (Bq/yr) entering the cover rocks from the host rock is shown in Figure 22 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. The most significant radionuclides (in terms of activity) that reach the cover rocks 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 23).

Long-lived radionuclides eventually migrate through the cover rocks to the biosphere. The calculated mean radiological risks from the marine pathway are small (several orders of magnitude less than the 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 24) or included (see Figure 25). 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 24). Note that the calculated mean radiological 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 are indicated in Figure 26 for the case in which rock matrix diffusion and sorption in the host rock are excluded. For all realisations I-129 and Cl-36 are significant contributors to risk. 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 from uranium isotopes via the well pathway at this time.

In most realisations, Ra-226, U-233, U-234 and U-238 only become significant contributors to 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, but is substantially lower than the estimated risk associated with radiological dose that might be received from natural background ionising radiation. However, the results are strongly dependent on 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.

Figure 27 shows the variability in calculated risks for different realisations. The results showing the mean value being higher than the 95th percentile are characteristic of a highly skewed distribution. A small number of realisations are contributing significantly to the calculated mean risk in the period up to about 100,000 years. As noted above, the results in this period are dominated by a low-probability realisation in which sampled parameter values are such that there are early arrivals of uranium isotopes in the biosphere.

Figure 22 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

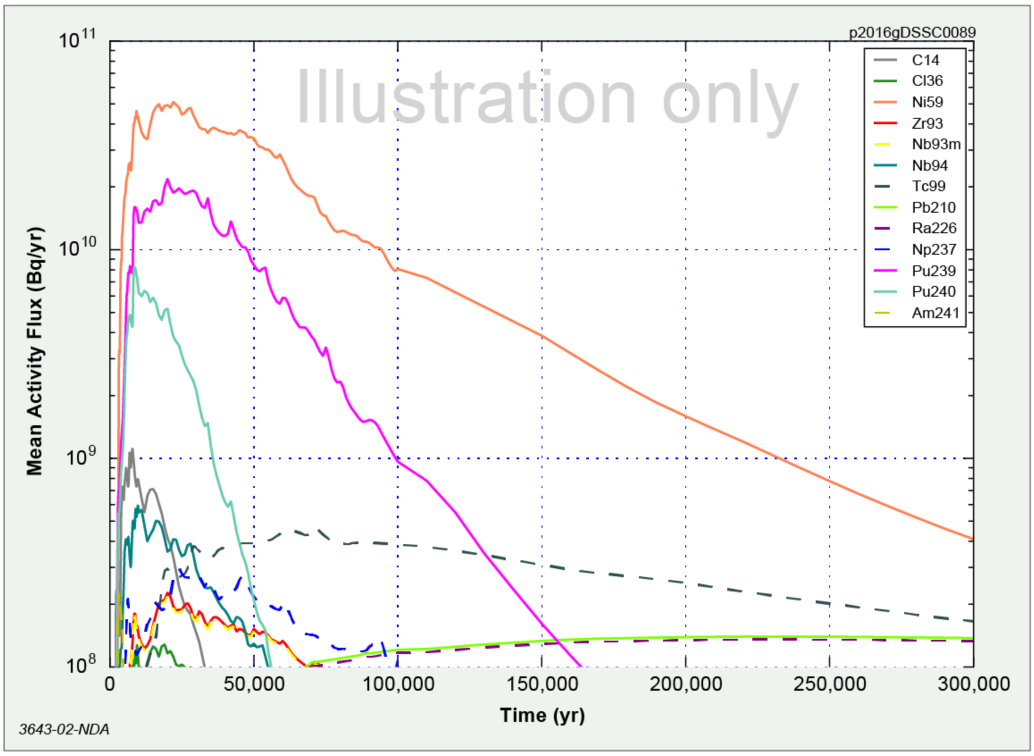


Figure 23 Mean radionuclide activity flux from the host rock to the cover rocks for the entire UILW/ULLW group disposed of in higher strength rock, with matrix diffusion and radionuclide sorption in the host rock

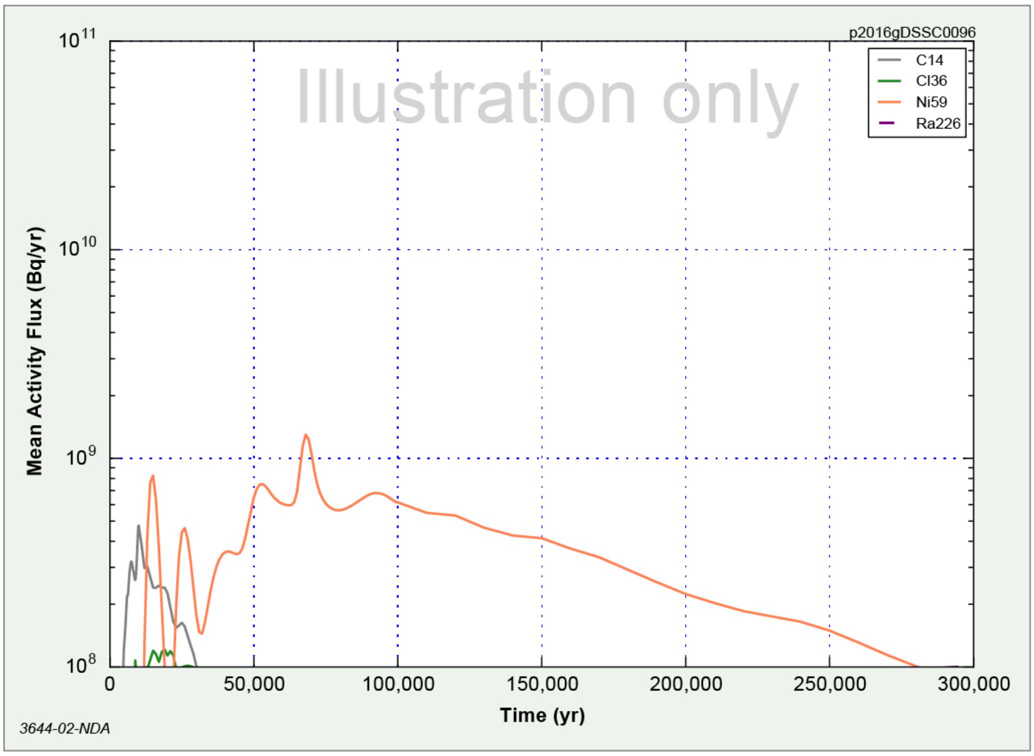


Figure 24 Mean radiological risk (total and significant contributors) via the marine pathway for the entire UILW/ULLW group disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock

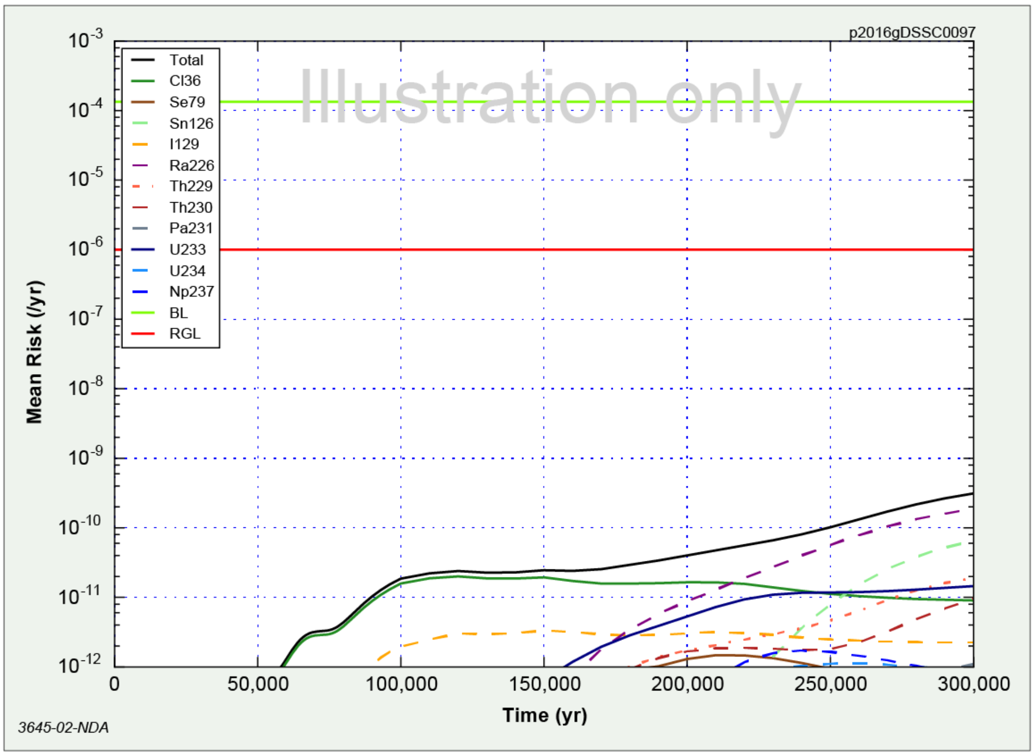


Figure 25 Mean radiological risk (total and significant contributors) via the marine pathway for the entire UILW/ULLW group disposed of in higher strength rock, with matrix diffusion and radionuclide sorption in the host rock

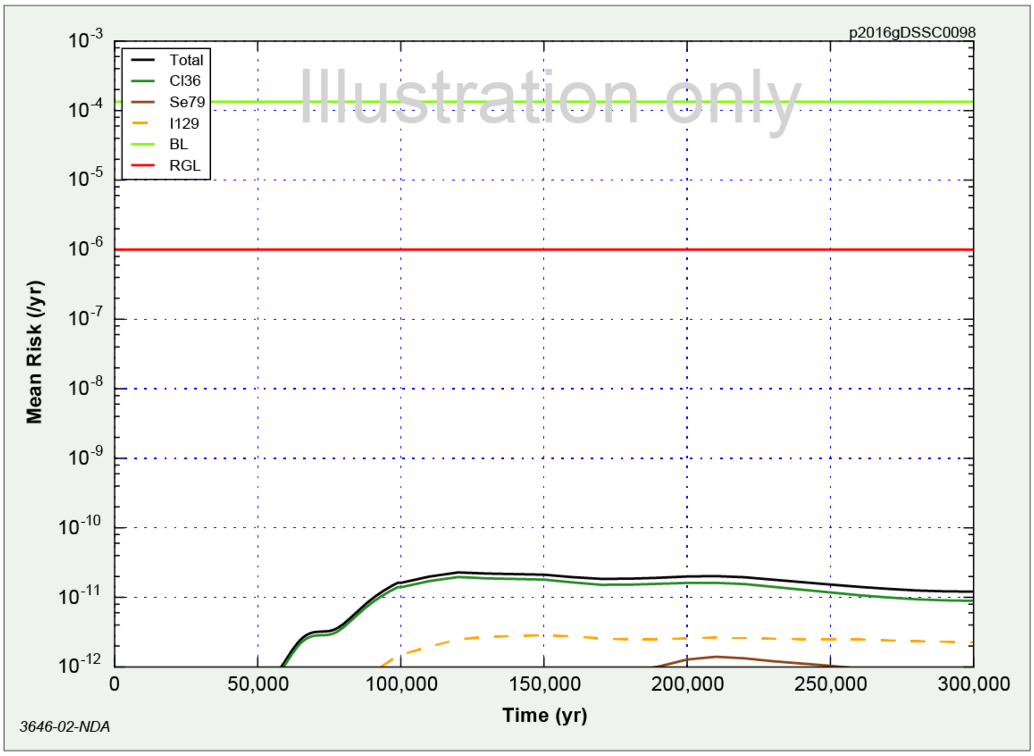


Figure 26 **Mean radiological risk (total and significant contributors) via the well pathway for the entire UILW/ULLW group disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock**

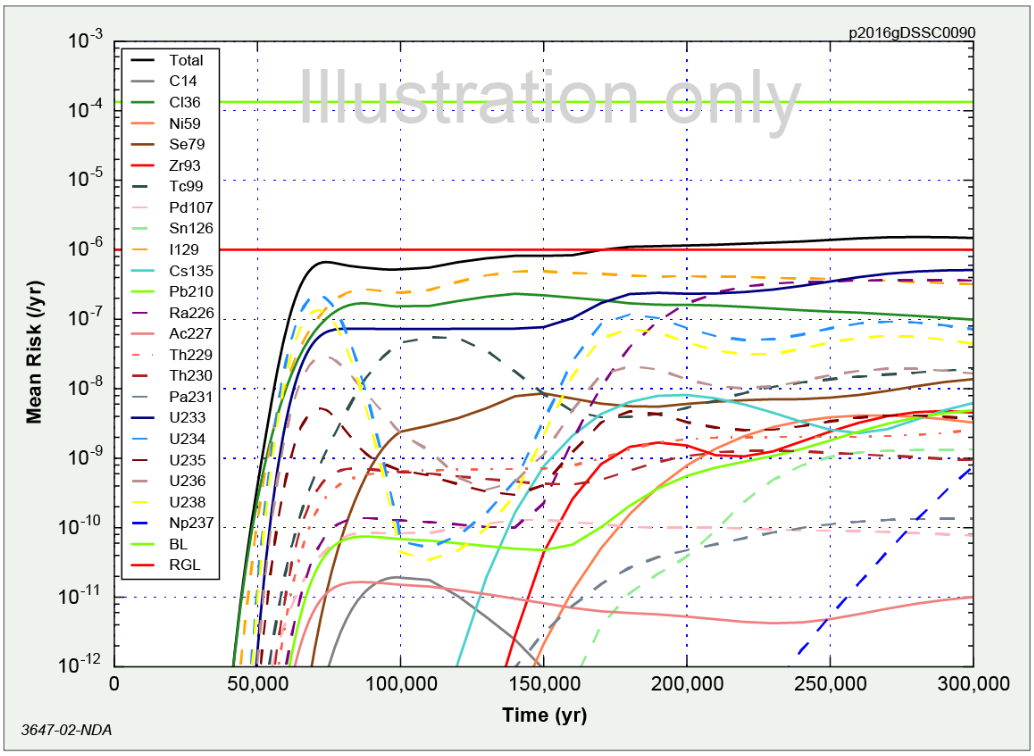
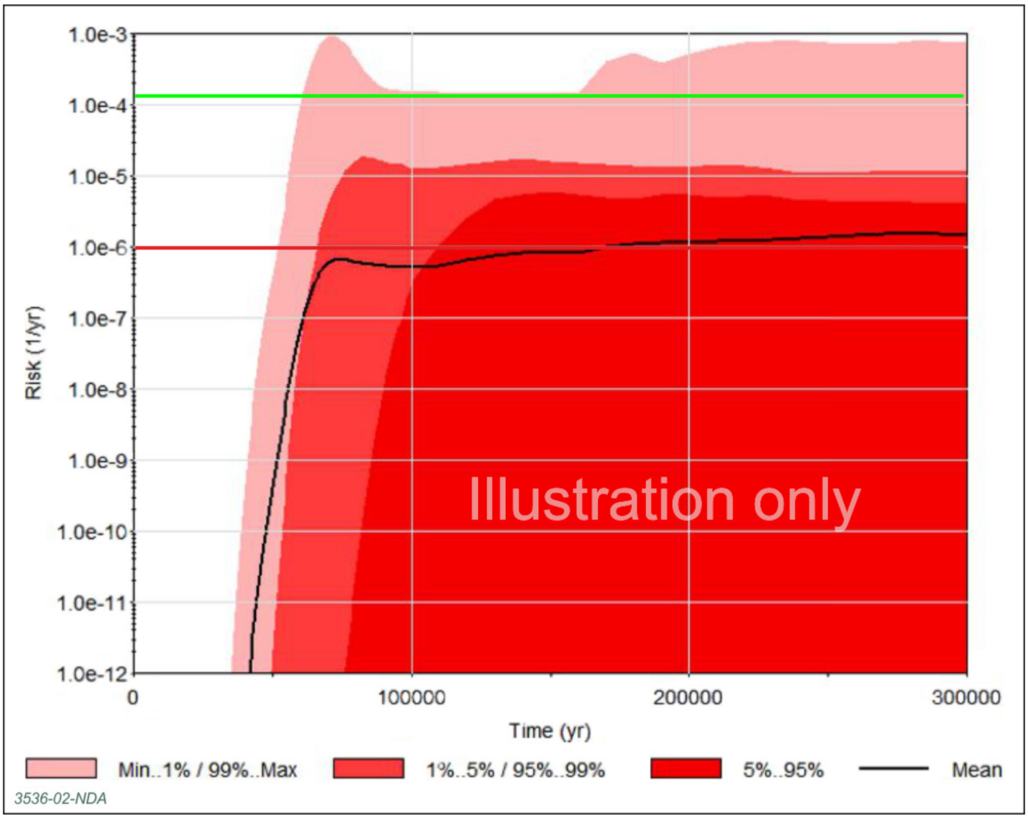


Figure 27 **Statistics for calculated total radiological risk via the well pathway for the entire UILW/ULLW group disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock**



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 uranium are retained in the host rock in all realisations, and no longer contribute significantly to risk on a 300,000 year timeframe (or longer), as indicated in Figure 28, which shows the calculated mean risk from UILW/ULLW disposal. Results for UILW/ULLW with no rock matrix diffusion are shown in Figure 26. However, I-129 and Cl-36 are not retarded in the host rock, so that they still contribute significantly to calculated mean risk in the assessment period. Thus, understanding I-129 and Cl-36 behaviour in the multi-barrier system is important to the demonstration of environmental safety of the illustrative disposal concept and remains a focus of RWM's research [15; 17].

Results for vaults containing SILW/SLLW are shown in Figure 29 in terms of mean total radionuclide activity fluxes entering the cover rocks from the host rock. The most significant radionuclides (in terms of activity) that reach the cover rocks on a timescale of 300,000 years are C-14 and Cl-36. The only significant contributor to calculated risk via the well pathway is Cl-36 as indicated in Figure 30, which shows a calculated mean risk just less than the RGL after around 75,000 years.

Mean radionuclide activity fluxes entering the cover rocks from the host rock for vaults containing DNLEU containers are shown in Figure 31. The most significant radionuclides in terms of activity are Pb-210 and Ra-226; short-lived Pb-210 is in secular equilibrium with Ra-226. The most significant contributors to calculated risk via the well pathway are U-234 and U-238 as indicated in Figure 32.

Figure 28 **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**

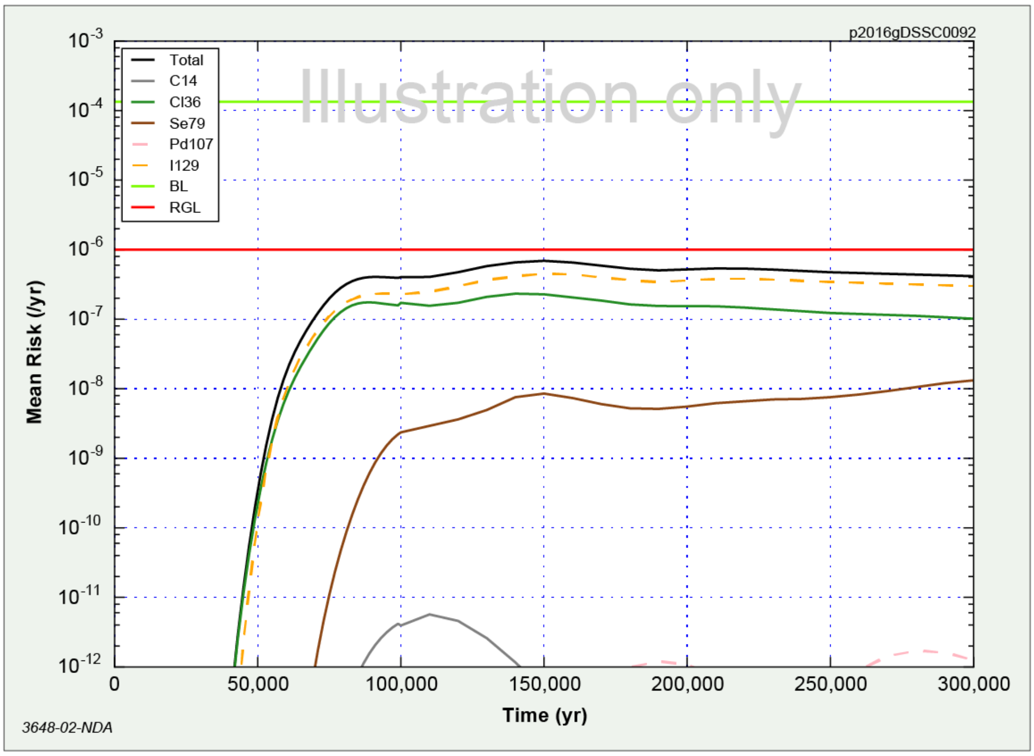


Figure 29 **Mean radionuclide activity flux from the host rock to the cover rocks for the entire SILW/SLLW group disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock**

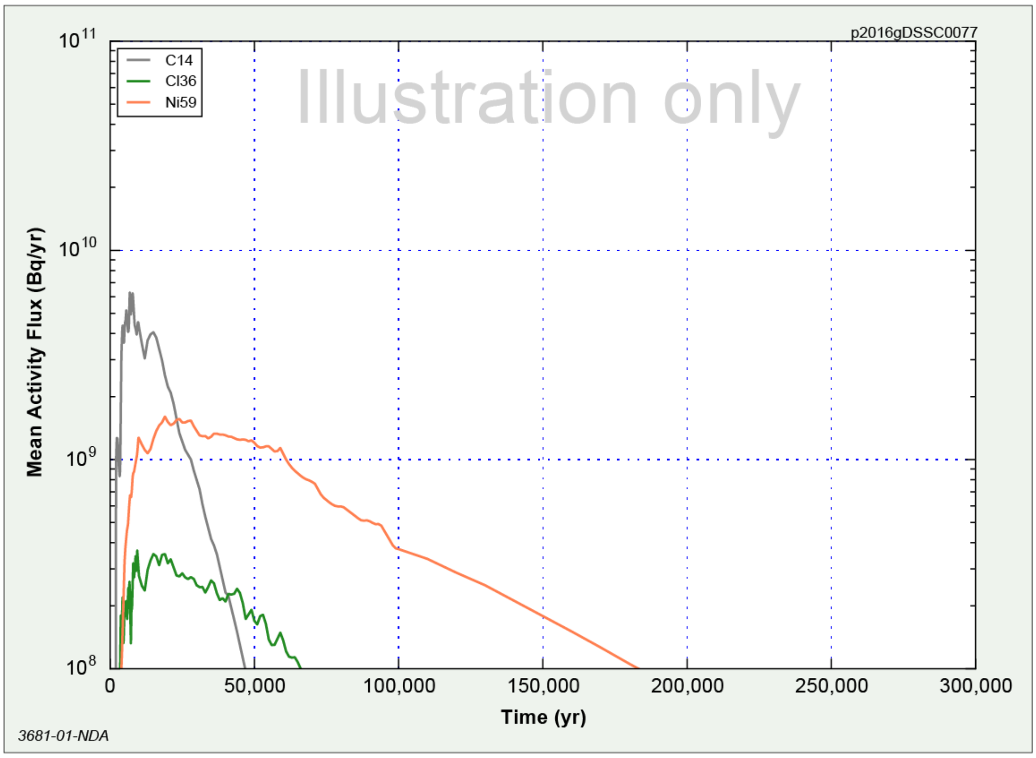


Figure 30 **Mean radiological risk (total and significant contributors) via the well pathway for the entire SILW/SLLW group disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock; the calculated total mean risk is almost entirely due to exposure to Cl-36 and the curves coincide**

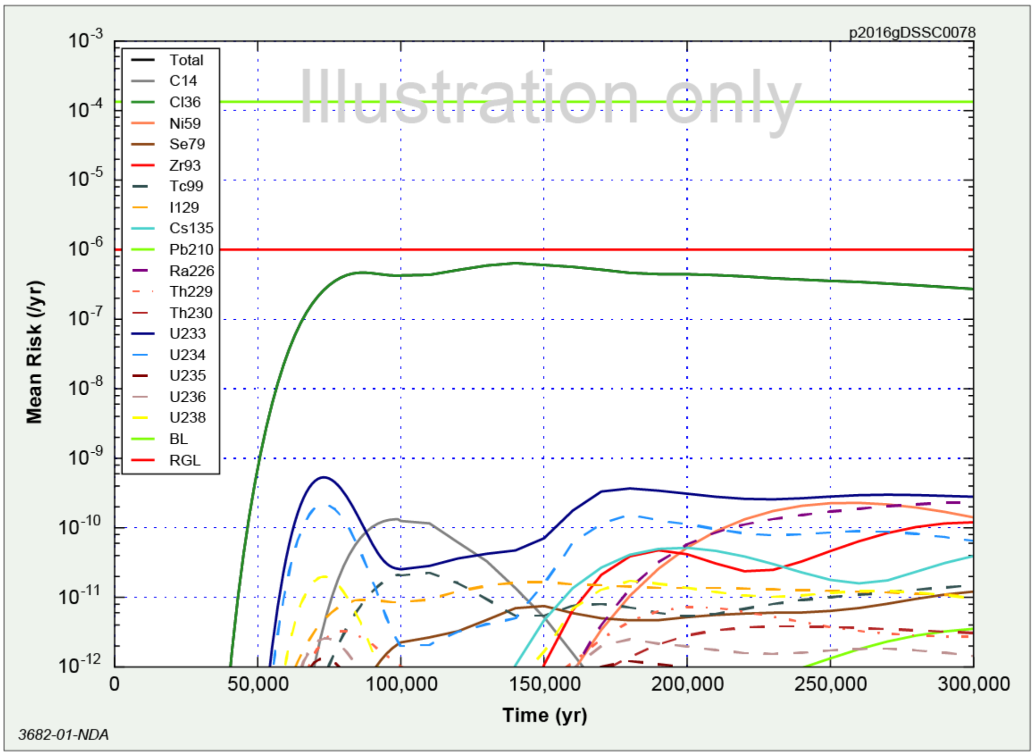


Figure 31 Mean radionuclide activity flux from the host rock to the cover rocks for DNLEU disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock

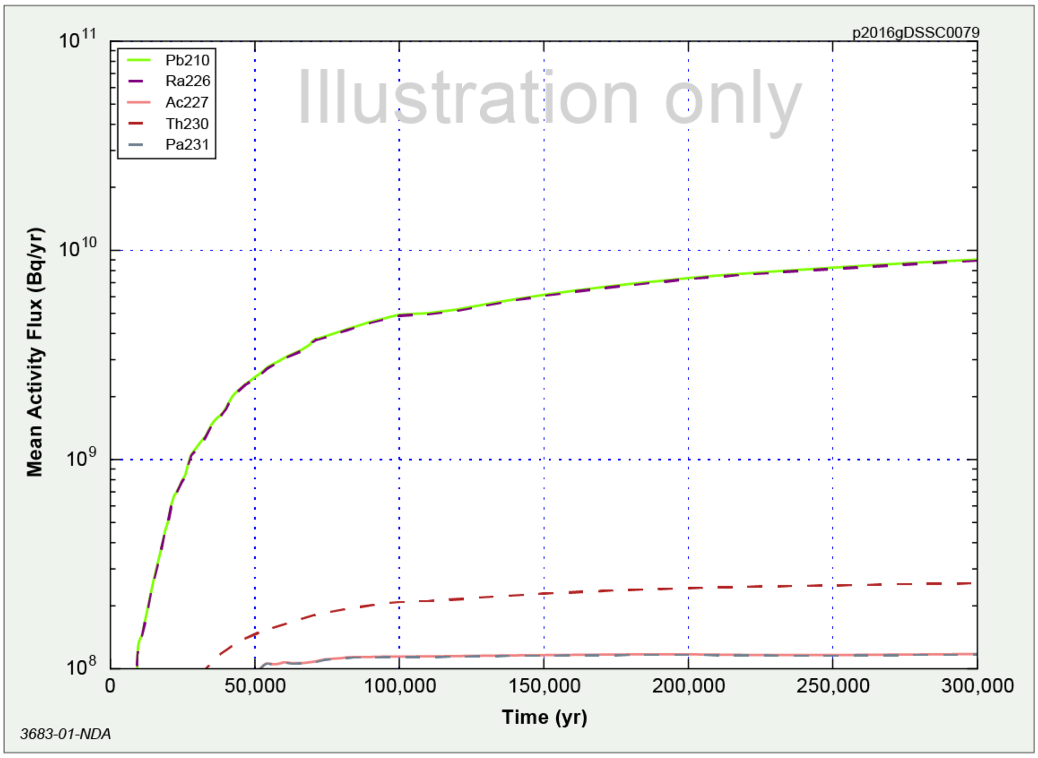
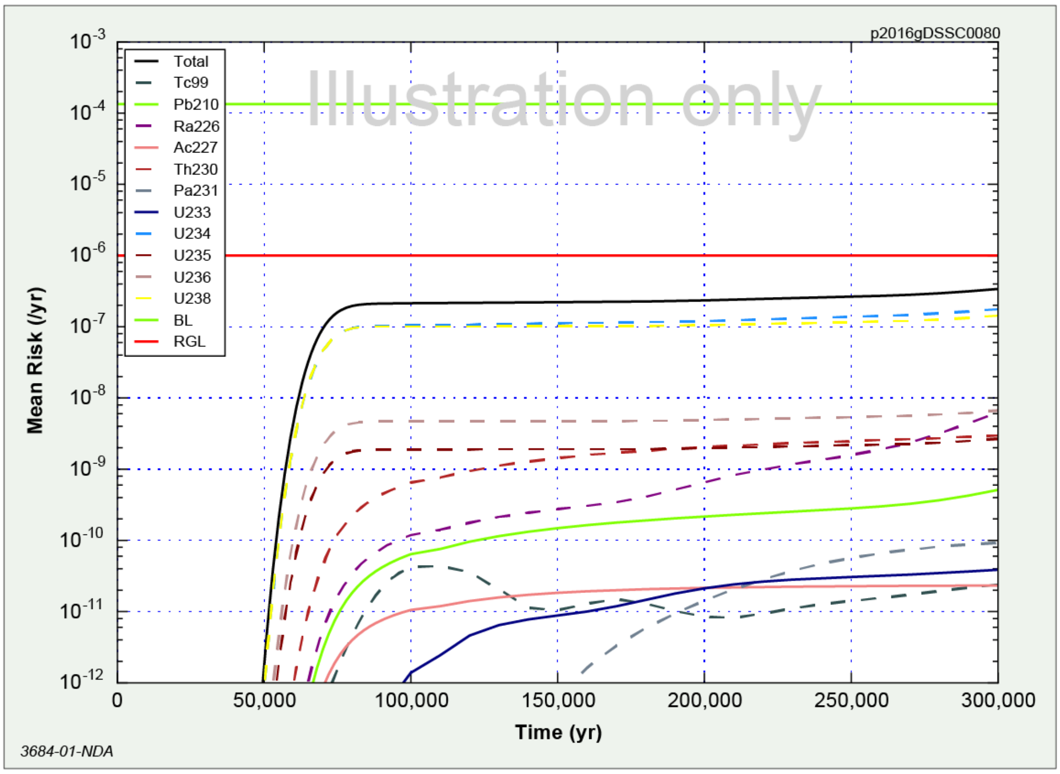


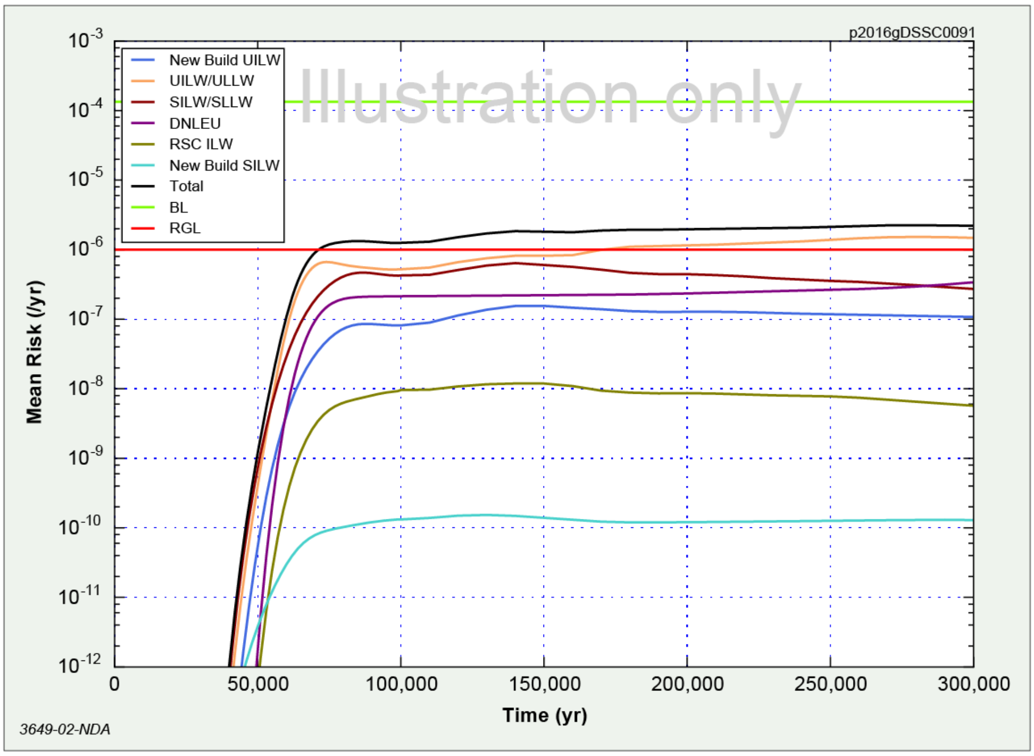
Figure 32 Mean radiological risk (total and significant contributors) via the well pathway for DNLEU disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock



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. The combined total mean risk is of the same order of magnitude as the risk guidance level and is substantially lower than the estimated risk associated with natural background ionising radiation.

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.

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**



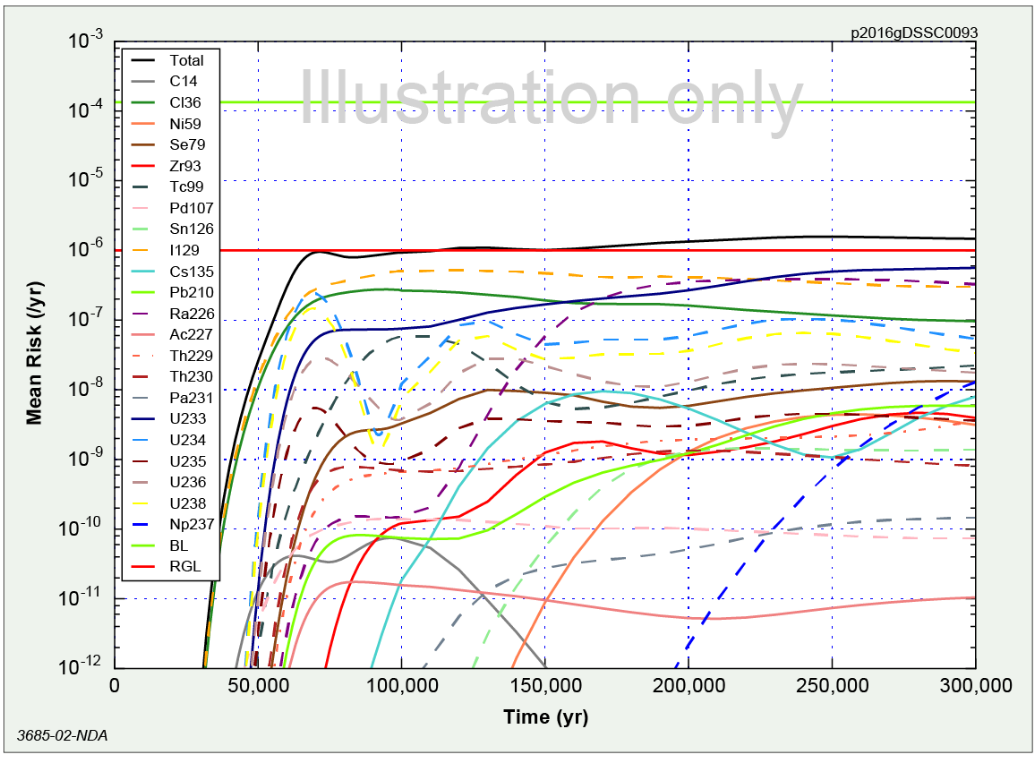
5.3.3 Variant scenario description

As discussed in the generic ESC [5, §5.8], the identification of variant scenarios has focused on the 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 contaminant transport are otherwise as assumed for the analysis of the base scenario.

5.3.4 Results

Early container failure has only a minor impact on calculated mean risk via the well pathway for UILW as indicated in Figure 34. Some realisations show earlier migration of I-129 and Cl-36 to the biosphere than in the base scenario (see Figure 26), but the total mean risk is little affected. Even for the most mobile radionuclides, the travel time to the biosphere for this illustrative geological environment is generally several tens of thousands of years or more and therefore a reduced period of waste package containment of this order or less does not have a significant impact on environmental safety. That is, radionuclides that decay in the waste packages on a timescale of several tens of thousands of years, will instead decay substantially in the host rock and cover rocks before reaching the biosphere.

Figure 34 Mean radiological risk (total and significant contributors) for UILW/ULLW disposed of in higher strength rock, with no matrix diffusion or radionuclide sorption in the host rock and where no credit is taken for containment in waste packages



5.4 Illustrative geological environment for lower strength sedimentary rock

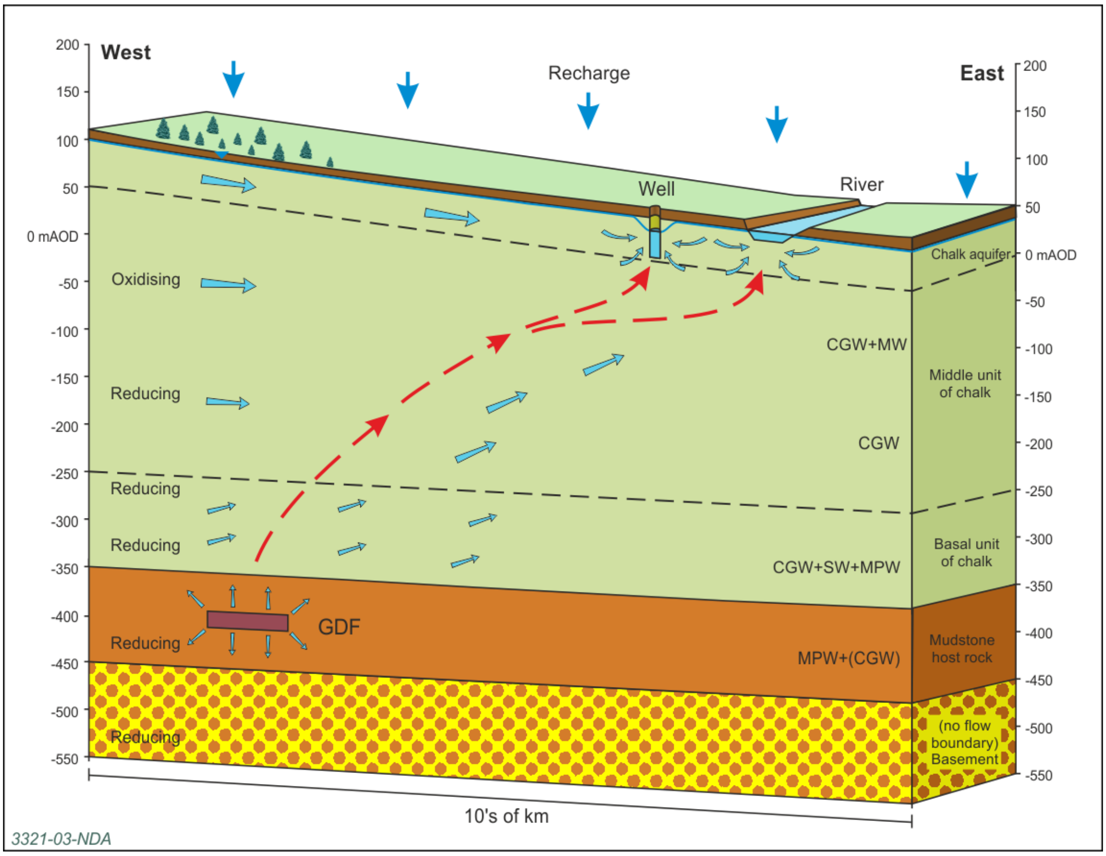
The illustrative geological environment adopted for these calculations is shown in Figure 35 and represents an example of a lower strength sedimentary rock overlain by higher permeability sedimentary rocks [19, §5.3.4]. The geological environment is assumed to have a ground surface sloping downwards from the west of the cross section at an elevation of slightly higher than 100 metres to the east of the section at an elevation of under 50 metres. The surface topography has a low point near to the east edge of the section.

The host rock is assumed to comprise a mudstone formation that is 100 metres thick, with its base at about 550 metres depth on the west of the section. The thickness of the mudstone is uniform across the section and is flat-lying with bedding parallel to the underlying contact with basement rock. 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 is assumed to fill 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. Chalk is a soft microporous limestone that is fissured, especially at shallower depths where it has suffered ‘cryoturbation’ (freeze-thaw cycling) in past ice age climatic conditions. The relatively shallow chalk (the uppermost 50 metres) generally has high permeability due to the abundant fissures and is therefore an aquifer. At greater depths, the chalk has less frequent fissuring and is also more compacted. Its permeability therefore tends to decrease with depth. The lowest stratigraphic part of the chalk contains significant amounts of clay, producing marly layers which decrease the permeability further.

In order to represent these depth-dependent changes in the physical and hydrogeological properties of the thick sequence of chalk in adequate detail, the chalk is subdivided into three segments, which are, from the top downwards: a 50-metre-thick upper unit of chalk (the ‘chalk aquifer’), a middle unit of chalk of variable thickness, and a 100-metre-thick basal unit[8]. 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 GDF, vertically-centred in the mudstone, is at a depth of 500 metres BGL, as shown in Figure 35. The middle unit is 300 metres thick to the west of the section, thinning to a thickness of 250 metres at the eastern edge of the section.

Figure 35 Possible transport pathway from a GDF to the surface environment where the lower strength sedimentary rock (mudstone) is overlain by a sequence of sedimentary formations and a river is the receptor[9]



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[8] 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.

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

Mudstone is a fine-grained, siliciclastic sedimentary rock having high clay content [19, §3.1.2]. Due to the weight and pressure exerted from overlying younger rocks through its geological burial and uplift history, the mudstone is slightly indurated. However, it is mechanically weak and open fractures cannot be sustained. The maximum depth of burial of this mudstone in the past has been between 1500 metres and 800 metres.

Solute transport in the host rock is assumed to occur predominantly by diffusion. Therefore, radionuclide releases from the EBS into the host rock would occur in all directions from the vaults and/or disposal tunnels. Radionuclides that diffuse vertically upwards to the chalk cover rock sequence are transported by advection in the chalk towards the biosphere.

5.4.1 Hydrogeological environment

The upper 50 metres of chalk rock is an aquifer, having sufficient storage, thickness and hydraulic conductivity to sustain water abstractions for public supply. With increasing depth the aquifer potential of chalk decreases due to less fracturing, decreasing pore volume and fracture apertures, and mineralogical changes in older parts of the chalk. Chalk has dual porosity, with groundwater moving predominantly in interconnected fractures and, to a lesser extent, in the larger matrix pores, although the pores are generally very small which gives the matrix its low permeability.

Recharge occurs across the full length of section and flows from the superficial deposits into the underlying chalk. Groundwater also flows more or less laterally from beyond the west of the section, where recharge at higher topography drives lateral flow through the chalk as shown in Figure 35. Lateral groundwater fluxes are greater in the chalk aquifer than in the deeper, less permeable, units of chalk rock.

The mudstone host rock has very low permeability and as a consequence the dominant mechanism for movement of solutes is diffusion. Radionuclides that diffuse upwards to the chalk cover rock sequence would be transported by advection towards the biosphere. Hydraulic gradients above the mudstone are determined by the distribution of hydraulic heads. As a generalisation and taking account of variations in permeability, lateral hydraulic gradients 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 upwards (or downwards, depending on topographic position and other factors) movement as shown by the arrows in Figure 35. The resulting predominant trajectory of groundwater movement and solute transport is, in this environment, as shown by the blue and red arrows in Figure 35.

The groundwater discharge location is an incised river as shown in Figure 35. The discharge point is a secondary river within a sub-catchment of a primary river. Flow in the secondary river is supported by run-off from the land surface and by base flow from discharge of near-surface groundwater in superficial deposits and in chalk which has a component of groundwater discharge from deeper chalk. If radionuclides from the GDF are transported to the near-surface in upwelling groundwater, they will initially be diluted in meteoric water within the sub-catchment of the secondary river. Subsequently, the radionuclides will 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 radiological 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 35). A well depth of 75 metres, typical for a public supply well in chalk, is assumed. A large abstraction rate is assumed and a cone of depression radiates (assumed symmetrically) around the well. The well affects the groundwater flow regime, drawing water towards it, both laterally and from below.

Where a plume of radionuclides exists in the vicinity of the well, part or all of it will be captured by the well. The concentration of radionuclides in the abstracted water can be calculated by diluting all, or part, of the flux of radionuclides entering the chalk aquifer by an amount that depends on the vertical cross-sectional area of the plume at the location of the well and the Darcy velocity of the water in the aquifer.

5.4.2 Groundwater composition

The assumed chemical composition of groundwater reflects precipitation that has infiltrated at the surface, rock type and the extent of reactions between rock and water, mixing with groundwaters that have flowed from other parts of the system, and varying proportions of water trapped at the time of deposition of the sedimentary rocks, dependent on the permeability and the extent of flushing. Groundwater compositions have been defined in terms of:

- Meteoric water, MW
- Chalk groundwater, CGW
- Seawater, SW
- Mudstone porewater, MPW

Figure 35 shows the combinations of the components from these end members that are expected to account in general for the groundwater salinities in the generic environment of the host rock.

The redox state of the two uppermost chalk units is described as ‘oxidising’, whereas the basal chalk unit is described as ‘reducing’.

5.4.3 Potential transport paths

As discussed above, two variants of the biosphere release pathway have been considered. One variant involves radionuclide discharge to a river from which water is abstracted and the second variant involves the use of contaminated water from an abstraction well (Figure 35). The terrestrial biosphere model is used to evaluate doses to potentially exposed groups via the groundwater discharge pathway as well as the well pathway (as discussed for the assessment of the GDF in higher strength rock). For the groundwater discharge pathway, the model calculates dose factors based on a unit discharge to one metre square of sub-catchment (H_{gw}, Sv/yr per Bq/m^2/yr). The total dose to a potentially exposed group (H_{ter}, Sv/yr) for a release of r (in Bq/yr) into the near-surface for the groundwater discharge pathway is given by:

$$H_{ter} = \frac{H_{gw}}{A} r$$

The value of A (m^2) is determined by the overall area of the sub-catchment into which the discharge occurs and the fraction of that area that comprises a discharge zone at some time during the year. That is:

$$A = A_{SC} f_{DA}$$

where:

A_{SC} is the total area of the sub-catchment (m^2)

f_{DA} is the maximum fractional area of groundwater discharge to the sub-soil (-)

The potential exposure pathways included in the biosphere model are external irradiation, ingestion of plants, animal produce, fish and water, inadvertent inhalation of suspended material, and inadvertent ingestion of soil [44]. The total dose is converted to a risk through a dose-to-risk conversion factor.

The total dose to a potentially exposed group via the well pathway is as discussed in Section 5.1 for disposal in higher strength rock.

Details of the mathematical model underpinning the TSM (and its implementation in GoldSim) are presented in the Post-closure Modelling Report [35, §4.4 and §6].

5.5 HHGW disposal in lower strength sedimentary rock

The concept for disposal of HHGW in lower strength sedimentary rock involves placing the wastes in carbon steel containers, which are emplaced in tunnels that are backfilled with bentonite. The base case scenario, describing the expected evolution of conditions in such a facility, is presented in the generic ESC [5, §6.7] and its evaluation is described below. A variant scenario involving early breach of carbon steel containers as a result of weld failure has also been evaluated. The environmental safety functions provided by the host rock in limiting radionuclide migration are important to the environmental safety of the illustrative disposal concept.

5.5.1 Base scenario description

Total system model calculations have been undertaken for the base case scenario to provide an illustration of the potential risks associated with HHGW disposal on a timescale of 300,000 years. Separate calculations have been undertaken for each type of HHGW; in each case, all disposal tunnels required to contain the entire inventory of the specific type of HHGW have been considered.

In the model, the carbon steel containers degrade and are breached sometime 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 [30]. The remaining containers are assumed to fail progressively thereafter over a period of between 1,000 and 25,000 years [30]. Once water penetrates the disposal container, the wasteform starts to dissolve and any radionuclides that have not decayed *in situ* may 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 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 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 of the illustrative geological environment.

5.5.2 Results

GoldSim TSM calculations have been undertaken for each HHGW group, except exotic fuels. Full details of the parameter values used in these calculations are presented in the Data Report [30]. Separate calculations have been undertaken for each type of HHGW; in each case, all tunnels containing the specific wasteform have been considered rather than single containers (as in the higher strength rock variant scenario).

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 packages. 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 36 for the example involving PWR spent fuel containers. As was found for the higher strength rock example, 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 safety function as indicated by Figure 37, 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 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 the terrestrial pathway and the well pathway on a timescale of 300,000 years is substantially less than 10^{-12}/yr for this illustrative example involving PWR spent fuel (not shown here) because of the slow rate of diffusion through the lower strength mudstone host rock.

Results for new build spent fuel, MOX spent fuel, AGR spent fuel and metallic spent fuel are similar to those for PWR spent fuel. For example, the calculated mean radionuclide activity fluxes entering the cover rock for the illustrations involving new build spent fuel and MOX spent fuel are shown in Figure 38 and Figure 39, respectively. Again, significant isotopes in terms of activity reaching the host rock are I-129, Cl-36 and Se-79, although activity fluxes are about an order of magnitude greater for new build spent fuel than for PWR spent fuel. Although the same radionuclides are the main contributors to the activity flux into the cover rocks for the HLW example, the I-129 activity flux is less than for the spent fuel examples (see Figure 40). In each case, calculated mean risks via the terrestrial pathway and the well pathway on a timescale of 300,000 years are substantially less than 10^{-12}/yr (not shown here).

The calculated mean radionuclide activity fluxes entering the cover rock for the examples involving Pu and HEU ceramic wastes are substantially less than 10^3 Bq/yr in the assessment period and, again, the mean risk is less than 10^{-12}/yr in each case.

In summary, the calculated total mean risk via each pathway for each type of HHGW is insignificant on a timescale of 300,000 years, due to the safety function provided by the host rock and the long travel time in the cover rocks.

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

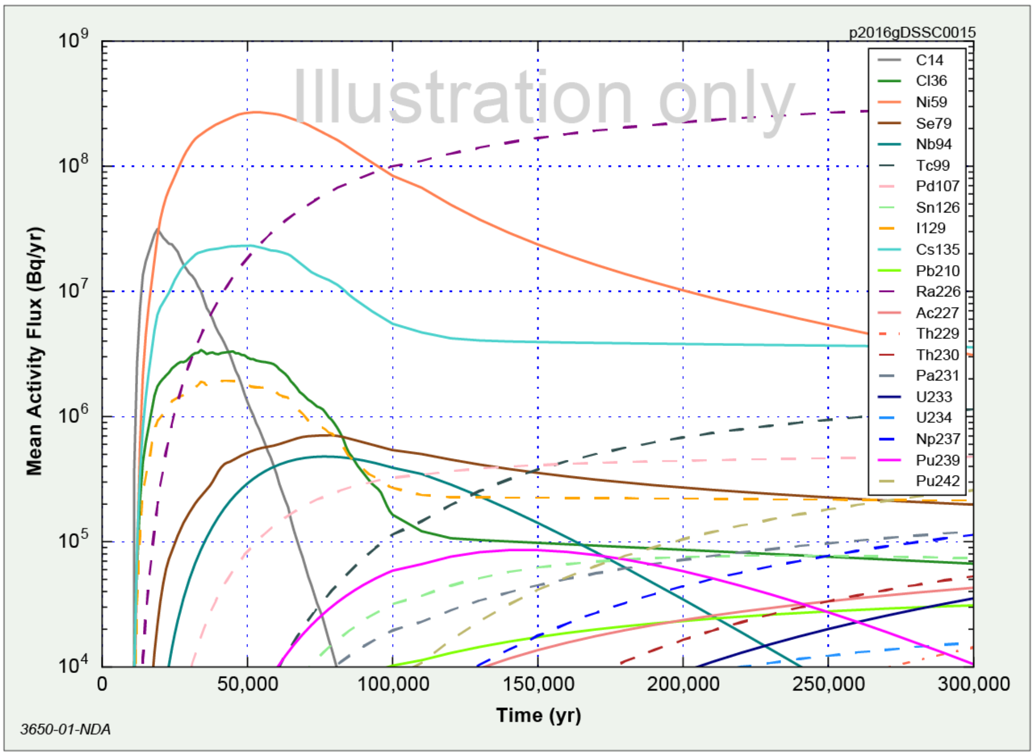


Figure 37 **Mean radionuclide activity flux from the host rock to the cover rocks for PWR spent fuel disposed of in a lower strength sedimentary rock**

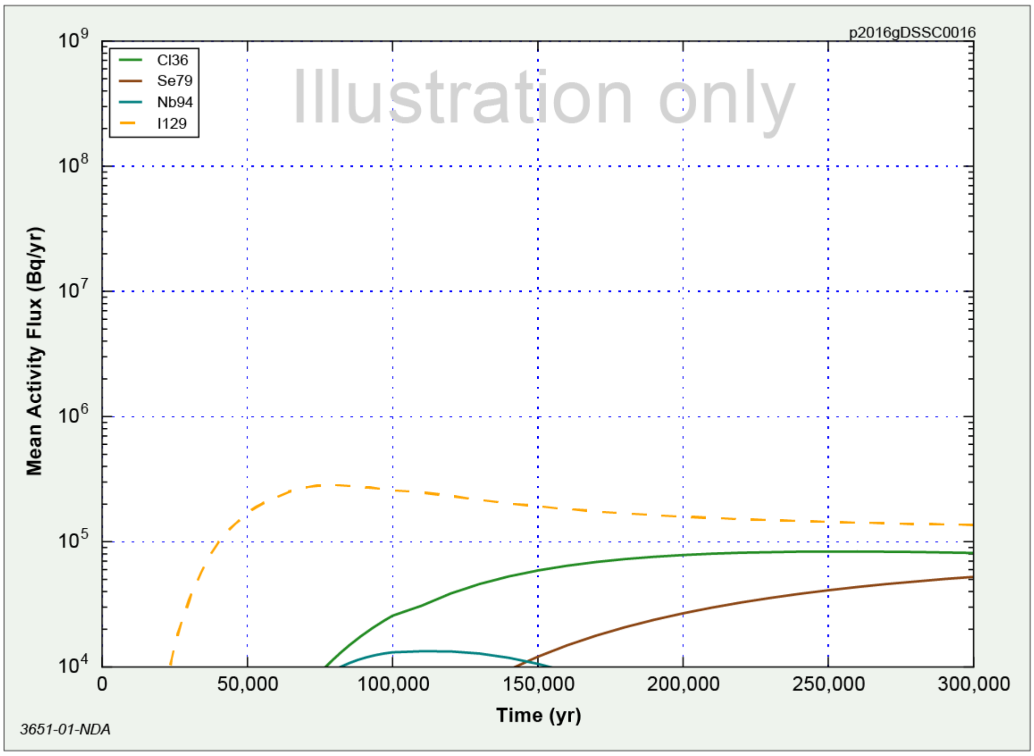


Figure 38 **Mean radionuclide activity flux from the host rock to the cover rocks for new build reactor spent fuel disposed of in a lower strength sedimentary rock**

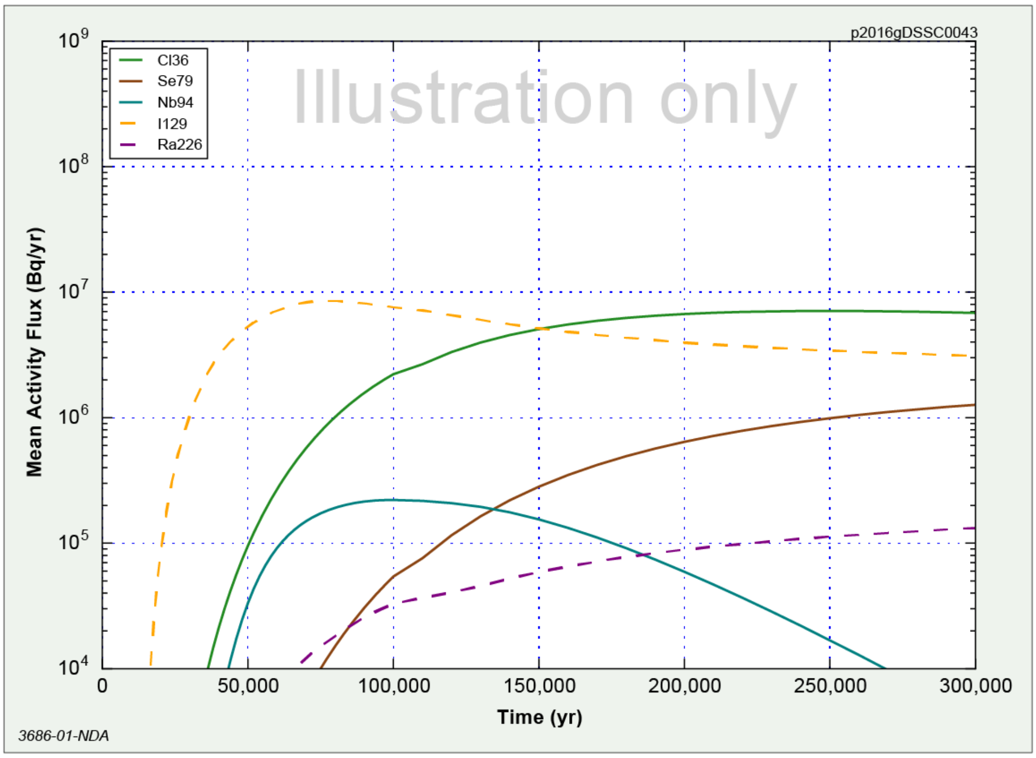


Figure 39 Mean radionuclide activity flux from the host rock to the cover rocks for MOX spent fuel disposed of in a lower strength sedimentary rock

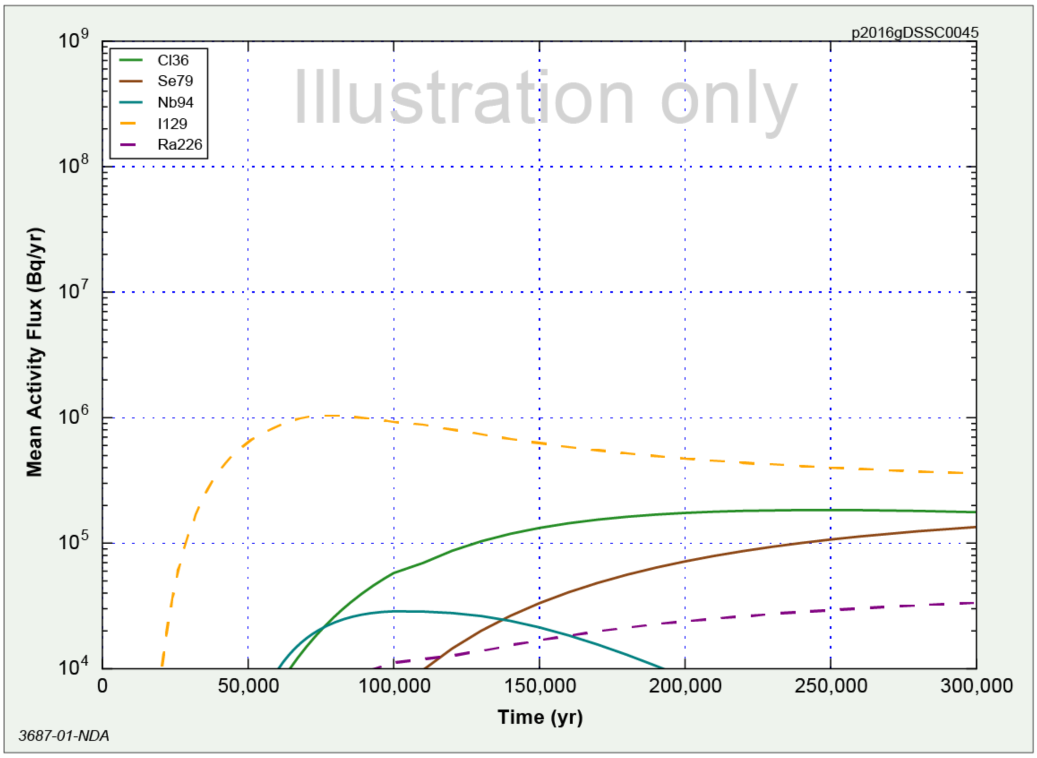
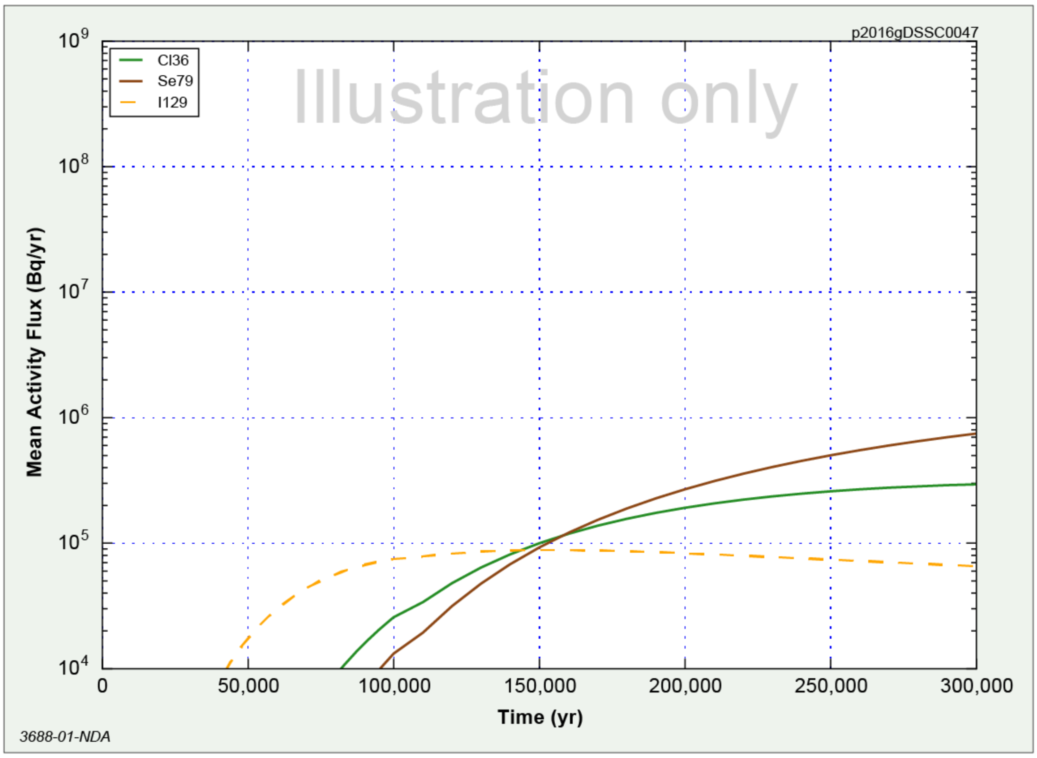


Figure 40 Mean radionuclide activity flux from the host rock to the cover rocks for HLW disposed of in a lower strength sedimentary rock



5.5.3 Variant scenario description

As discussed in the ESC [5, §6.8], the identification of variant scenarios has focused on the safety functions provided by the containers. The variant scenario involves early breach of carbon steel containers as a result of weld failure under the mechanical stresses imposed by swelling bentonite. The conditions for contaminant transport are otherwise as assumed for the analysis of the base case scenario.

5.5.4 Results

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 (predominantly from I-129) remain less than 10^{-9}/yr even after one million years. This is consistent with the findings of the insight analysis illustrated in Figure 7; breakthrough of even a small fraction of a source of radionuclides such as I-129 by diffusion across a 50 metre thick clay layer would be expected to take of the order tens to hundreds of thousands of years.

5.6 LHGW disposal in lower strength sedimentary rock

The concept for the disposal of LHGW in lower strength sedimentary rock involves emplacing the waste packages in vaults that are backfilled with a cementitious material [3]. For the illustrative disposal concept, the vault dimensions have been maximised based on consideration of the stacking requirements of the different types of waste package and 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.

The safety functions provided by the host rock in limiting contaminant migration are important for the environmental safety of the illustrative disposal concept. Also, establishing alkaline and reducing conditions in the EBS ensures that the corrosion rates of metal containers are low and that the rate of release of contaminants from the waste packages and through the backfill is limited.

However, after hundreds of thousands of years, it is likely that degradation of the engineered barriers would be such that they would no longer be able to perform their original safety functions fully. Therefore, total system model calculations have been undertaken for the base scenario to provide an illustration of how the components of the barrier system contribute to the environmental safety of LHGW disposal, based on a post-closure timescale of 300,000 years.

Also, a variant scenario has been evaluated that involves errors in backfill emplacement, leading to early breach of stainless steel containers as a result of corrosion under oxic and low pH conditions in the presence of groundwater rich in chloride.

5.6.1 Base scenario description

The analysis of the base scenario has focused on the evolution of conditions in vaults containing SILW/SLLW, UILW/ULLW, ILW in RSCs, DNLEU, new build SILW or new build UILW. In each case, the containers are assumed to degrade and to be breached sometime after GDF closure. 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 [30].

After container failure, radionuclides are released from the waste packages and diffuse into and through the host rock, before migrating to the surface environment through the cover rocks. 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 35), with transport pathways assumed to exist from the host rock to the biosphere. Again, radionuclide transport in 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 longitudinal dispersion along the transport paths and radionuclide decay and ingrowth are included in the model. Exposure to radionuclides can occur via discharge to a river and via a water abstraction well, as discussed in Section 5.4.

Details of the mathematical model underpinning the TSM (and its implementation in GoldSim) are presented in the Post-closure Modelling Report [35, §4.2 and §6].

5.6.2 Results

The radionuclide activity fluxes (Bq/year) across each barrier have been evaluated using the TSM. The calculated mean of the radionuclide activity fluxes entering the cover rocks from the host rock is shown in Figure 41 for radionuclides released from degraded stainless steel UILW/ULLW containers. 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.

The host rock provides a significant radionuclide containment function as indicated by Figure 42, which shows the mean of the total radionuclide activity fluxes entering the cover rocks from the host rock for UILW/ULLW. 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 in this illustration.

Results for vaults containing SILW/SLLW containers are shown in Figure 43 in terms of mean radionuclide activity fluxes entering the cover rocks from the host rock. The most significant radionuclide (in terms of activity) that reaches the cover rocks on a timescale of 300,000 years is Cl-36.

The mean radionuclide activity flux entering the cover rocks from the host rock for vaults containing DNLEU containers is shown in Figure 44. The only radionuclide entering the cover rocks with a potentially significant activity flux is Ra-226.

The calculated mean risks via the terrestrial and well pathways on a timescale of 300,000 years are substantially less than 10^{-12}/yr for each illustrative example (that is, for vaults containing SILW/SLLW, UILW/ULLW, ILW in RSCs, DNLEU, new build SILW or new build UILW), because of the safety function provided by the host rock and the long travel time in the cover rocks.

Figure 41 Mean radionuclide activity flux from the backfill to the host rock for UILW/ULLW disposed of in a lower strength sedimentary rock

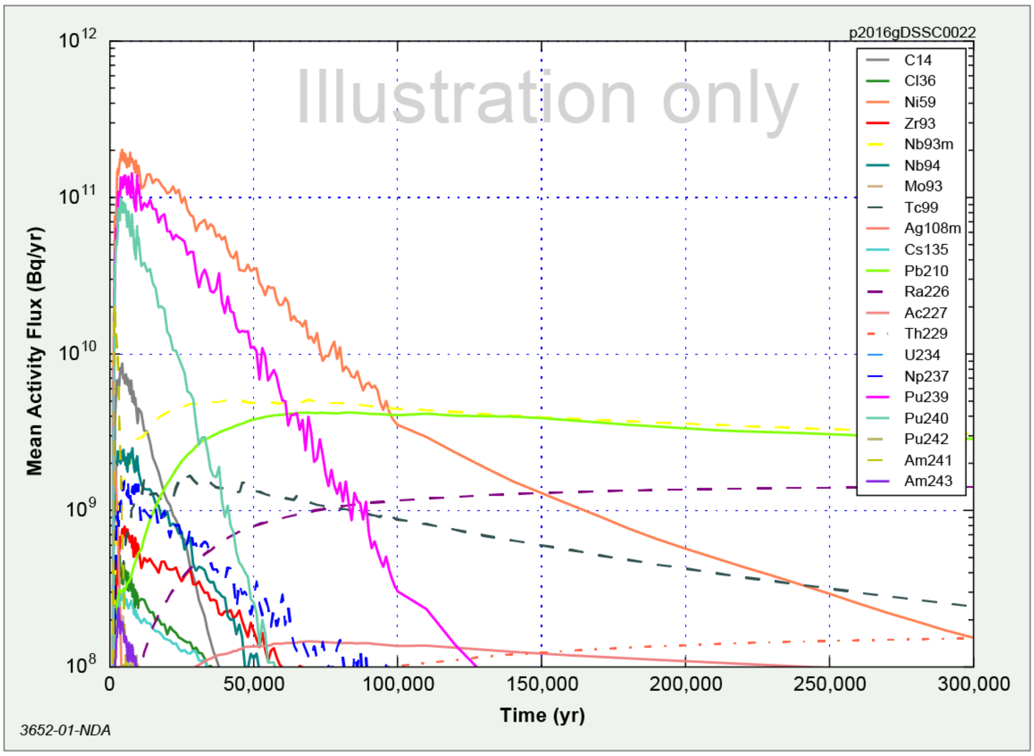


Figure 42 Mean radionuclide activity flux from the host rock to the cover rocks for UILW/ULLW disposed of in a lower strength sedimentary rock

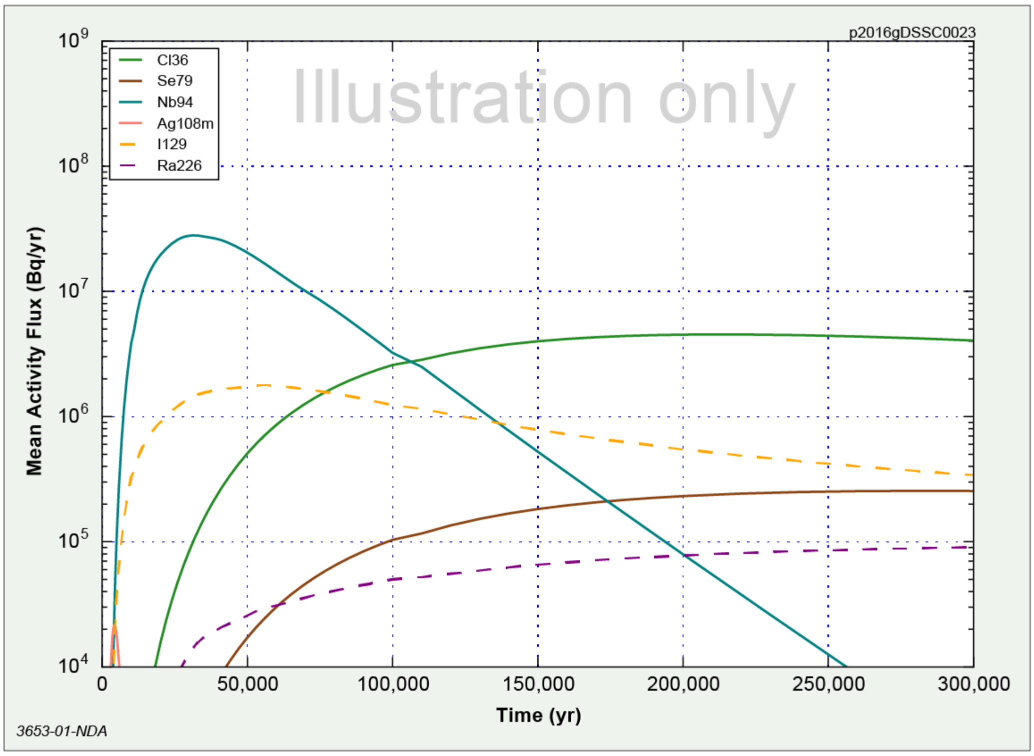


Figure 43 Mean radionuclide activity flux from the host rock to the cover rocks for SILW/SLLW disposed of in a lower strength sedimentary rock

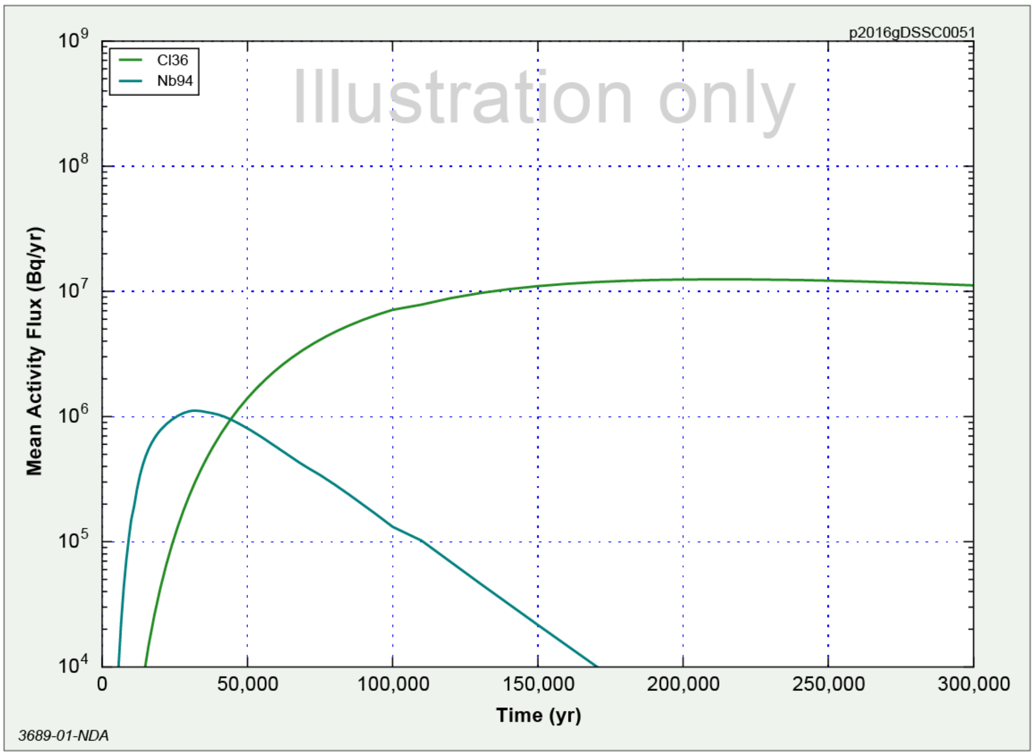
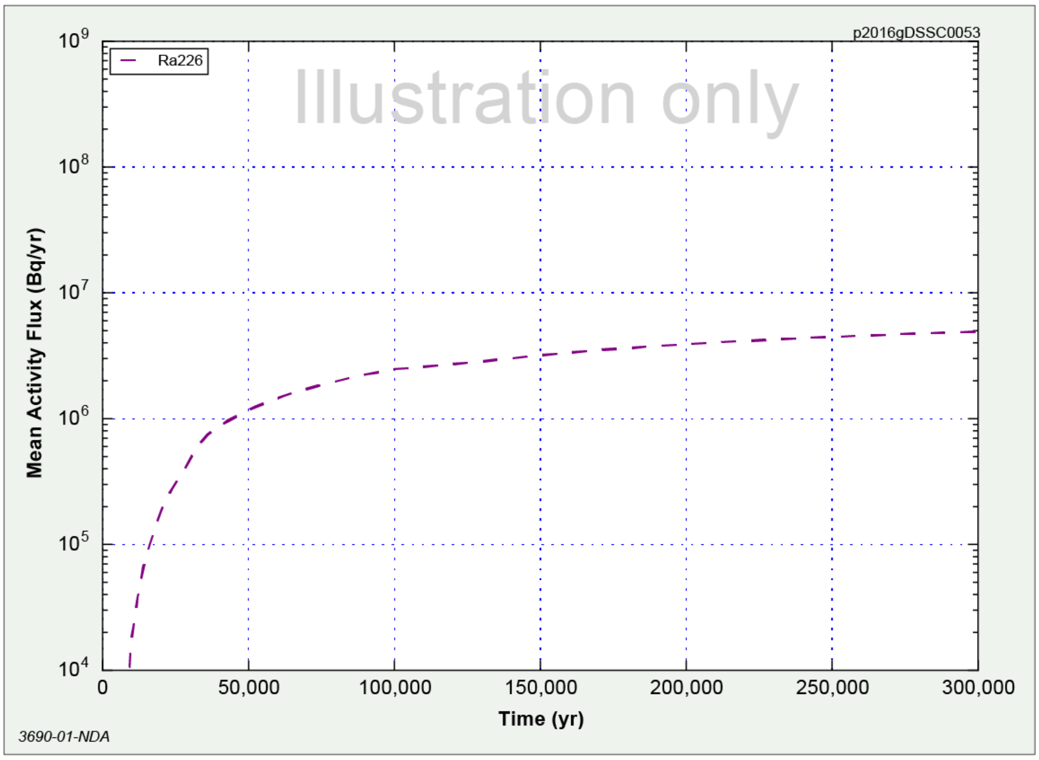


Figure 44 Mean radionuclide activity flux from the host rock to the cover rocks for DNLEU disposed of in a lower strength sedimentary rock



5.6.3 Variant scenario description

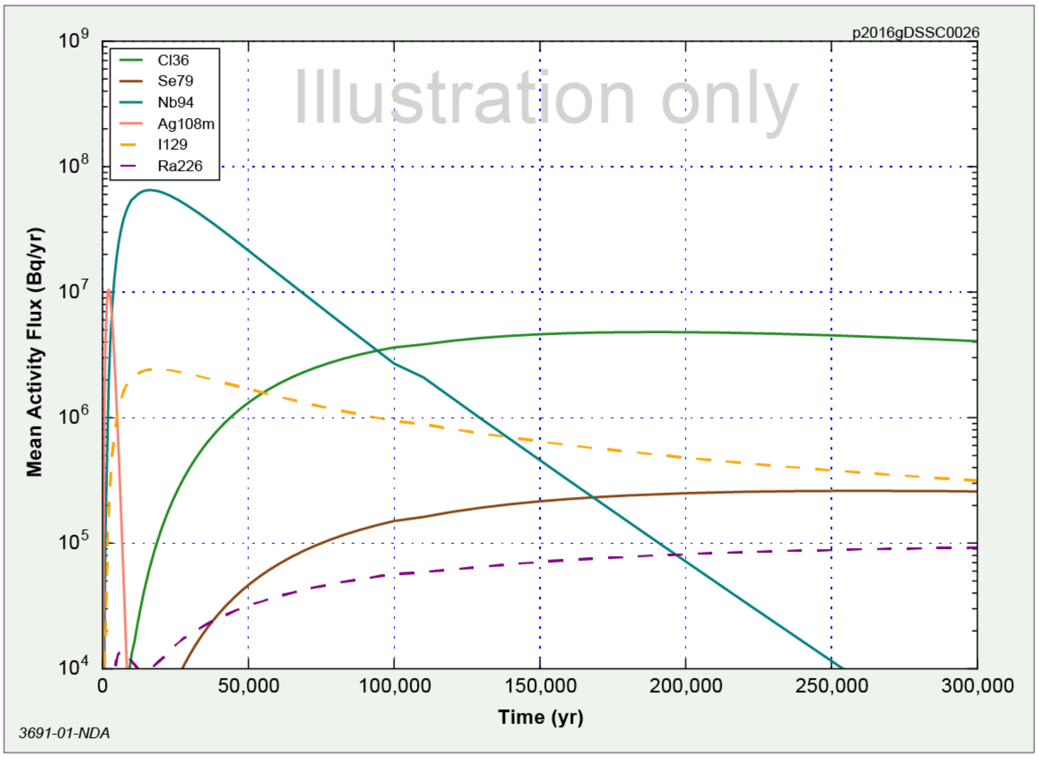
As discussed in the generic ESC [5, §7.8], the identification of variant scenarios has focused on the safety functions provided by the backfill. The identified variant scenario involves errors in backfill emplacement, leading to early breach of stainless steel containers as a result of corrosion under oxic and low pH conditions in the presence of groundwater rich in chloride. The conditions for contaminant transport are otherwise as assumed for the analysis of the base case scenario.

5.6.4 Results

The calculated mean of the radionuclide activity fluxes entering the cover rocks from the host rock for UILW/ULLW is shown in Figure 45. The peak of each mean radionuclide flux entering the cover rock occurs sooner and its magnitude is slightly greater than in the illustration without early container failure (see Figure 42). The activity flux of Ag-108m (half-life of 418 years [30]) is substantially increased, because there is no period of containment and decay in the waste packages. However, in many realisations, 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.

Calculated risks via the terrestrial pathway and the well pathway on a timescale of 300,000 years remain substantially less than 10^{-12}/yr.

Figure 45 **Mean radionuclide activity flux from the host rock to the cover rocks for UILW/ULLW disposed in a lower sedimentary strength where no credit is taken for containment in waste packages**



5.7 HHGW and LHGW disposal in evaporite rock

The expected evolution of disposal facilities in evaporite rock is not expected to result in radionuclide releases to the biosphere via groundwater, primarily because there would be little water available to facilitate radionuclide migration in the evaporite rock and rock creep would be expected to encapsulate the wastes after disposal, closing any fractures and voidage that could act as radionuclide transport pathways (see the Geosphere Status Report [19, §6.8.5]). Therefore, no quantitative analysis of radionuclide transport in groundwater has been undertaken for this geological environment.

6 Gas Assessment

Gases may be formed from natural processes occurring in many waste packages, such as corrosion of metals in the waste, radioactive decay and radiolysis of water [18, §2] and some of the gases generated may be radioactive. This section presents illustrative calculations of radioactive gas generation and migration for the different illustrative disposal concepts being considered in the DSSC. However, illustrative calculations of risk associated with human exposure to radionuclides in the gas phase have not been undertaken.

As stated in the Gas Status Report [18, §2.2], the main gas generating processes that will occur in wastes in the GDF are:

- corrosion of metals (with the release of C-14 from neutron-irradiated metals)
- microbial degradation of organic materials, including the hydrolysis of cellulose to smaller organic compounds
- radiolysis, in particular of water and some organic materials

However, gas generation could also occur by [18, §2.2]:

- diffusion, notably the release of tritium by solid state diffusion from metals
- radioactive decay of radium, which leads to the generation of Rn-222
- the release of radioactive gases containing tritium or C-14 by leaching of irradiated graphite
- alpha decay in the waste producing stable helium

Reactions involving components of the EBS will also contribute to gas generation after their emplacement. For example, anaerobic corrosion of stainless steel waste containers and gamma radiolysis of porewater in a cementitious backfill will produce gas.

The bulk of the gas generated in the GDF will be hydrogen, from the corrosion of metals (only under anaerobic conditions for steels and uranium) and the radiolysis of water and organic materials, and methane and carbon dioxide that will be generated mainly by microbial degradation of organic materials [18, §2.2]. As noted in the Gas Status Report, production of helium through radioactive decay is usually small in comparison with overall bulk gas production for intermediate-level wastes, where most containers are vented. For spent fuel packages, where the containers are sealed, the volume of helium produced is expected to be small relative to the void volume of the container.

Radioactive gases that will be generated include tritiated hydrogen, tritiated methane, C-14-bearing methane, C-14-bearing carbon dioxide and Rn-222. 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 human and non-human biota [18, §2] if they were to migrate through the EBS, the host rock and the overlying rocks, and reach the biosphere. Any bulk gas that is generated could also act as a carrier for these radioactive gases.

The main radioactive gas that requires consideration in the GDF post-closure performance assessment is C-14 (which has a half-life of 5,730 years [30]). Any tritiated gas generated would decay before it could migrate from the GDF (H-3 has a half-life of about 12 years [30]) and does not require detailed consideration in post-closure performance assessments. Rn-222 is produced from radioactive decay as part of the radium series decay chain, but has a short half-life (approximately four days) and is therefore not significant in terms of post-closure safety when generated in a disposal facility. However, it is important to note that Rn-222 may be a concern if long-lived uranium or thorium isotopes in the radium series (that is U-238, U-234 and Th-230) migrate to the biosphere. Note also that Rn-222 is produced naturally from some rocks and will be an important site-specific consideration.

The rate of gas generation and the quantities and types of gas generated in the GDF will depend on the properties of the waste, EBS and geological environment, and the evolving environmental conditions in the GDF. For example, gas generation processes are sensitive to the presence of oxygen or water, the presence of hydrogen or chloride ions and temperature [18, §2.2]. Also, gas generation and release of gases from wastes during storage at a waste producer's site will reduce the inventory of materials with the potential to generate gas in the GDF (as would the aerobic corrosion of steels although this produces no hydrogen). Similarly, gas generation and release from waste packages during the operational phase of the GDF would reduce the inventory of gas generating material present after closure; the duration of waste package transport would be expected to be too short to be of significance in this respect [18, §2]. Gas generation and assessment in the operational period is discussed in the Gas Status Report and the OESA [18; 4].

The main way in which radionuclides released from waste packages are likely to migrate from a disposal facility after closure is through dissolution from the wasteform followed by transport in groundwater [18, §3]. However, gas generation could be sufficient to cause a gas phase to form and co-exist with the groundwater at some time after closure; that is, a two-phase system may be present. Any free gas that is generated may migrate to the biosphere, but this would require the gas to be transferred [18, §3.1]:

- out of the waste packages or disposal containers (for gas generated by the wasteforms)
- through the engineered barrier components of the GDF (for example buffer and backfill) and any engineering disturbed zone (EDZ) present; and
- through the host rock and overlying rocks.

The generic ESC [5, §10.4] discusses the potential for gas generation and migration and its impacts for the specific conditions assumed within the illustrative geological disposal concepts. This PCSA provides detailed example calculations to support understanding of gas generation and migration processes. A more detailed discussion of RWM's general understanding and modelling of gas generation and migration is provided in the Gas Status Report [18].

6.1 Illustrative gas generation calculations

RWM has been carrying out a range of research and assessment activities on C-14 through an integrated project to develop a holistic approach to C-14 management in the GDF [46], and through involvement in an EC project on Carbon-14 Source Term (CAST) [47; 48]. RWM has also undertaken several studies into post-closure gas generation in different geological environments [49; 50; 51; 52]. Calculations have been undertaken for a range of different assumptions and scenarios to examine the effect of uncertainty in gas generation calculations; these are presented in full in the Gas Status Report [18]. The purpose of this section is to demonstrate that, through this research and assessment work, RWM sufficiently understands and can evaluate the gas generating processes that could occur within the different types of geological environment that could host a GDF.

6.1.1 HHGW disposal in higher strength rock

The illustrative concept for the disposal of HHGW in higher strength rock involves packaging the wastes in cast iron inserts inside copper containers [5, §4] and placing the containers in vertical deposition holes lined with a bentonite buffer. The chemical forms and dryness of spent fuel, HLW, HEU and Pu mean that they will produce negligible volumes of gas within the disposal containers. Small amounts of radioactive gas could leak from any defective spent fuel pins, but such gas would be retained within the high-integrity containers [18, §4.4]. Vitrified HLW and the stainless steel canister within which it is contained will not generate gas when dry within the intact disposal container. RWM has undertaken some illustrative calculations of gas generation from HLW and spent fuel to support this understanding [53].

As the corrosion of copper under anaerobic conditions is slow and is only likely to proceed in the presence of sulphide, the HHGW containers in this illustrative geological disposal concept example will generate minimal gas from corrosion under disposal conditions [18, §6.1.4]. If a copper container degrades and is breached after disposal and water enters the container, then corrosion of metals in the container and the wasteforms and radioloysis of the water could generate gas. In particular, corrosion of the cast iron insert could generate bulk hydrogen gas. The rate of gas generation will depend on factors such as the size of the perforation in the container and water availability. If the perforated region is small, then gas pressurisation in the container may slow the rate of inflow of water. Also, the iron corrosion product will gradually increase the volume of solids in the container. Corrosion will be focused around the perforation eventually closing the gap between the insert and the copper shell in the perforated region, thus restricting the movement of water and the potential for corrosion of metals in the container. If corrosion occurs at a rate of 0.1 $\mu m\ y^{-1}$, unrestricted by water availability, it could take around 10,000 years for a small (~1 mm) gap between the insert and the copper shell to be closed [53, §5.3.6].

Gas transfer analysis has indicated that the impact of any gas that escapes from a waste container and migrates through the surrounding buffer material is not likely to have a significant effect on barrier performance [18, §6.1.4]. If the perforation in the copper container is small, then the rate at which hydrogen will be able to diffuse in the liquid phase away from the container will be less than the rate of hydrogen generation. Therefore, the gas pressure in the container will rise. When the gas pressure reaches a threshold value, pathways in the bentonite will open and allow the hydrogen to flow away from the container. The pathways in the bentonite may stay open for as long as gas production is sufficient and may then close [18, §6.2.2; 53; 54]. This process may then become episodic as corrosion progresses and gas pressures begin to increase again.

6.1.2 LHGW disposal in higher strength rock

The illustrative concept for the disposal of LHGW in higher strength rock involves stacking waste packages in large vaults backfilled with Nirex Reference Vault Backfill (NRVB), which is a cementitious material [5, §5]. Illustrative calculations of gas generation from unshielded ILW packages have been undertaken for this disposal concept based on the 2007 Derived Inventory[10] [55]. Results of the calculations are shown in Figure 46 [50]. The rate of generation of bulk gases (hydrogen (H_2) and methane (CH_4)) is plotted against the left-hand axis. The rate of generation of radioactive gases (H-3, $^{14}CH_4$ and Rn-222) is plotted against the right-hand axis. Carbon dioxide (CO_2) is assumed in the calculation to react with cementitious materials and is not released as a free gas. Thus, CO_2 as a bulk gas and CO_2 containing C-14 do not appear on the figure.

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[10] Gas generation calculations based on the 2013 Derived Inventory are discussed later in this section. The calculation for the 2007 Derived Inventory is discussed here because it provides the base case for the scenario calculations addressing the effect of uncertainty.

Figure 46 **Illustrative calculations of bulk and radioactive gas generation (at STP) from UILW following disposal in the GDF in higher strength rock, based on the 2007 Derived Inventory [50, Figure 5.1]; carbon dioxide (including C-14-bearing CO_2) is not shown because it is assumed to react with cementitious materials and is not released as a free gas**

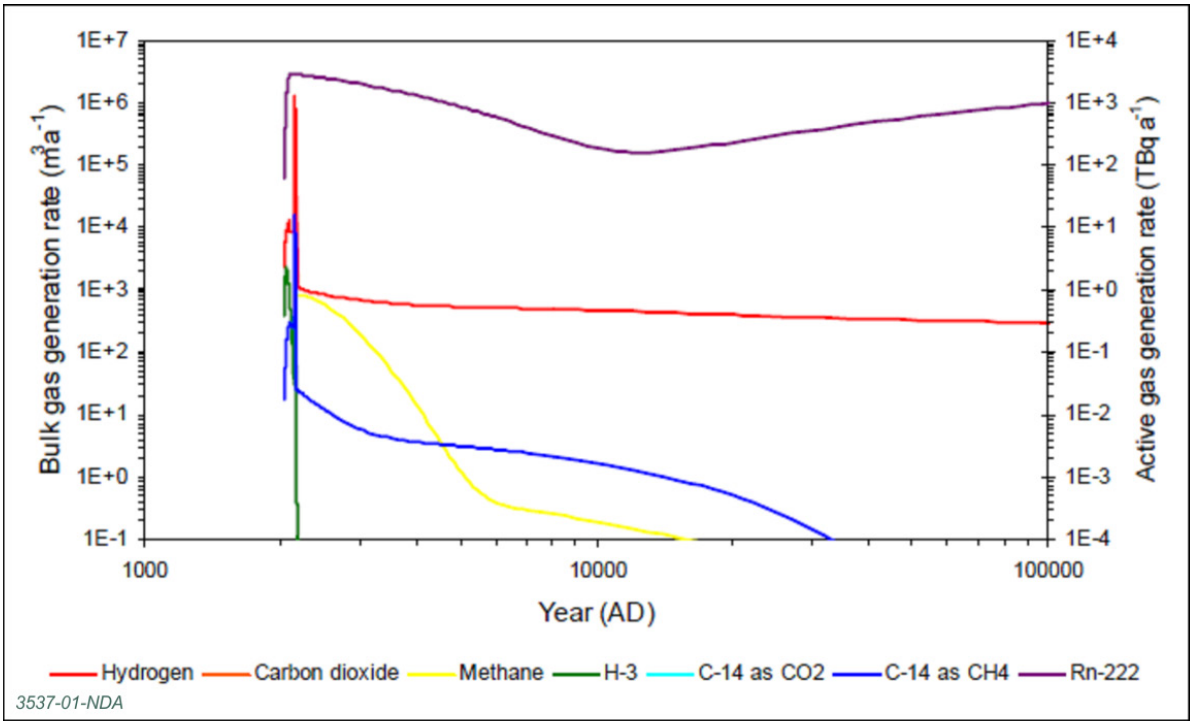

Figure 46 indicates that hydrogen gas is generated at a rate that decreases slowly from about one thousand $m^3 y^{-1}$ to a few hundred $m^3 y^{-1}$ at standard temperature and pressure (STP) over about 100,000 years. Long term hydrogen generation is mainly from the radiolysis of water, with some contribution from the radiolysis of organic polymers and the corrosion of stainless steel containers, and smaller contributions from the corrosion of stainless steel wastes, carbon steel wastes and containers, Zircaloy and radiolysis of oils and cellulose [18, §6.1.1]. Methane is generated until around 10,000 AD from the microbial degradation of small organic molecules, for example from the alkaline degradation of cellulose. The long-term generation of $^{14}CH_4$ is mainly due to the degradation of small organic molecules containing C-14 (although the major waste stream of this type may now not be disposed of in the GDF[11]) and there are also contributions from the corrosion of stainless steel, carbon steel and Zircaloy wastes, radiolysis of organic molecules and releases from irradiated graphite [18, §6.1.1].

The evolution of the generation rate of Rn-222 (half-life approximately 4 days) is complex. Rn-222 is produced by the radioactive decay of Ra-226, as part of the U-238 decay chain. As the half-life of Ra-226 is 1600 years [30], Rn-222 will continue to be produced well beyond the operational phase of the GDF. In the longer term, Rn-222 will also be generated by Ra-226 that arises from the decay of U-238 (half-life 4.46×10^9 years [30]) and its daughters either disposed of in the GDF or occurring naturally in the surrounding rock. The time required to achieve secular equilibrium (see Box 3) between the parent and the Ra-226 progeny is determined by the half-lives of the various radionuclides in the chain, and is very long; for example, it will take about one million years for Ra-226 to reach

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[11] This calculation included GE Healthcare waste stream 1A07, a waste stream that may not be destined for a GDF but is included in both the 2007 and 2013 Derived Inventories.

secular equilibrium with U-234. Hence, degrading waste materials, such as fuel residues from which Ra-226 will have been separated, typically will not have included the Ra-226 at secular equilibrium with uranium isotopes. As a result, the maximum Ra-226 inventory, and therefore the maximum generation rate of Rn-222, is calculated to occur about 100,000 years after GDF closure [50]. Discussion of other radioactive gases considered in this illustrative example, and indicated in Figure 46, is provided in the Gas Status Report [18] and in [50].

More recent calculations of C-14 gas generation have been made based on the 2013 Derived Inventory [7] and have included some of the improved understanding of C-14 release from waste materials discussed in the Gas Status Report [18, §2.3.2]. The calculated long-term generation rates of C-14-bearing gases according to the type of waste material are presented in Figure 47 (legacy UILW/ULLW), Figure 48 (legacy SILW/SLLW) and Figure 49 (UILW from the operation of new-build reactors). The results are discussed in detail in the Gas Status Report [18, §6.1.1].

The corrosion of Magnox metal, irradiated stainless steel AGR fuel cladding (waste stream 2F03/C), assembly components (waste stream 2F08) and Zircaloy are calculated to be the main contributors to the generation of C-14-bearing gas from UILW/ULLW [18, §6.1.2]. The release of gaseous C-14 from SILW/SLLW is primarily from the corrosion of irradiated mild steel; the contribution from irradiated graphite falls away because the leachable fraction of C-14 is depleted relatively quickly. The corrosion of stainless steel is the only significant source of C-14 from waste from new build UILW described in the 2013 Derived Inventory [46].

Figure 47 Illustrative calculations of C-14 gas generation during GDF operations and the early post-closure phase from legacy UILW/ULLW following disposal in the GDF in higher strength rock, based on the 2013 Derived Inventory [51]

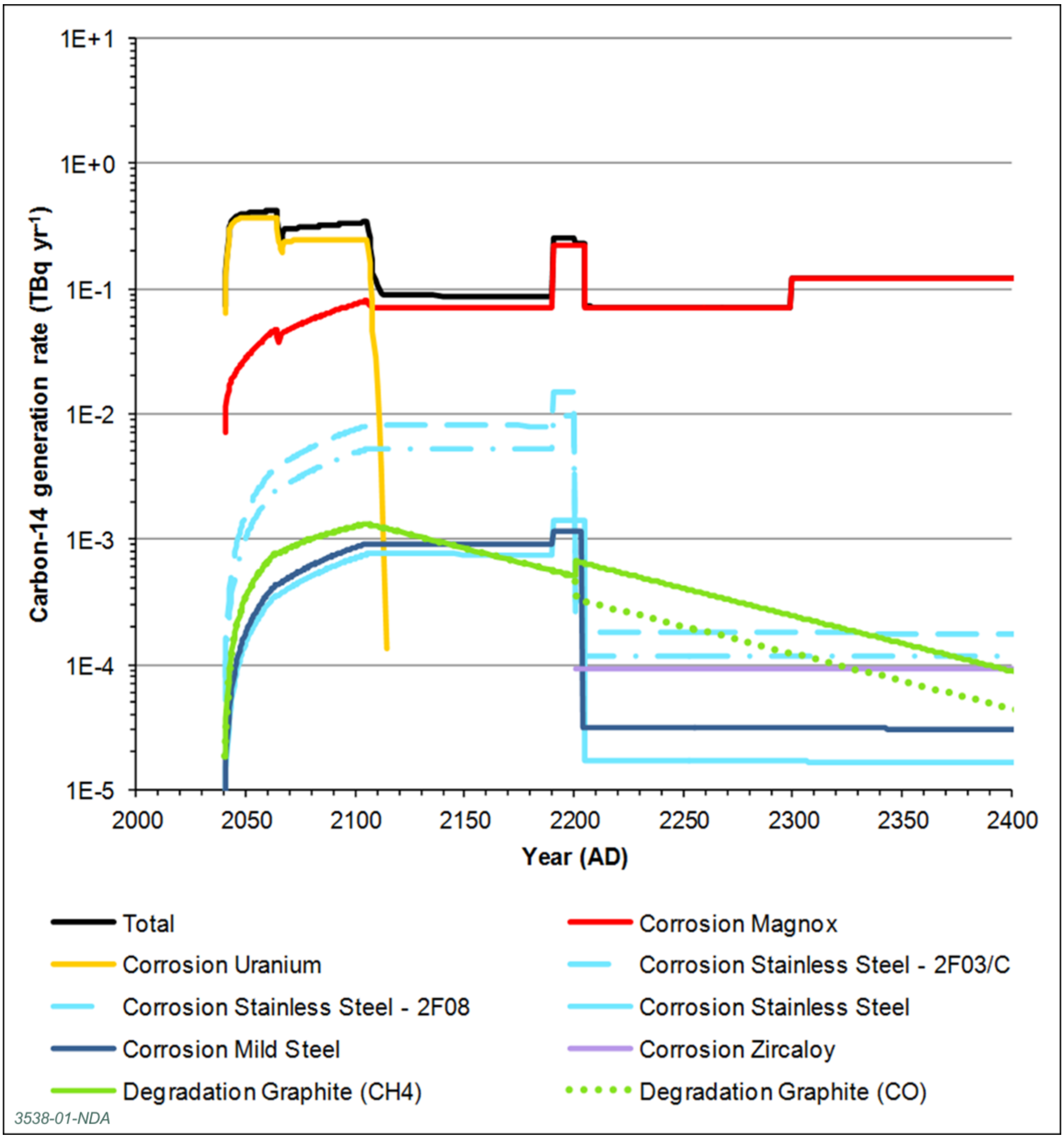


Figure 48 **Illustrative calculations of C-14 gas generation during GDF operations and the early post-closure phase from legacy SILW/SLLW following disposal in the GDF in higher strength rock, based on the 2013 Derived Inventory [51]**

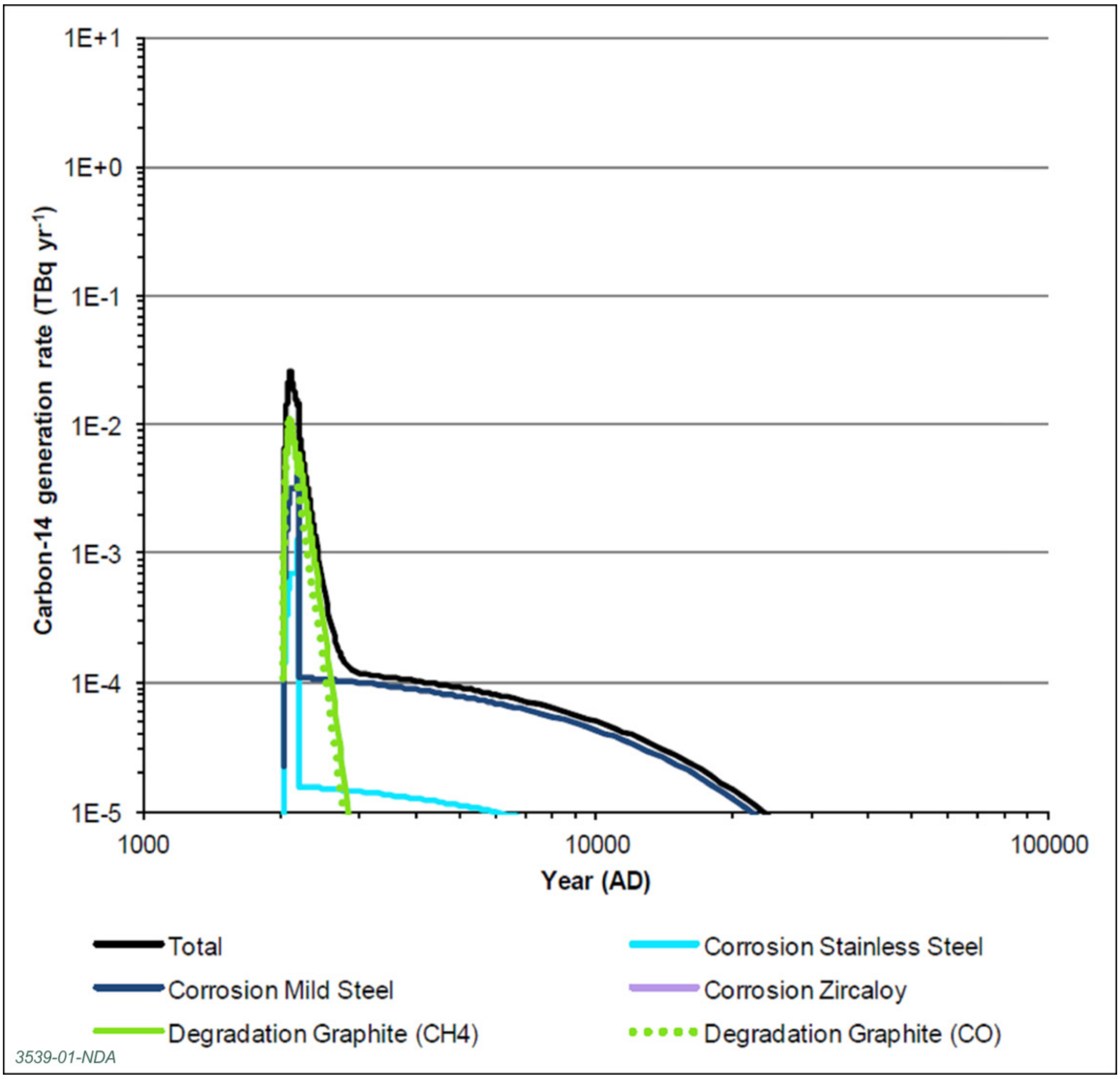
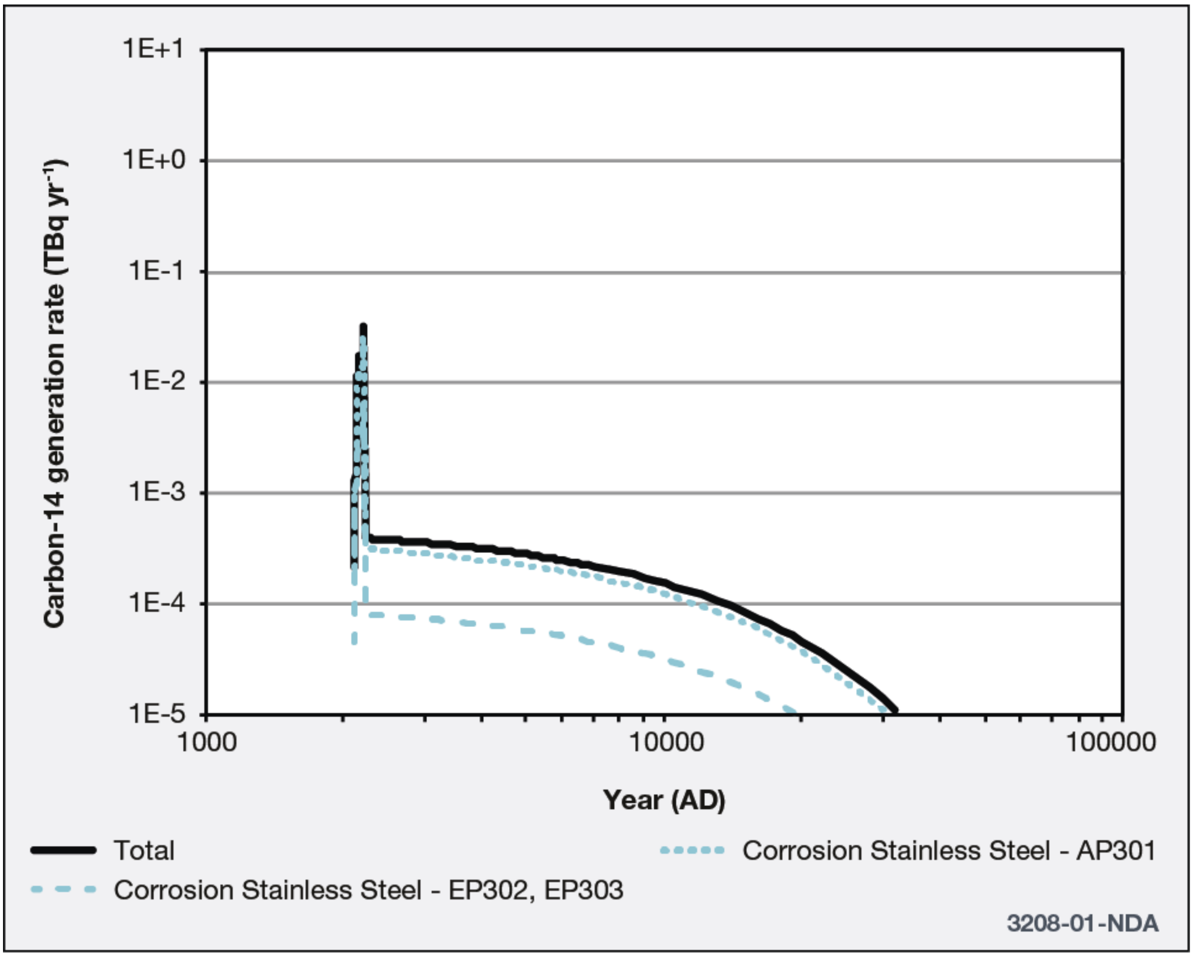


Figure 49 **Illustrative calculations of C-14 gas generation during GDF operations and the early post-closure phase from new-build ILW following disposal in the GDF in a higher strength rock, based on the 2013 Derived Inventory [51]**



6.1.3 HHGW disposal in lower strength sedimentary rock

As discussed in the generic ESC [5, §6], the illustrative concept for the disposal of HHGW in lower strength sedimentary rock involves packaging the wastes within thick-walled carbon steel containers. According to the concept, the waste packages are placed on bentonite plinths in tunnels and the tunnels are backfilled with pelleted bentonite. In the base scenario the chemical forms and dryness of spent fuel, HLW, Pu and HEU mean that the wasteforms will produce negligible volumes of gas in the disposal containers. Therefore, corrosion of the container will be the main contributor to gas generation (hydrogen) after disposal. All the disposal containers will eventually corrode, but the slow movement of water through the host rock and bentonite buffer will limit water availability for corrosion, as discussed in the Gas Status Report [18, §6.1.4; 53].

6.1.4 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. The vaults will be backfilled with a cementitious material [5, §7]. As noted above, the slow movement of groundwater through the host rock will limit the availability of water for gas generation reactions, and the chemical composition of the conditioned groundwater in the vaults will limit corrosion rates.

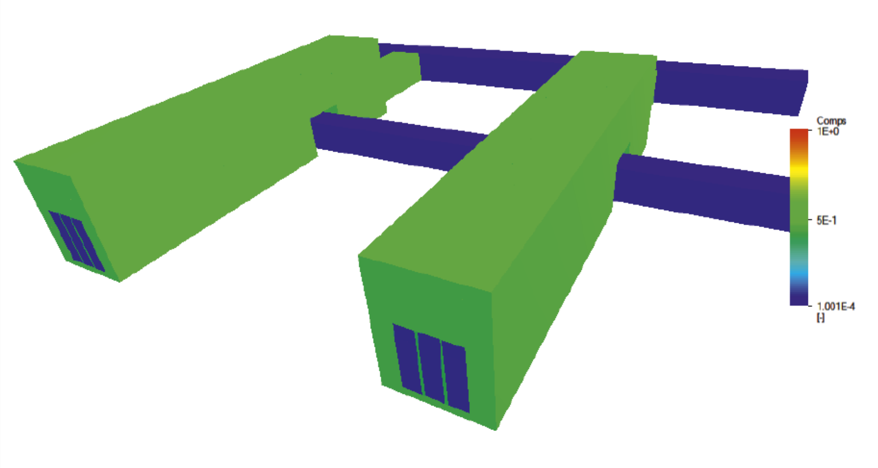
Modelling of coupled gas generation and water saturation processes in UILW vaults in lower strength sedimentary rock has been undertaken [56]. The results are complex because resaturation and the generation of gas are strongly coupled [18, §6.1.2]. Figure 50a shows water saturation after three years, when the vaults are backfilled and closed, but the service and transfer tunnels are still open and being dewatered (increasing water saturation is shown by the colour changing from blue through green towards red). At this time, the closed vaults begin to resaturate and gas starts to be generated from the wastes. After 30 years the service and transfer tunnels are closed. Figure 50b shows water saturation at 30 years; the wasteforms 'pull' water in from the backfill and the vault backfill has largely dried out. However, in reality the containers could remain intact for tens of thousands of years and will prevent water being drawn into the waste directly. Water would have to be drawn in through the container vents that are present to allow gas release. After 1,000 years, the service and transfer tunnels, concrete plugs, waste packages and some of the vault backfill have largely resaturated, but gas is trapped in the vault crown spaces, which are desaturated (Figure 50c).

The gas cannot readily escape from the vault so that water saturation starts to decrease. After 10,000 years the backfill is calculated to be fully desaturated (Figure 50d). The quantity of gas that can be generated is now limited by the amounts of water and gas generating materials remaining in the waste packages. After 100,000 years, the waste packages, vault backfill, service and transfer tunnels are calculated to have become fully desaturated (Figure 50e).

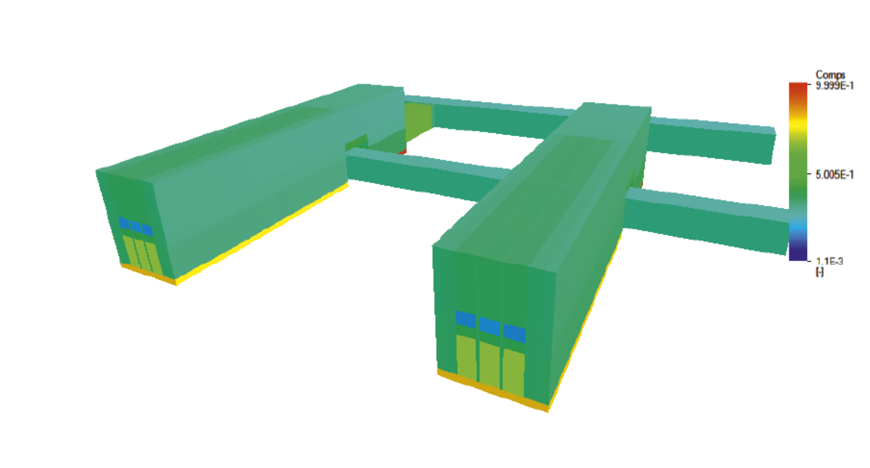
The potential impacts of gas transfer through vents on GDF performance are being studied by RWM. For example, the implications of gas release on the properties of surrounding backfill are the subject of ongoing research (Tasks 277 and 282 of the Science and Technology Plan [32]).

Figure 50 **Illustrative calculations of water saturation in ILW tunnels and vaults in a lower strength sedimentary rock [56]**

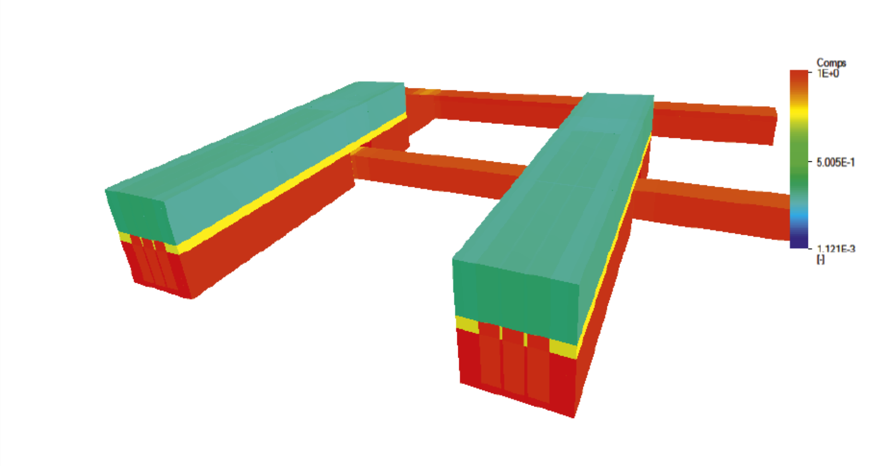
a) Water saturation in ILW vaults and tunnels at 3 years in a lower strength sedimentary rock. Vaults are closed but transfer and service tunnels remain open.



b) Water saturation in ILW vaults and tunnels at 30 years in a lower strength sedimentary rock. Transfer and service tunnels are closed at this time.



c) Water saturation in ILW vaults and tunnels at 1,000 years in a lower strength sedimentary rock.



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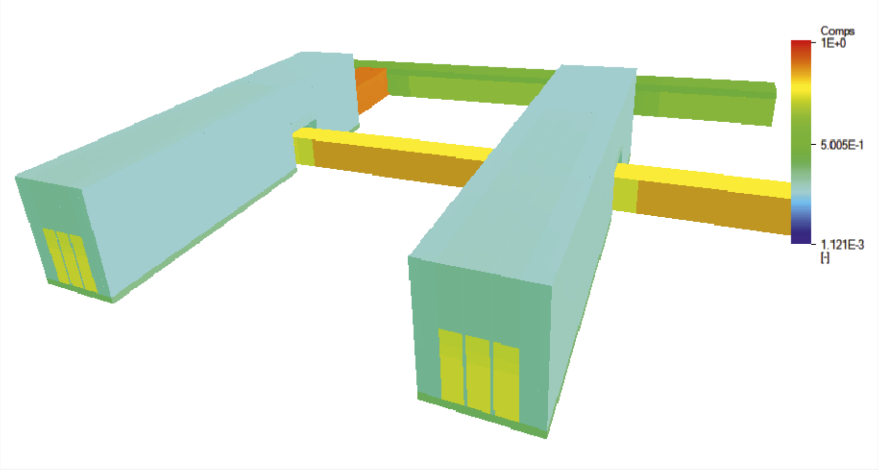
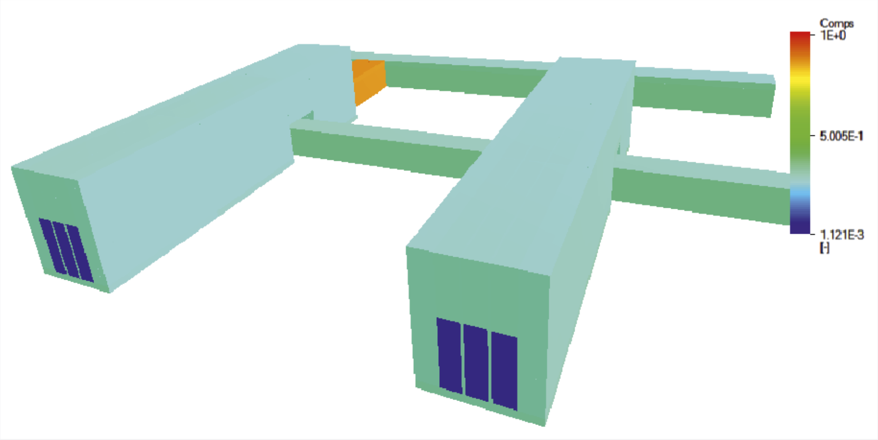
d) Water saturation in ILW vaults and tunnels at 10,000 years in a lower strength sedimentary rock.



e) Water saturation in ILW vaults and tunnels at 100,000 years in a lower strength sedimentary rock.



3212-01-NDA

6.1.5 HHGW disposal in evaporite rock

The illustrative concept for the disposal of HHGW in evaporite rock involves packaging the wastes within thick-walled carbon steel containers. The waste packages are placed on the floor of tunnels (unlined) and the tunnels are backfilled with crushed host rock [5, §8].

The disposal containers and the host rock will contain negligible amounts of water. The main source of water could be from granular salt if it is used to backfill the underground openings, as granular salt may be wetted to facilitate compaction. The amount of water that would be introduced into the GDF in such salt has been estimated to be 10 kg per 1 m^3 of backfill [57, §5.2.1]. Gas will form, at least until all the water has been consumed. However, because the backfill will be compressed (or 'tight', becoming impermeable) [57, §5.2.1], the gas will be unable to migrate away from the GDF, which will lead to an increase in pressure within the GDF. If this pressure approaches the minimum principal stress in the host rock, then it is likely that pore spaces will open or fracturing will occur, resulting in some flow of gas through the barrier system until pressures are reduced.

6.1.6 LHGW disposal in evaporite rock

The illustrative concept for the disposal of LHGW in evaporite rock 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 and void space will reduce as a result of creep closure [5, §9].

The gas generation rate will be limited because of the lack of water in the host rock. The water content of the waste packages at closure will constrain the amount of gas that can be generated [18, §6.1.3]. Therefore, depending upon the waste packages, it is likely that there would be only a small amount of gas generated in this geological environment [57].

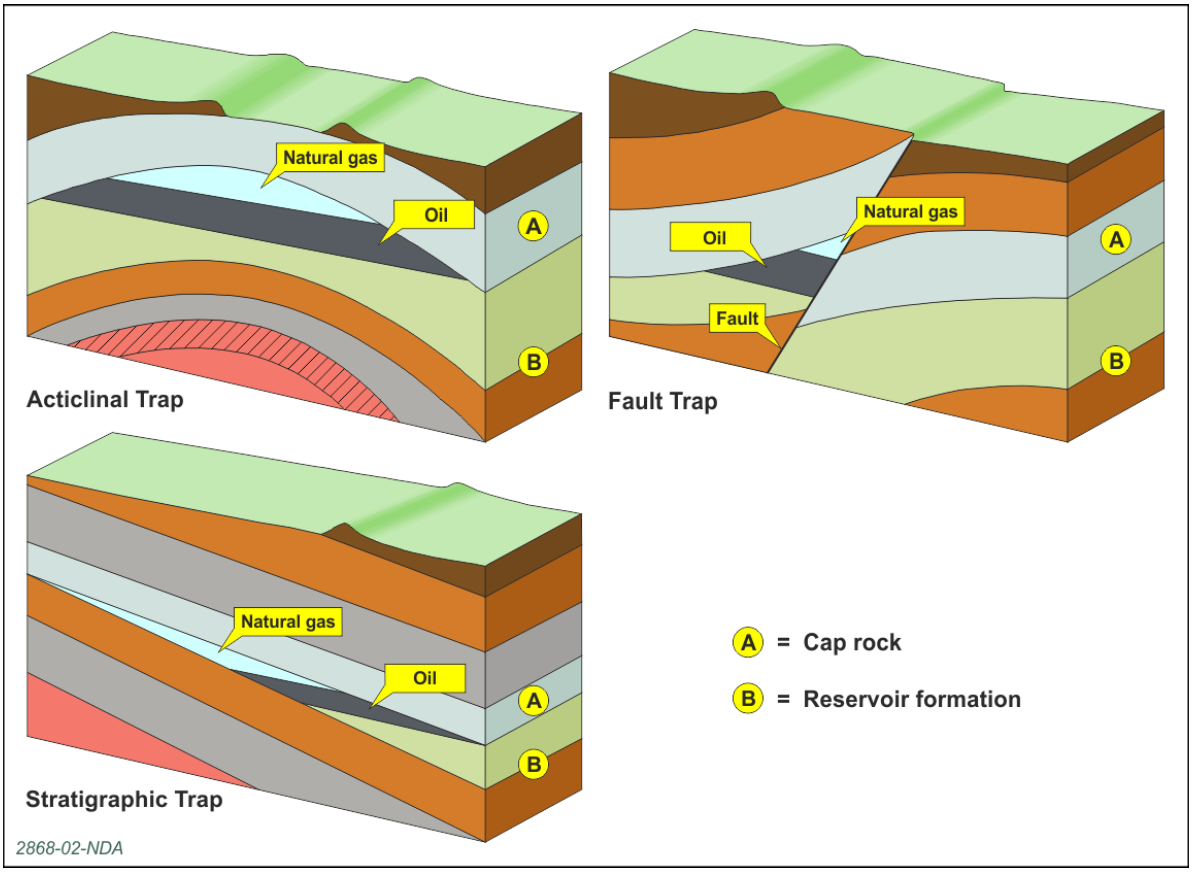
6.2 Illustrative gas migration calculations

As noted above, RWM has been carrying out research and assessment activities on C-14 behaviour through an integrated project on C-14 management in the GDF [46], through participation in the EC project CAST [47; 48], and through several studies on post-closure gas migration in different geological environments [49; 50; 51; 52]. This section discusses RWM's understanding of gas migration in different geological environments, and provides illustrative calculations of how gas migration could be evaluated for a GDF in different geological environments.

The way in which gas moves through the engineered barriers of the GDF in different geological environments is discussed in detail in the Gas Status Report [18, §6.2]; the results of the quantitative assessments presented in the Gas Status Report are discussed here.

Gas migration from the GDF will be significantly affected by the nature of the rocks overlying the host rock. In some geological environments, there may be features such as cap rocks or gas traps that could delay or prevent gas migration to the biosphere [18, §6.3.1]. Natural gas reservoirs are likely to have formed as a result of features such as structural and stratigraphic traps, as illustrated in Figure 51. Structural traps, such as anticlines and fault traps, are regions into which gas can flow but from which gas is unlikely to escape. Stratigraphic traps relate to the original geometry of the deposited sediments and may result from high permeability units pinching out, or eroding prior to later sedimentation to form an unconformity. The presence or otherwise of such features in the vicinity of the GDF will affect the potential for transfer of C-14 in the gas phase from the GDF to the biosphere.

Figure 51 Illustrations of structural gas traps (anticlinal and fault traps) and a stratigraphic gas trap [18, Figure 43]



6.2.1 Gas migration in higher strength rock

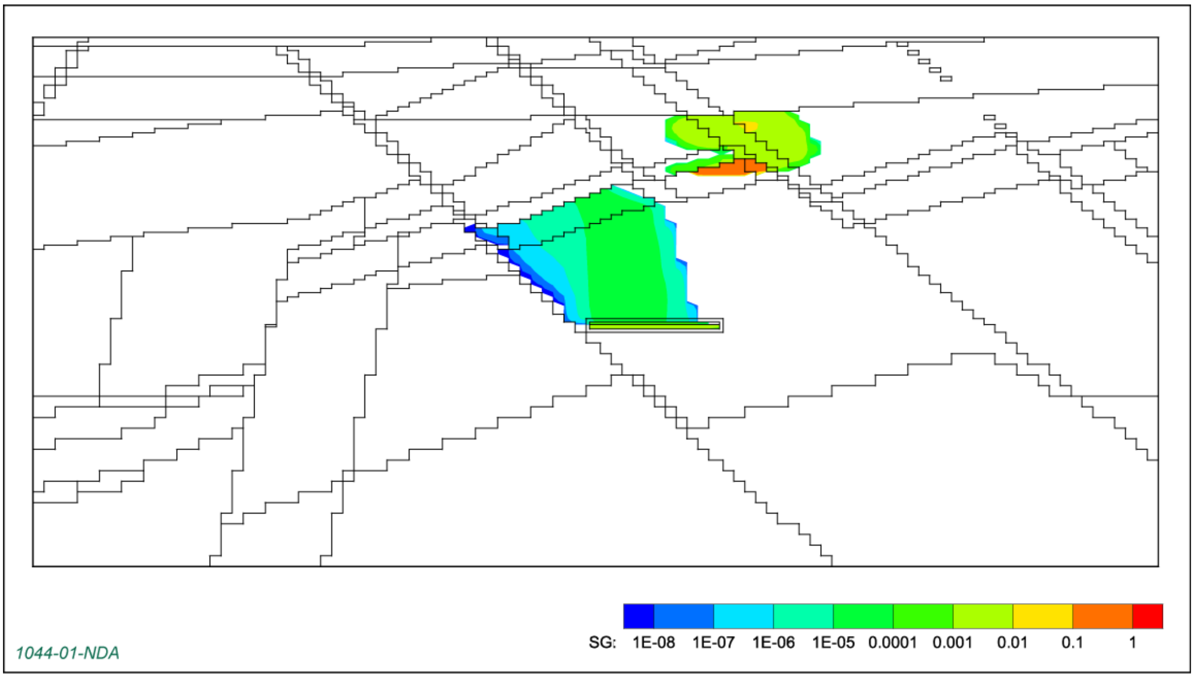
As discussed in the Gas Status Report [18, §6.3.2], fractured higher strength rocks typically do not form a significant barrier to gas migration. Also, dependent on the flux of water through the vaults, some or all of the gas generated in the GDF will dissolve in, and will be transported by, groundwater. This section discusses how these factors affect gas migration from the GDF in higher strength rock.

Before closure, the presence of the GDF at atmospheric pressure will lead to a region of drawdown around the facility, where the groundwater pressure is reduced and where groundwater flows towards the facility [18, §6.3.2]. Thus, at the time of closure, a GDF will include a quantity of gas (air). After closure, groundwater will flow into a GDF at a rate that depends on the hydrogeological conditions and the layout and properties of the engineered barrier system. As the groundwater is no longer drained and any gas being generated is not removed, the gas pressure in the facility may start to build up [18, §6.3.2]. It is expected that at some time relatively soon after closure the gas will be compressed sufficiently that its pressure will become comparable to hydrostatic pressure; simulations for ILW vaults in an example higher strength rock suggest that this pressure change could occur on a timescale of a few tens of years [49; 18; 58]. After pressures have equilibrated, groundwater flows will no longer be directed towards a GDF, and gas may begin to move out of the facility into the surrounding rock. Figure 44 of the Gas Status Report [18] shows the calculated build-up of pressure in the GDF in higher strength rock.

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 both the volume of groundwater contacted and the gas solubility (the latter is a function of pressure, temperature and salinity) [18, §6.3.2].

Figure 52 and Figure 53 show some examples of two-dimensional TOUGH2v2 calculations of gas migration in a vertical cross section, as free gas and as dissolved gas, respectively, through an illustrative, but realistic geological environment [49]. The location of the GDF is depicted by the rectangle in the centre of the two figures. The gas saturation shown in Figure 52 is the fraction of the pore space in the rock that is occupied by gas. In the figures, different types of rock are demarcated by black lines.

Figure 52 Contour plot of gas saturation in a vertical cross-section through a higher strength rock 240 years after GDF closure[12] [58, Figure 4.6]



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[12] These illustrative calculations use information from the 2004 UK Radioactive Waste Inventory.

Figure 53 **Contour plot of mass fraction of dissolved gas in a vertical cross-section through a higher strength rock at 240 years after GDF closure[12] [58, Figure 4.6]**

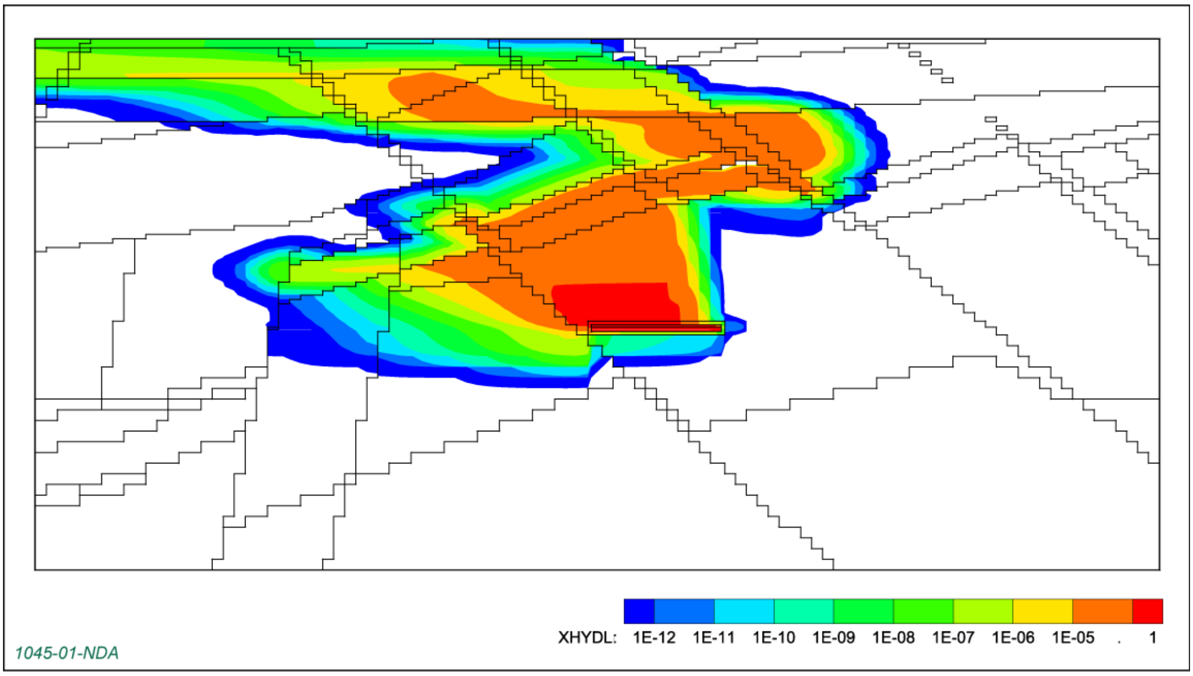


Figure 52 shows gas moving upward through the host rock and overlying rocks until it comes to a low-permeability formation with a high 'gas entry pressure' (that is, a barrier layer, or 'cap rock'). The barrier layer forces the gas to move towards the right of the system until it finds a place where a major fault breaks the continuity of the barrier layer. The gas is then able to move upwards into more permeable, near-surface rocks, where it encounters a large flow of groundwater into which it dissolves. A free gas phase then ceases to exist [18, §6.3.2] and in this case there would be no radiological risk via the gas pathway.

Figure 53 shows the corresponding plume of dissolved gas in terms of the mass fraction of dissolved gas. The red end of the colour spectrum on the figure corresponds to the highest concentrations of dissolved gas. This example illustrates that the gas pathway will be complex and specific to both a site and the design of the GDF [18, §6.3.2].

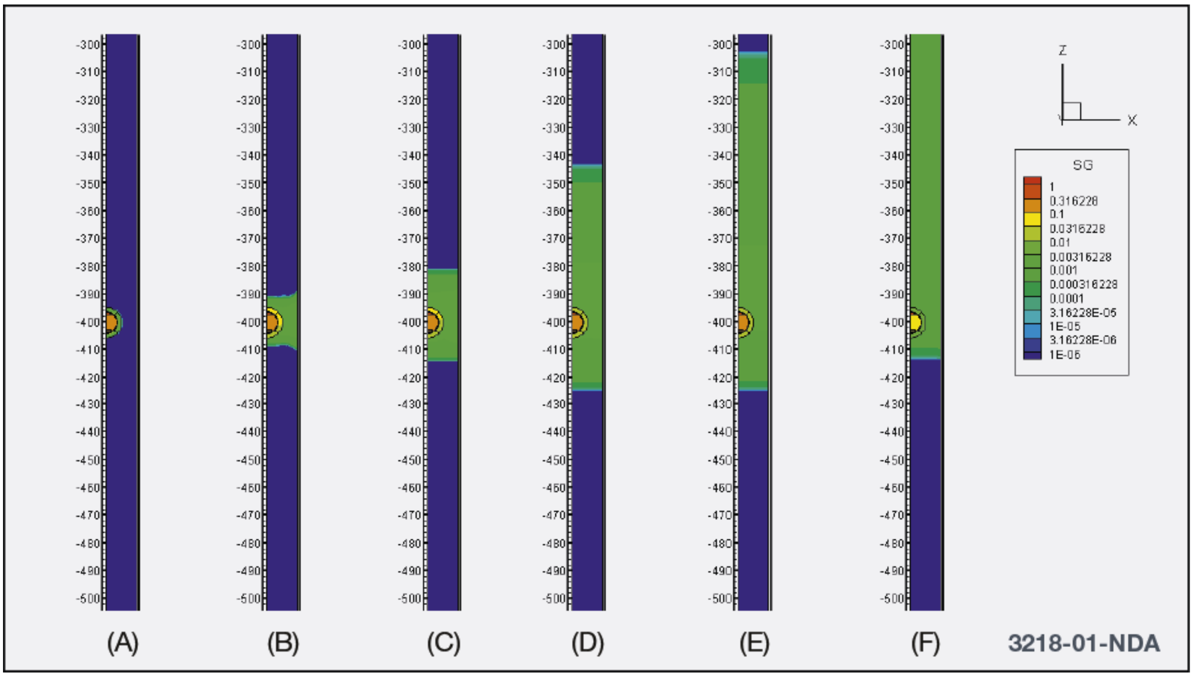
6.2.2 Gas migration in lower strength sedimentary rock

Clay formations tend to act as cap rocks, able to trap gas in nature. They have very small intergranular pores [18, §6.3.3] and the movement of gas through these will be very slow. This suggests that any gas generated in the GDF situated within a lower strength sedimentary rock may not reach the surface environment. However, the pressure required for gas to enter a lower strength sedimentary rock may be so high that, if all the gas generated in the GDF cannot be dissolved, it may not be possible for a free gas phase to migrate from the GDF sufficiently quickly through undisturbed clay to relieve the build-up of pressure [18, §6]. Therefore, fracturing and resultant gas migration could occur.

Figure 54 shows the results of an illustrative calculation for a gas phase migrating from the GDF located at 400 metres below ground level in clay [56]. The gas saturation (SG) (the fraction of the pore space in the rock that is occupied by gas) is colour shaded with colours to the red end of the spectrum corresponding to higher gas saturation. Bar (A) is at closure, (B) is at 100 years post-closure, (C) is at 1,000 years post-closure, (D) is at 10,000 years post-closure, (E) is at 20,000 years post-closure and (F) is at 100,000 years post-closure. In the model, free gas is released through the top boundary (at z = -280m) at approximately 20,000 years after closure. The system then settles down to a pseudo steady-state, in which the gas leaving the model is approximately equal to the gas generated, with the gas crossing the host rock in a relatively short period (of the order of years). Gas dissolves in the groundwater all along the pathway, followed by the migrating free gas.

A model that couples together waste evolution and heat/gas production, water inflow, and gas migration away from the facility may be required to simulate this fully. As stated before, these calculations provide an illustration of potential gas migration and pressurisation associated with gas migration in a lower strength sedimentary rock. These illustrative calculations also demonstrate RWM's understanding of the important aspects of gas migration. When a site for a GDF is selected it will be important to incorporate these aspects into a full assessment of the gas pathway.

Figure 54 **Illustrative calculation of gas saturation post-closure for gas migration from the GDF in a clay rock (such as a lower strength sedimentary rock) [58, Figure 4.23]**



6.2.3 Gas migration in evaporite rock

In the absence of an artificially imposed hydraulic gradient, there is likely to be no brine flow through an evaporite host rock due to its extremely low permeability. Some fluid movement may occur due to thermal gradients generated by the presence of heat-generating wastes [18, §6.3.4]. However, brine availability for gas generation reactions will be limited. Also, undisturbed evaporite rock is virtually impermeable to gas [18, §6.3.4].

If gas generation and migration do require evaluation for a GDF in evaporite rock, then the modelling approach would be similar to the approach discussed for a GDF in lower strength sedimentary rock, except that rock creep would need to be taken into account. As discussed in the Gas Status Report [18, §6.3.4], the rock around a GDF in an evaporite rock will begin to deform as soon as the GDF is excavated. As a result, there will be some degree of brittle fracturing and an EDZ will form around the facility. The host rock will subsequently creep, with the result that excavation damage to the host rock will tend to self-heal and voids will be filled. If crushed salt is used as a backfill (as with the illustrative concept for HHGW disposal) its permeability will also decrease due to creep. Despite the rock creep in the EDZ, depending on the timing of gas generation, there may be some very slow migration of gas through the fractures and it will be important to consider this in site-specific calculations should a GDF be situated in an evaporite rock.

6.3 The potential consequences of gas generation

The Gas Status Report [18, §6] has illustrated various possible consequences of gas generation in the GDF, including:

- for LHGW disposal in higher strength rocks, the possible release to the biosphere of radioactive and flammable gases by transport through the geological barrier
- for lower strength sedimentary rocks and for evaporite rocks, over-pressurisation and potential damage to a GDF and surrounding rock
- for lower strength sedimentary rocks and for evaporite rocks, possible displacement of contaminated water from the GDF by gas pressurisation; conversely the accumulation of gases in and around the GDF might reduce the groundwater flow into the facility, thereby reducing radionuclide transport from the GDF in groundwater
- for higher strength rocks, water-borne contaminant transport coupled with gas migration from the GDF, including the possibility of contaminant transport by bubble flow because of colloid sorption at the gas-liquid interface

These consequences may, or may not, occur and are highly dependent on the GDF layout, the engineered barrier system and the geological environment (including the host rocks and the overlying rocks). For example, factors that will affect the potential consequences of gas generation include:

- water availability for gas-generating reactions, which will be limited in low-permeability systems, and will also be reduced as gas accumulates and displaces water
- the potential for pathways created at high gas pressures in bentonite barriers and clay host rocks to close and heal after pressure reduction
- the presence of features in the barrier system and geological environment that could accommodate and trap gases preventing them from migrating to the biosphere or delaying their transfer [18, §6.3.1]

The most significant consequence of gas generation in higher strength rocks is the potential release of C-14-bearing methane from LHGW to the biosphere [18, §6.3.2].

RWM's research on C-14 behaviour included a number of illustrative calculations of risk associated with exposure to C-14 generated from LHGW based on different assumptions about how the gas will migrate through 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 [46].

For a LHGW disposal facility in higher strength rock, 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 [46, §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 [46, §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%.

For an illustrative LHGW disposal concept in lower strength sedimentary rock, no releases of gaseous C-14 were calculated to occur in the first thousand years following GDF closure [46, §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.

More detailed analysis of gas generation and its effects will be developed as relevant site-specific and GDF design-specific information becomes available.

7 Human Intrusion

The GRA [13, §6.3.35] requires RWM to assess the potential consequences of human intrusion after the period of authorisation; that is, when 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.

Only inadvertent human intrusion is required to be considered; that is, where the intrusion takes place without knowledge of the hazards associated with the GDF site. There is no requirement to consider any deliberate acts of breaking into the engineered barriers of the GDF. The GRA also states that the timing, type and extent of human intrusion into a GDF are so uncertain that they should be explored as 'what-if' scenarios, separately from the base scenario. 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, within the document, discussion will be provided on the strategies which may be employed to ensure that inadvertent human intrusion into a GDF will be extremely unlikely.

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 [59]. While 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 4.

The most important of these is the depth of the GDF, likely to be several hundreds of metres below the surface. This is well below the depth accessed for any surface works, such as construction for buildings or roadways.

The most credible scenarios for human intrusion into a GDF at several hundred metres below the surface involve future drilling or mining to exploit mineral resources. This is why 'resources' is one of the five geological topics proposed for consideration as part of the National Geological Screening [60], in order that they can be avoided. The attributes being considered for geological screening are the locations of existing deep mines, locations of intensely deep-drilled areas and the potential for future exploration or exploitation of resources. It is proposed that the National Geological Screening will include maps of the known resources of a range of metal ores, industrial minerals, coal and hydrocarbons below a depth of 100 metres that are exploited today or have been exploited in the past. Future exploration often takes place at sites where shallower mining has occurred in the past, for example with a view to finding deeper reserves. This is the reason why mining below 100 metres is considered relevant. Shallower resources that clearly have no deeper extension, such as sand, gravel or peat, are not considered relevant as they only exist well above the depth being considered for a GDF. The National Geological Screening process and the subsequent siting process will ensure that any location with potentially exploitable resources at GDF depths will not be considered.

Table 4 **Impact of controls on human intrusion (HI) potential (from IAEA HIDRA project) during different periods after GDF closure**[13]

	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	Inventory for disposal	Decaying inventory	Decay may be significant

As identified in Table 4, another important strategy for avoiding inadvertent human intrusion is maintaining records so that knowledge of the GDF location and its contents is not lost. RWM is participating in the NEA Records, Knowledge and Memories project [61], which is developing best international practices in this area. Areas being considered in this project include the role of local, national and international archives and libraries and the use of site markers. In the context of records management it is helpful to consider examples where records have survived for long periods of time. For example the Doomsday Book, which still survives today, provides a detailed documentation of land use in England in the eleventh century (that is, almost 1,000 years ago).

There may also be potential design features that could be considered to reduce the likelihood or consequences of human intrusion. The IAEA Human Intrusion in the context of Disposal of Radioactive waste (HIDRA) project [59] has developed a strategy for the identification and consideration of potential design measures that could help to reduce the likelihood or consequences of human intrusion. The approach consists of four steps, as illustrated in Figure 55.

The first step of the strategy is the definition of the framework for decision-making (that is the regulatory context, inventory for disposal, disposal system design and any other constraints, for example stakeholder requirements). The second step involves compilation of general measures that could be considered – the HIDRA project has compiled a database of measures that provides a helpful checklist for this step [59]. Examp-les of measures within the database include waste separation and encapsulation, the inclusion of plugs and seals made of robust materials in boreholes and shafts, and the use of indicators or markers (both on the surface or within the geosphere) to warn those who may inadvertently intrude. The third step is the identification of potential measures relevant to the actual site and disposal context that could enhance the inherent measures already present in the illustrative disposal concept design. The benefits of these potential

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[13] 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.

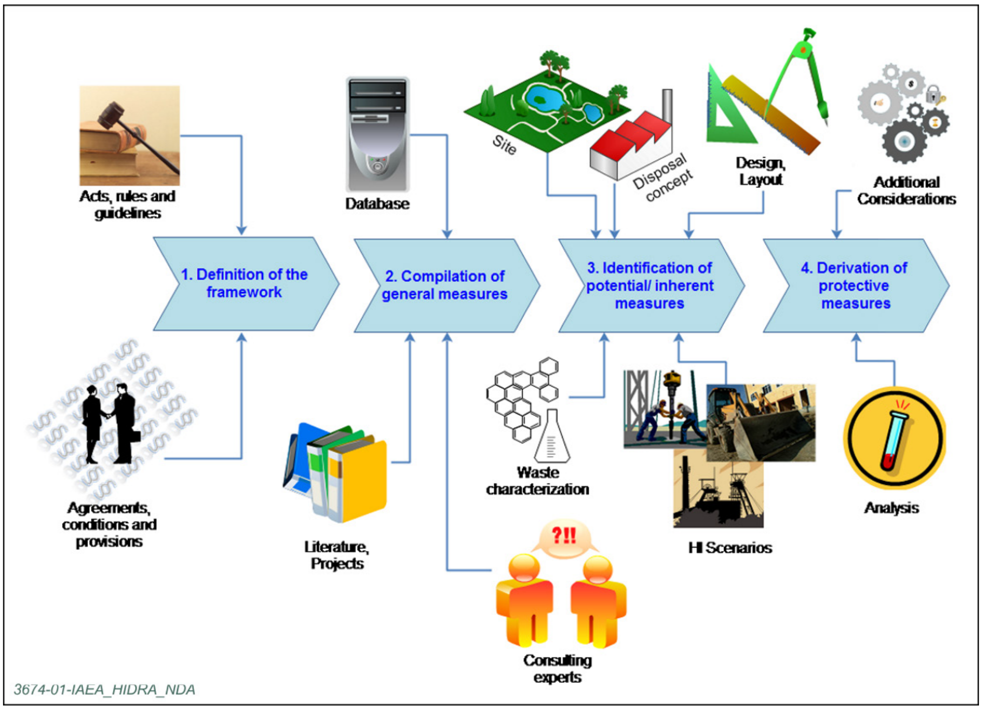
measures are then evaluated in the context of relevant, but stylised, human intrusion scenarios. Finally, the fourth step involves the analysis of the proposed measures in the context of the overall safety case to determine any protective measures that should be implemented, in the context of optimising the disposal facility.

The GRA recognises that it is not easy to judge the benefits of such measures and therefore it may not be possible to claim absolute credit for them in the ESC [13, §6.3.42]. Explanations of measures taken to reduce the likelihood of human intrusion therefore typically take the form of supporting, qualitative safety arguments.

At this generic stage, it is not considered practicable or desirable to consider detailed design measures for GDF optimisation. Hence there is little purpose in undertaking human intrusion calculations that would simply be based on assumptions about an illustrative design in an illustrative geological environment and would not be relevant for any optimisation considerations. However, it is possible to consider the timescales for which there is confidence that inadvertent human intrusion can be excluded and to consider the extent to which the inventory for disposal will have decayed over that period. In particular, active institutional controls are expected to be in place for at least 100 years following the sealing and closure of the GDF. There could, therefore, be no inadvertent intrusion during this period. Referring to the inventory decay curves presented in Section 4.3.1, it can be seen that after 100 years, in terms of radioactivity, the HHGW inventory would have fallen to 36.1% of its value at GDF closure and the LHGW inventory will have fallen to 53.5%.

Based on the analogy of the Doomsday Book, it may be possible to argue further that it would be extremely unlikely for any inadvertent human intrusion to occur for at least 1,000 years. Referring again to the inventory decay curves presented in Section 4.3.1, it can be seen that after 1,000 years, the HHGW inventory would have fallen to 10.4% of its initial value and the LHGW inventory will have fallen to 7.5%.

Figure 55 Schematic illustration of the four steps to derive protective measures (from IAEA HIDRA project [59])



In a site-specific ESC, stylised human intrusion scenarios will be considered as variants against which any potential protective measures will be evaluated as part of the GDF optimisation process. This will be an important area for discussion with the environment agencies, not least as the implementation of any measures intended to reduce the likelihood of human intrusion would be subject to the environment agencies' specific agreement [13, §6.3.42]. Quantitative assessment of human intrusion into a GDF will involve evaluation of a 'what-if' scenario, consistent with the GRA [13, §6.3.27].

Note that future human actions involving any area outside the engineered barriers of the GDF, for example the sinking of a well into an aquifer contaminated by radionuclides from the GDF, are not considered to be 'human intrusions' as discussed in this section. Such actions require assessment against the regulatory risk guidance level. For example, potential radionuclide releases to the biosphere via wells were considered in the groundwater assessment in Section 5.

8 Criticality Assessment

Radioactive wastes include substantial quantities of fissile radionuclides (mostly U-235 and Pu-239). If enough fissile material (both in quantity and concentration of fissile radionuclides) was to come together under disposal conditions, an uncontrolled nuclear chain reaction (nuclear criticality) could occur, resulting in radiation and energy releases. Controls on the packaging of wastes that include fissile material will ensure that criticality does not occur in a disposal facility while the waste packaging provides containment. (The Criticality Safety Status Report discusses how controls, such as fissile material limits, are established for waste packages [21, §3.3].) However, deterioration of the physical containment provided by the waste packages in the long term after GDF closure and relocation of fissile material could in principle result in criticality [21, §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 the GDF's 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 criticality if it does occur.

The need to consider post-closure criticality in an ESC is reflected in the environment agencies' GRA [13, §7.3.31], which states that:

> *"If significant amounts of fissile material are being disposed of at the facility, the developer/operator will need to demonstrate as part of the environmental safety case that the possibility of a local accumulation of fissile material such as to produce a neutron chain reaction is not a significant concern. The environmental safety case should also investigate, as a "what-if" scenario, the impact of a postulated criticality event on the performance of the disposal system."*

RWM has undertaken substantial research to understand the likelihood and potential consequences of post-closure criticality; the results of this research are discussed in the Criticality Safety Status Report [21, §5, §6]. The research concluded that criticality after GDF closure is unlikely to occur and that, if it did occur, the consequences would not be significant.

Consistent with the GRA guidance to consider 'what-if' scenarios, the research on the consequences of criticality involved consideration of scenarios in which accumulations of fissile material sufficient to result in criticality were assumed to occur. Assessment of these 'what-if' scenarios involved consideration of the types of criticality that, although unlikely, could conceivably occur at different times and under different conditions after disposal, and how such criticality could affect the GDF's multiple barrier system [21, §6.1]. The research considered two types of criticality, as follows:

- 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. Such a configuration could last for many thousands of years. The power generated would be limited to a few kilowatts and the maximum temperature increase would be a few hundred degrees Celsius. The consequences of a quasi-steady state criticality in a GDF would be highly localised and would not affect the surrounding host rock significantly.
- 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 timescale for a rapid transient is less than one second. Rapid transient criticality could only occur for a narrow range of hypothetical conditions, generally involving Pu-239, and is not credible after about 100,000 years due to the decay of Pu-23; wasteforms that contain potentially

significant quantities of Pu-239 are expected to be stable and contain the Pu-239 for such a period.

Thus, the research on the likelihood and consequences of criticality has supported the view that post-closure criticality is not a significant concern. However, RWM has undertaken further analysis of what-if criticality scenarios to understand how disruptions to a GDF's barrier system caused by criticality could affect the environmental safety of the GDF, which has been reported in a post-closure criticality consequences assessment (PCCCA) [62]. The PCCCA provided an evaluation of how GDF performance could be affected by criticality by causing localised mechanical disruption, temperature increases and increased radiation levels, as well as changes to the inventory of radioactive material. The magnitude of these impacts was bounded by drawing on the results of the recent research projects on the likelihood of criticality and consequences of criticality. This involved identification of the maximum credible masses of fissile material that could accumulate based on consideration of how conditions in the disposal facility could evolve and the potential consequences of such accumulations.

The results of the 2010 PCSA [6] provided the baseline against which variant scenarios defined by postulated criticality events were evaluated in the PCCCA. That is, 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). The effects of criticality on the transport and potential exposure to non-radiological species were also assessed and this is discussed in Section 9.3 as part of the non-radiological assessment.

The PCCCA focused on the impacts of criticality in disposal facilities for LHGW and HHGW in higher strength rock and lower strength sedimentary rock. Post-closure criticality will not occur in the GDF in an evaporite rock because conditions are expected to be sufficiently dry that the processes required to lead to waste package degradation and fissile material relocation will not occur. Further, if the disposal facility did become saturated with brine, the presence of chlorine[14] in the brine would limit the potential for fissile material accumulations to result in criticality.

The PCCCA considered the potential impacts of quasi-steady state and rapid transient criticality on disposal system performance [62, §2.1.1; 21, §2.1, §6.1]. The following sub-sections discuss the results of the PCCCA analysis of the potential effects of criticality on the groundwater, gas and human intrusion pathways.

8.1 Effects of criticality on radionuclide transport in groundwater

The PCCCA analysis of the impacts of criticality on radionuclide transport in groundwater involved application of the GoldSim total system model that was used in the 2010 PCSA (which is different from the GoldSim model used in the radiological assessment of the groundwater pathway described in Section 5) as well as insight modelling. For LHGW and HHGW disposal in higher strength rock, total system modelling and insight modelling confirmed that highly mobile and long-lived radionuclides (primarily I-129 and Cl-36) are the most important contributors to calculated risk. These radionuclides have long half-lives and are not retarded significantly in the host rock. Other radionuclides are contained in the barrier system for long periods, allowing a long time for radioactive decay. The environmental safety functions provided by the EBS are most significant in cases where the host rock provides only a limited containment function. Therefore, the local damage to the EBS caused by criticality may affect the calculated peak radiological risk associated with the groundwater pathway. In order to better understand the potential effects of criticality on

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[14] Chlorine is an effective neutron absorber, which means that it has a high probability of capturing neutrons, reducing the potential for fission.

the performance of the GDF in higher strength rock, detailed calculations of risk were undertaken using the GoldSim total system model.

The effects of quasi-steady state and rapid transient criticality were evaluated for LHGW and HHGW disposal in higher strength rock. For the calculations, the following assumptions were made about the location, timing and impacts of different types of criticality event [62, §4.4.2]:

- criticality occurs in a UILW/ULLW vault and in a PWR spent fuel container
- rapid transient criticality occurs 10,000 years after GDF closure and quasi-steady state criticality occurs 100,000 years after GDF closure
- rapid transient criticality is instantaneous (involving a mass of 10 kg of fissile oxide, which was judged to be bounding for rapid transient criticality involving Pu-239, based on a cautious estimate of the timescales for fissile material accumulation under disposal conditions [62, §3.2.2]), but quasi-steady state criticality persists indefinitely (or at least until the end of the one-million-year assessment period) as a result of the continuous arrival of U-235
- the change in inventory associated with rapid transient criticality is insignificant, but is potentially significant for quasi-steady state criticality
- 0.007% of a UILW vault volume is affected by quasi-steady state criticality and 1% of a UILW vault volume is affected by rapid transient criticality
- quasi-steady state or rapid transient criticality occurs in a single HHGW container, but the nearest neighbouring containers are damaged by rapid transient criticality
- there is no sorption or solubility limitation in the region affected by criticality
- the flow rate is increased in the region affected by criticality

The modelling assessment showed that criticality will have little effect on calculated peak radiological risk [62, §4.4.3]. In particular, by the time criticality occurs in a LHGW vault, the I-129 originally present in the waste has been leached from degraded waste packages and its transport is unaffected by criticality. However, following quasi-steady state criticality for both the LHGW and HHGW examples, there is a very low risk from exposure to I-129 associated with the constant production rate of fission products. Also, following rapid transient criticality in the HHGW example, there is a small calculated risk from I-129 associated with dissolution of the waste in the containers neighbouring the waste package in which the criticality event occurred.

For HHGW and LHGW disposal in lower strength sedimentary rock, total system modelling and insight modelling confirmed that I-129 and Cl-36 are the key radionuclides for which calculated risk is non-negligible [62, §4.3.4]. Other radionuclides are contained in the host rock, allowing a long period for radioactive decay. These conclusions are consistent with those reached following the analysis reported in Section 5 of this PCSA. Where the host rock provides the most important environmental safety function, any disruptions caused by the types of criticality considered in this variant scenario will not affect the performance of the GDF. Even disruptions to the EBS and host rock caused by rapid transient criticality involving 10 kg of fissile material would not affect GDF performance significantly.

8.2 Effects of criticality on radionuclide transport in gas

The PCCCA included a qualitative assessment of the effects of criticality on the transport of radionuclides in the gas phase [62, §5]. The gases of greatest radiological significance in terms of potential post-closure risks are C-14-bearing gases (see Section 6). Increased temperatures associated with criticality could increase the rate of gas generation reactions (such as corrosion of reactive metals), which could increase the rate of C-14 generation in the gas phase. However, the inventory of reactive metals (such as Magnox) with corrosion rates that are highly sensitive to temperature would be exhausted by the time of any credible criticality event. The increase in the rate of gas generation from steel corrosion (which is not highly sensitive to temperature) would be limited.

Also, the half-life of C-14 (5,730 years [30]) is short compared to credible timescales for post-closure criticality, and the risk associated with C-14 is negligible after about 50,000 years. In the unlikely event that 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. Note that the increase in the inventory of radioactive gases associated with criticality would be negligible.

8.3 Effects of criticality on the human intrusion pathway

The PCCCA considered the potential impacts of inadvertent human intrusion into a region of the GDF affected by a criticality event [62, §6]. The analysis considered how the estimated radiological dose to exposed groups at the time of an intrusion and after the intrusion might differ if the intrusion were to occur after a criticality event. It was concluded that 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 inventory for disposal. Consequently, the calculated radiological dose to potentially exposed groups at the time of intrusion and thereafter would not be changed significantly.

Consideration was also given as to whether a human intrusion event could increase the likelihood of criticality, for example by changing the hydrological and geochemical conditions in such a way as to lead to fissile material relocation and accumulation. The PCCCA concluded that it is not plausible that human intrusion could lead to criticality directly at the time of intrusion, but disruption of the barrier system could lead to criticality earlier than considered possible or where otherwise judged to be highly unlikely. For example, human intrusion may be the only credible initiating factor for criticality in a disposal facility in evaporite rock, by establishing a flow pathway that introduces groundwater to the disposal region, resulting in the material degradation and relocation processes that could lead to criticality. However, the effects of criticality following human intrusion on the performance of the GDF would not be significantly greater than those discussed above for the groundwater and gas pathways.

9 Non-radiological Assessment

Some wastes may be harmful for reasons other than their radioactivity (for example due to their chemotoxicity); and some packaging materials and materials used in the construction of the GDF may be potentially harmful to the environment. As discussed in the generic ESC [5, §10.3], it is important to assess the effects of such non-radiological contaminants in the GDF. The generic ESC [5, §10.3] discusses the regulatory requirements with regard to the assessment of non-radiological species and the approach that RWM has taken at this generic stage.

9.1 Groundwater assessment

As discussed in the generic ESC [5, §10.3] the recently updated DSS [11, §2.5.1] notes the changes in the groundwater regulations as described in the Environmental Permitting (England and Wales) Regulations 2010 (EPR 2010) [63]:

> *"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."*

These criteria are referred to in this report as the 'prevent the input' and 'limit the input' criterion.

Following adoption of the Groundwater Daughter Directive (GWDD) into UK legislation, the Environment Agency issued supplementary guidance [64] (to be read alongside the GRA [13]) explaining how a developer could meet requirement R10 of the GRA and meet the requirements of EPR 2010. Box 12 contains some definitions of the key terms used in the description of the EPR. As discussed in Section 1.1, RWM has developed illustrative disposal concept for radioactive waste disposal in higher strength rocks, lower strength sedimentary rocks and evaporite rocks. With regard to assessments of the migration of hazardous substances in groundwater, note that evaporite rocks (in particular, halites) generally provide a dry environment [19, §3.3.1] and it is highly unlikely that there will be any groundwater (as defined by EPR 2010) present in such rocks.

Box 12. Key Terms

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 [65]. 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 [66].

Non-hazardous pollutants

EPR 2010 [65] 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–

1. be harmful to human health or the quality of aquatic ecosystems or terrestrial ecosystems directly depending on aquatic ecosystems,
2. result in damage to material property, or
3. 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' [65].

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.' [65].

Groundwater Body

A groundwater body is 'a distinct volume of groundwater within an aquifer or aquifers' [65].

9.1.1 Hazardous substances

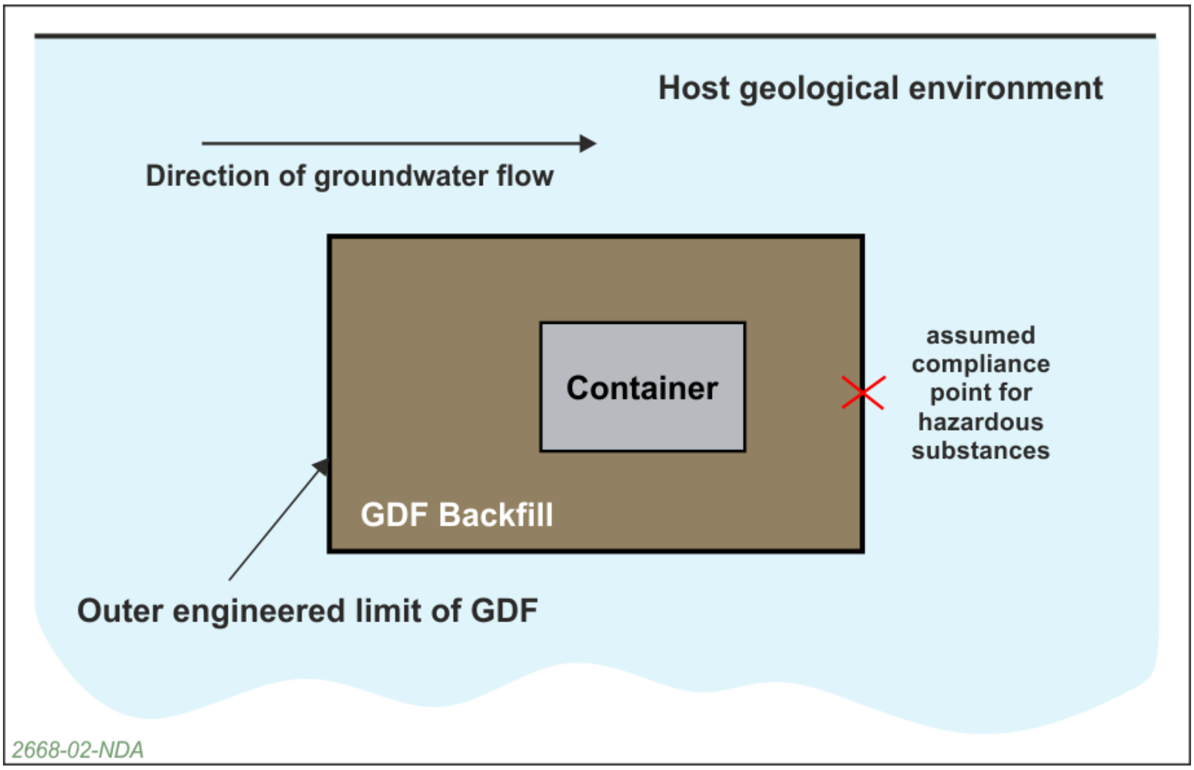
RWM has undertaken a scoping study [67] using conservative assumptions to identify which hazardous substances (as defined by the UK environment agencies' JAGDAG [68]) may be present in the inventory of higher activity wastes and are important in terms of geological disposal. As discussed in the generic ESC [5, §10.3], not all these substances are currently reported in the UK Radioactive Waste Inventory (UKRWI). Therefore, detailed information on the total mass of hazardous substances requiring disposal is not available at this stage. In the absence of a known inventory of hazardous substances requiring disposal, the scoping study assumed the presence of a unit (1 g) of each of the substances to be assessed. This assumption was made in order to calculate a maximum allowable inventory of each substance that could be safely disposed (noting that this assessment was based on several other assumptions which are detailed below).

The work reported in the scoping study was designed to be a first step in developing RWM's understanding of how the effects of hazardous substances in the GDF could be assessed and it is recognised that additional modelling might be required. For example, only wastes, their constituents and some possible degradation products were considered in the study. However, a GDF may include hazardous substances other than those associated with the wastes. For example, machinery used in the GDF (including any potential fuels associated with it), rock bolts and backfill (including the use of any superplasticisers) may result in the presence of hazardous substances in the GDF. The presence of such potentially hazardous substances in the GDF will be considered in RWM's ongoing programme of work on this topic.

Prior to the identification of a site for a GDF, the regulatory compliance point for evaluation of the effects of hazardous substances is assumed to be the most conservative location at the outer boundary of the GDF's engineered barrier system (see Figure 56 which shows a sketch of a vertical section through the GDF).

In support of a 'prevent the input' criterion, the Environment Agency has published Minimum Reporting Values (MRVs) for a number of hazardous substances [69]. For the purposes of this scoping work, RWM proposes to use these MRVs (or, where not available, a multiple of the limit of detection of a substance) to calculate a threshold inventory (that is a maximum allowable mass of material in the GDF) for each substance studied. These thresholds will be determined by modelling the performance of the EBS and surrounding rock (taking account of sorption and solubility) to determine the concentration of the substance at the appropriate compliance point and comparing this with appropriate limits or guidance levels. A preliminary scoping study was undertaken as discussed below [70].

Figure 56 Regulatory compliance point location for hazardous substances in generic scoping work



In order to reduce the number of hazardous substances to be assessed in the scoping study (in terms of priority for assessment), categories of hazardous substances were developed based on knowledge of the inventory of higher activity wastes. The categories considered are:

- Category 1: present in higher activity wastes (information from UKRWI)
- Category 2: may be present in higher activity wastes (could be present in components in UKRWI – for example may be a constituent of rubber or paints which are known to be present)
- Category 3: unlikely to be present in significant quantities in higher activity wastes (present in components of the waste inventory in small or trace amounts)
- Category 4: unlikely to be present in higher activity wastes (are not known to be used in components of the waste, but would usually be used in other industries ie pesticides)
- Category 5: data are lacking, but there is no information to suggest presence in higher activity wastes

A total of 49 species were identified that are, or may be, present in the GDF in significant quantities [70]. These species are listed in Box 13.

The list of hazardous substances was analysed and priority was given to those known to be present or most likely to be present in the GDF and those with known MRV or limit of detection (LoD) values. Also, the analysis ensured that a selection of different types of species was chosen for assessment. A shortlist of twenty species was identified for modelling, as shown in Box 13.

A ‘best estimate’ and ‘upper and lower limits’ for solubility limits and sorption distribution coefficients were assumed in the modelling. These values are presented in the scoping study report and are described in the status report on the behaviour of radiological and non-radiological species [17].

Two compliance criteria (or ‘hazard thresholds’) were defined to enable comparison between concentrations calculated using the GoldSim model and the available MRV or LoD data, as follows:

- hazard threshold A, which is the MRV if it exists, or five times the LoD
- hazard threshold B, which is the MRV if it exists, or ten times the LoD

GoldSim calculations were undertaken to determine the concentrations of each hazardous substance, assuming each has a unit inventory (1 g), within the vaults for shielded ILW in the GDF. Using these concentrations, the inventories of hazardous substances that would correspond with the two hazard thresholds were derived. These inventories are referred to as ‘threshold inventories’ and the results of these calculations are presented in Table 5. Note that benzo(a)pyrene, styrene and mercury compounds are potentially solubility limited and may not reach the threshold concentrations (these substances have been highlighted in red in Table 5).

Following completion of this scoping study on hazardous substances, RWM plans to use the results to identify the substances that should be included in future inventory updates. Such a revision would involve changing the questions asked to the waste producers when compiling the update to the inventory. Note that the questionnaires for the 2016 UKRWI have already been issued and, therefore, the revised request for information is likely to be made ahead of preparation of the 2019 UKRWI.

Box 13. Hazardous substances in higher activity waste

Hazardous substances that will, or may, be present in higher activity waste are as follows:

- 1,1,1-trichloroethane
- 1,1,2-trichloroethane
- 1,1-dichloroethane
- 1,2,4-trichlorobenzene
- 1,2,4-trimethylbenzene
- 1,2-dichloroethane
- 1,2-dichloroethene
- 1,2-dichloropropane
- 1,3-dichloro-2-propanol
- 1-bromopropane
- 2-chloro-1,3-butadiene
- 4-chlorotoluene
- alkanes, C=>18, chloro
- alkanes, C10–13, chloro
- alkanes, C14–17, chloro
- anthracene
- benzene
- benzo(a)pyrene
- **bitumen**
- **cadmium**
- chloroethylene
- chloroform
- dibutyl bis(oxylauroyl)tin
- dibutyltin oxide
- dibutyltin salts
- dichloromethane
- dodecyl benzene
- epichlorohydrin
- ethylbenzene
- hexachlorobenzene
- hexachloroethane
- **mercury compounds**
- **mineral oil**
- **petroleum oil**
- phenylmercury acetate
- styrene

Substances shown in bold type are known to be present in higher activity wastes (based on information in the UKRWI [7]). A prioritised list of hazardous substances identified for assessment in the scoping study of the effects of such species is as follows:

- **1,1,2,2 tetrachloroethane**
- 1,2,4-trichlorobenzene
- 1,2-dichloroethane
- 2-chloro-1,3-butadiene
- alkanes C10-13, chloro
- benzene
- benzo-a-pyrene
- **cadmium**
- chloroethylene
- dodecyl benzene (as sodium dodecyl benzene sulphonate)
- hexachlorobenzene
- **mercury compounds**
- **mineral oil**
- **petroleum oil**
- styrene

Table 5 **Calculated concentrations of hazardous substances at the compliance point for assumed unit inventories of each species, and threshold inventories that would correspond with the Hazard Thresholds A (5 × LoD) and B (10 × LoD). Substances highlighted in red are potentially solubility limited and may not reach the threshold concentrations.**

Hazardous Substance	Unit concentrations (g/l)			Threshold inventory A (g)			Threshold inventory B (g)		
	Lower Bound Sorption	Median	Upper Bound Sorption	Lower Bound Sorption	Median	Upper Bound Sorption	Lower Bound Sorption	Median	Upper Bound Sorption
Cadmium	1.0E-09	1.6E-11	1.6E-13	9.7E+01	6.2E+03	6.2E+05	9.7E+01	6.2E+03	6.2E+05
Benzo(a)pyrene	1.5E-10	2.9E-13	1.6E-15	3.3E+02	1.7E+05	3.1E+07	6.5E+02	3.4E+05	6.2E+07
Benzene	2.8E-09	2.4E-09	1.5E-10	3.5E+02	4.2E+02	6.5E+03	3.5E+02	4.2E+02	6.5E+03
Dodecyl benzene	2.8E-09	2.4E-09	1.5E-10	1.8E+05	2.1E+05	3.3E+06	3.5E+05	4.2E+05	6.5E+06
Toluene	2.8E-09	2.4E-09	1.5E-10	1.4E+03	1.7E+03	2.6E+04	1.4E+03	1.7E+03	2.6E+04
Mineral oil	2.8E-09	2.8E-09	2.8E-09	1.8E+01	1.8E+01	1.8E+01	3.5E+01	3.5E+01	3.5E+01
Petroleum oil	2.8E-09	2.8E-09	2.8E-09	1.8E+04	1.8E+04	1.8E+04	3.5E+04	3.5E+04	3.5E+04
Styrene	2.8E-09	2.4E-09	1.5E-10	1.8E+03	2.1E+03	3.3E+04	3.5E+03	4.2E+03	6.5E+04
Mercury compounds	1.0E-09	1.6E-11	1.6E-13	9.7E+00	6.2E+02	6.2E+04	9.7E+00	6.2E+02	6.2E+04
Alkanes	2.8E-09	2.7E-10	1.6E-12	1.8E+05	1.9E+06	3.1E+08	3.6E+05	3.7E+06	6.2E+08
Chloroethylene	2.8E-09	2.3E-09	1.5E-10	1.8E+03	2.2E+03	3.3E+04	3.5E+03	4.4E+03	6.5E+04
Hexachlorobenzene	1.5E-10	5.7E-13	1.6E-14	6.5E+00	1.7E+03	6.2E+04	6.5E+00	1.7E+03	6.2E+04
1,1,2,2-tetrachloroethane	2.8E-09	2.7E-10	1.6E-12	3.6E+02	3.7E+03	6.2E+05	7.2E+02	7.5E+03	1.2E+06
1,2,4-trichlorobenzene	2.9E-10	3.2E-12	3.2E-14	3.4E+01	3.1E+03	3.1E+05	3.4E+01	3.1E+03	3.1E+05
1,2-dichloroethane	2.8E-09	2.3E-09	1.5E-10	3.5E+02	4.4E+02	6.5E+03	3.5E+02	4.4E+02	6.5E+03

Hazardous Substance	Unit concentrations (g/l)			Threshold inventory A (g)			Threshold inventory B (g)		
	Lower Bound Sorption	Median	Upper Bound Sorption	Lower Bound Sorption	Median	Upper Bound Sorption	Lower Bound Sorption	Median	Upper Bound Sorption
2-chloro-1,3-butadiene	2.8E-09	2.3E-09	1.5E-10	1.8E+03	2.2E+03	3.3E+04	3.5E+03	4.4E+03	6.5E+04
Trichloroethylene	2.8E-09	1.1E-09	1.6E-11	3.6E+01	9.1E+01	6.2E+03	3.6E+01	9.1E+01	6.2E+03
Tributyl-phosphate	2.8E-09	2.4E-09	1.5E-10	1.8E+04	2.1E+04	3.3E+05	3.5E+04	4.2E+04	6.5E+05
Triphenyl-phosphate	2.8E-09	2.4E-09	1.5E-10	8.8E+01	1.0E+02	1.6E+03	1.8E+02	2.1E+02	3.3E+03
Tributyltin oxide (TBTO)	1.0E-09	2.9E-12	1.6E-14	9.7E-01	3.4E+02	6.2E+04	9.7E-01	3.4E+02	6.2E+04

9.1.2 Non-hazardous pollutants

Following the work on hazardous substances, RWM plans to undertake similar work on non-hazardous pollutants. Some case studies have already been undertaken for non-hazardous pollutants, such as lead [71]. However, such work started before the inclusion of the requirements of EPR 2010 in the DSS [10; 11] and therefore these regulations were not considered.

9.2 Gas assessment

As discussed in the generic ESC [5, §10.3.2], at this stage in the siting process RWM is focusing non-radiological assessment work on impacts on humans and groundwater. Consideration has primarily been given to transport of non-radiological species via the groundwater pathway. However, as RWM develops its understanding of non-radiological assessment, consideration will be given to the potential environmental safety impacts of the generation of non-radiological gases.

9.3 Criticality assessment

The PCCCA included insight modelling to evaluate the potential effects of criticality on the behaviour of non-radiological pollutants in the GDF [62, §7]. Non-radiological species were treated in an identical way to radionuclides in terms of their transport via the groundwater pathway, but instead of assessing risk to a potentially exposed group, the calculated near-surface concentrations of non-radiological species in groundwater were considered in the context of drinking water standards.

The inventory of non-radiological species in the GDF will be dominated by the contributions from UILW/ULLW and the uranium in spent fuel and DNLEU. The PCCCA analysis focused on the inventory of non-radiological species in UILW/ULLW and spent fuel. The additional mass of non-radiological species generated during a criticality event was estimated to be small compared to the mass already present in the waste inventory.

The PCCCA insight calculations focused on the effects of criticality on the transport of non-radiological species in UILW/ULLW for disposal concepts in higher strength rock and lower strength sedimentary rock. The effects of criticality were accounted for by excluding sorption and solubility limitation in the EBS. It was shown that the calculated peak concentrations of most non-radiological species in near-surface groundwater are governed by the transport of those materials through the geological environment, so that the effects of criticality on the safety functions of the EBS are insignificant. However, the EBS does have a significant impact on nickel migration behaviour; the exclusion of nickel sorption and solubility limitation in the EBS resulted in increased concentrations of nickel in near-surface groundwater.

10 Summary and Key Messages

10.1 Summary

This PCSA presents the approaches to and results of the quantitative analyses that support the ESC. That is, the PCSA provides a quantitative underpinning of the arguments presented in the ESC that explain how the geological disposal of higher activity wastes can be accomplished in a way that ensures environmental safety in the long-term.

While a site is being sought for a GDF in the UK, the ESC is necessarily generic, focusing on the assessment of illustrative concepts for radioactive waste disposal in different geological environments. The PCSA has focused on quantifying how the different barriers of these illustrative disposal concepts act together to provide long-term containment of radionuclides and non-radiological species. The assessment approach described in this PCSA and the illustrative results demonstrate the quantitative understanding that will underpin the future development of a site-specific ESC.

Demonstrating how a GDF provides environmental safety requires an understanding of how conditions in the GDF will evolve over hundreds of thousands of years or more. This generic PCSA supports this understanding by providing:

- evaluations of the expected evolution (or base scenario) for different disposal concepts to support demonstrations of how disposal facilities would be expected to meet environmental safety requirements
- evaluations of variant scenarios based on the consideration of FEPs that, although considered unlikely to occur, could disrupt the performance of the GDF

The models developed for the generic PCSA are relatively simple, but of sufficient detail to facilitate understanding of the roles that different barriers play in providing post-closure environmental safety. In particular, whilst a disposal site is being sought, the properties of illustrative geological barriers have been derived for modelling based on expert knowledge of hydrogeological and geochemical systems. Once potential disposal sites have been identified, site-specific information will be gathered to develop site descriptive models that will then underpin the performance assessment modelling.

The quantitative analysis has involved the use of insight models and probabilistic total system models. Insight models have been used to develop understanding of GDF performance at a high level, focusing on evaluating the effects of radioactive decay and ingrowth and the environmental safety functions provided by each component of the barrier system. Probabilistic total system models have been used to evaluate radionuclide migration along groundwater pathways to the biosphere for different disposal concepts and geological environments. A deterministic approach has been taken to defining the structure of illustrative radionuclide transport pathways from the disposal areas to the biosphere for disposal facilities in different geological environments. In reality, a 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 transport to the surface environment for the actual GDF. However, based on analysis of these illustrative disposal concepts and geological environments, the calculations have provided a means of identifying the key radionuclides that could contribute to radiological risk.

Key results of the assessment calculations are as follows:

- Assessment of HHGW disposal in higher strength rock focused on the impacts of a variant scenario involving early failure of individual disposal containers of different types of waste. Different types of spent fuel show similar characteristic behaviour with regard to calculated mean radiological risk. In all illustrative cases, the calculated mean radiological risk from the marine pathway is negligible. The main contributor to calculated radiological risk is from exposure to I-129 (a long-lived and mobile radionuclide) via a well pathway. The highest calculated radiological risks from I-129 are associated with the instant release fraction from spent fuel following container failure. The compositions of HLW and Pu and HEU ceramic and their very slow degradation rates under disposal conditions mean that their contributions to calculated radiological risk are minor over the assessment period. These calculations indicate that the illustrative concept for the disposal of HHGW in higher strength rock is robust to early failure of several thousand HHGW packages.

- For most types of LHGW disposal in higher strength rock, the main radionuclides contributing to the calculated mean radiological risk for the base scenario are I-129 and Cl-36 via the well exposure pathway; the calculated mean radiological risk from the marine pathway is negligible. However, in general, the calculated radiological risk from Ra-226, U-233, U-238 and U-234 increases and becomes significant on timescales of hundreds of thousands of years (especially for DNLEU), although this depends on the level of retardation of these radionuclides in the host rock. By taking account of diffusion into micro-fractures and inter-connected porosity surrounding fractures, with sorption on available surfaces, the calculated risk from radium and uranium isotopes reduces substantially.
- Sensitivity studies for the disposal concepts in higher strength rock found that the capacity for the host rock and cover rocks to contain and dilute long-lived actinides (for example, by sorption, diffusion and dispersion processes) and the existence of transport pathways to the biosphere have a strong influence on the potential for such radionuclides to contribute to radiological risk in the very long term.
- Analysis of the concepts for HHGW disposal in lower strength sedimentary rock confirmed the importance of the host rock as a barrier to radionuclide transport. The illustrative calculations found that only the most mobile and long-lived radionuclides (mainly I-129, Cl-36 and Se-79) migrate through the assumed 50 metres of host rock above the disposal region on a timescale of 300,000 years. Calculated mean radiological risk is extremely small even for the well exposure pathway.
- Results for LHGW disposal in lower strength sedimentary rock are similar to those for HHGW disposal; only Nb-94, I-129, Cl-36, Se-79 and Ra-226 migrate through the host rock on a timescale of 300,000 years and the calculated mean radiological risk is insignificant.
- The expected evolution of disposal facilities in evaporite rock is not anticipated to result in radionuclide releases to the biosphere, primarily because there would be little water available to facilitate radionuclide migration in the evaporite rock and rock creep would be expected to encapsulate the wastes after disposal.

The illustrative calculations presented in this PCSA have shown the importance of different components of a multi-barrier system in containing radionuclides. Even if pathways exist for radionuclides to be transported in groundwater from the GDF to the biosphere, the radiological exposure risks will be small due to the long period of containment provided by the engineered barriers and the effects of processes such as radionuclide decay, diffusion, dispersion, sorption and dilution in the engineered barrier system and geological environment.

These findings are based on an understanding of the properties and behaviour of HHGW and LHGW and the barriers associated with illustrative disposal concepts for HHGW and LHGW in different geological environments, as discussed in RWM's research status reports. The results of the illustrative calculations have highlighted how the behaviour of relatively few radionuclides (mainly I-129, Cl-36, Ra-226, U-233, U-238 and U234) dominates evaluations of environmental safety. These results are based on an understanding of radionuclide transport in groundwater and human exposure pathways for each illustrative disposal concept considered. The illustrative results give an indication of key areas for future research to support assessments of radionuclide transport in groundwater as part of future site-specific work.

The main radioactive gas that requires consideration in the GDF post-closure performance assessment is C-14. Calculations of C-14 transport in the gas phase found that, for disposal concepts in higher strength rocks, release of radioactive gases to the biosphere could occur, but this requires connected gas-permeable pathways to be present. For disposal concepts in lower strength sedimentary rocks and for evaporite rocks, gas generation could lead to over-pressurisation and potential damage to a GDF and surrounding rock, which could affect C-14 migration. Clearly, the migration of C-14 is highly dependent on the geological environment at the site of the GDF and its assessment will be an important component of a site-specific ESC.

The PCSA has also considered the potential for nuclear criticality to affect the performance of the GDF by damaging the GDF’s multi-barrier system and changing the inventory of fission products. The potential impacts of a hypothetical criticality event were assessed in terms of how the environmental safety functions provided by the engineered and natural barriers in the GDF could be affected by criticality and how as a result, the calculated radiological risk could change for different exposure pathways. The effects of criticality on the transport of and potential exposure to non-radiological species were also assessed. Broadly, the analysis for HHGW and LHGW disposal in higher strength rock and lower strength sedimentary rock found that criticality will not have a significant effect on the calculated risk associated with disposal or on the behaviour of non-radiological species.

The need for an ESC to consider inadvertent human intrusion into a GDF has been discussed in the PCSA. However, it was concluded that there is little benefit in undertaking calculations to evaluate specific impacts of human intrusion prior to selection of an actual GDF site and design, along with the associated preventative measures for reducing the likelihood and consequences of an inadvertent human intrusion. Instead, different lines of argument have been considered, such as evidence for the longevity of records to support the view that knowledge of the presence of the GDF could be maintained for at least 1,000 years after closure. Substantial decay of the radioactive waste inventory will have occurred in this time.

Assessment of the potential impacts of non-radiological species on the environmental safety of geological disposal has focused on a methodology to calculate a maximum allowable inventory of hazardous substances that could be disposed of safely. This analysis will enable RWM to identify the substances that should be included in future radioactive waste inventory updates.

10.2 Future developments of the PCSA

Once a location for a GDF has been identified, it will be possible to develop a site-specific ESC based on knowledge of the geological environment and details of a suitable GDF design. Understanding of the geological environment at the GDF site will be obtained through a site characterisation process. Site characterisation will involve the development of a site descriptive model that summarises 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 engineered barrier system will be used as the basis for producing a site-specific PCSA that assesses system evolution and the behaviour of radionuclides and non-radiological species as part of the demonstration of environmental safety.

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, including inventory understanding, the Disposal System Specification, disposal concepts and disposal system designs. The PCSA will be developed as part of this process. As discussed in the ESC, key areas for the development of RWM's knowledge base have been identified and confirmed through the analysis presented in the PCSA. Some key topics where further research on barrier system behaviour will be beneficial to the development of future ESCs (and PCSAs) are as follows [5]:

- Further understanding of the instant release fraction of radionuclides at the time of container failure (Science and Technology Plan [32, Task 546]).
- Further understanding of the corrosion behaviour of HHGW containers under disposal conditions, especially for the higher strength rock disposal concept (Science and Technology Plan [32, Tasks 647 and 648]).
- Further understanding of how radionuclides migrate through low-permeability fractured rock (Science and Technology Plan [32, Task 372]).
- Development of methodologies to assess a broad range of variant scenarios of disposal system evolution.

10.3 Key messages

This PCSA provides:

- descriptions of the types of model that can be used to support assessments of the environmental safety of geological disposal; both insight and probabilistic total system models have been discussed and used in example calculations
- example applications of the insight and total system models based on illustrations of plausible geological environments and radioactive waste disposal concepts, as a means of demonstrating aspects of the detailed quantitative analysis that will be undertaken when a disposal site is available
- a means of identifying the most important components of GDF barrier systems in terms of the environmental safety functions they provide
- 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
- an outline of an approach to considering the environmental safety functions provided by the barrier components of the GDF as part of the waste package Disposability Assessment process.

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Glossary

A glossary of terms specific to the generic DSSC can be found in the Technical Background.

Appendix A – Post-closure Disposability Assessment Example

As discussed in Section 2.3, the assessment approach taken in this generic PCSA and the generic ESC [1] has resulted in an update to the PCPA methodology that forms part of the Disposability Assessment process. The revised approach involves reference to the environmental safety functions provided by a proposed waste package and an assessment of how the waste package could influence the environmental safety functions provided by other waste packages or components of a multi-barrier disposal system.

This section provides a worked example to illustrate how a PCPA would be undertaken as part of this revised process. The example is based on consideration of an existing waste package concept for a waste stream in the Derived Inventory that has been chosen in order to demonstrate the principles of the new process. The example does not form an actual assessment. The example concept selected is for packaging ammonium diuranate (ADU) flocculation (floc) waste; this waste stream is recorded in the Derived Inventory as waste stream 5B22 [2].

The ADU floc waste was derived from flocculation of alpha-contaminated low and medium activity streams arising from Prototype Fast Reactor (PFR) fuel and breeder reprocessing. The waste is packaged in accordance with the packaging specification for LHGW [3]. For the purposes of this example, the waste is to be grouted into 500 litre drums by in-drum mixing with cement after chemical conditioning.

This example PCPA has been undertaken without considering information from other areas of technical assessment usually associated with a disposability assessment [4, Table 5]. Instead, for this example, qualitative statements have been made about waste package characteristics and it has been highlighted where, in reality, additional information would be required from the other technical assessment areas.

The level of this example assessment is consistent with a conceptual stage disposability assessment [4], where the compatibility of the proposed waste treatment and packaging process with anticipated long-term waste management requirements is assessed (although in reality the packaging proposal for waste stream 5B22 is already at an advanced stage in RWM's Disposability Assessment process). A conceptual stage assessment is usually based on information describing the expected waste inventory and volume, outline packaging proposals and development plans. At the conceptual stage it is expected that the disposability assessment would be in outline form only, but sufficiently developed to judge the overall feasibility of the packaging concept. For this test example, further detailed (or quantitative) information that would be required for a conceptual stage assessment has been highlighted. Of course, a real PCPA would draw upon the existing technical evaluations undertaken by the competent specialists in those areas [4].

A1 Wasteform

The generic ESC [1, §3.1] describes at a generic level the environmental safety functions that could be provided by a wasteform. The generic environmental safety functions are listed in Table 1 of the main text. A wasteform will contribute to the overall containment provided by the engineered barrier system of the GDF if it is a durable solid that immobilises the radioactive content of the waste (as well as any potential non-radiological hazard) [5, Box 3]. In particular, once a container has been breached following degradation (for example, by corrosion) after GDF closure, a wasteform will continue to contribute towards containment if the rate of any leaching of contaminants into groundwater is low [1, §3.1]. The generic environmental safety functions that could be associated with a wasteform are:

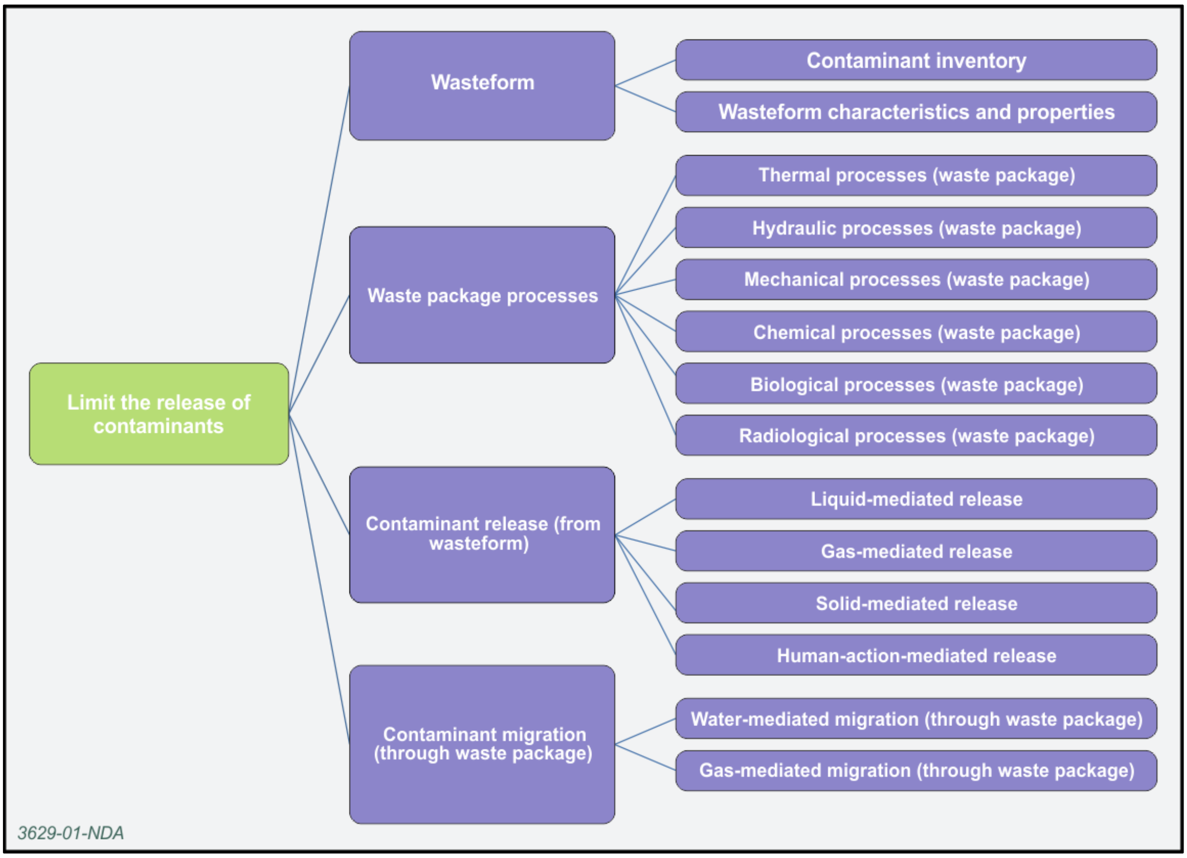
- limit the release of contaminants

- stabilise the structure and geometry of the engineered barriers
- protect the internal surface of the waste container
- limit the potential for nuclear criticality

The generic ESC [1, §3.1] discusses how different FEPs could affect how the safety functions are achieved for different barrier components, such as the wasteform. As an example, Figure A1 [1, §3.1] shows the waste package FEPs listed on the OECD NEA international FEP database [6] that could affect how a wasteform's safety function to limit the release of contaminants is achieved.

The following sub-sections present discussions of FEPs that are considered important to the wasteform environmental safety functions for the particular waste packaging example being considered in this example PCPA.

Figure A1 Illustration of the waste package FEPs [6] 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 [1, Figure 8]



A1.1 Limit contaminant release

The impacts of different FEPs on the release of radionuclides and non-radiological contaminants from ADU floc waste package are discussed below.

FEP: Wasteform – Contaminant inventory

The radiological content of the ADU floc wastes will be uniformly distributed across the waste packages. Key radionuclides present with regard to long-term post-closure safety are Pu-238, U-234, U-235, U-236, U-238, Th-230, Th-234, Tc-99 and I-129. Note that in a real PCPA, the quantities of key radionuclides in the ADU floc waste packages would be assessed in order to determine if they represent significant contributors to calculated radiological risk.

As discussed in Section 9, the presence of non-radiological substances in wastes could be harmful. Packaged ADU Floc waste may contain traces of tributyl phosphate (TBP), dibutyl phosphate (DBP) and monobutyl phosphate (MBP), which are potentially hazardous substances (see Section 9). During ADU floc storage prior to disposal most of the TBP would have been affected by radiolysis, with little if any remaining at the time of disposal. In an actual assessment, information on the masses of these substances in the wastes would be used, as provided from other assessment areas [4, Table 5].

FEP: Wasteform – Wasteform characteristics and properties

The cementitious material to be used in the ADU floc waste immobilisation process is based on a 1:1 pulverised fuel ash (PFA)/ordinary Portland cement (OPC) formulation in a 1:1 ratio with the waste.

FEP: Waste package processes – Hydraulic processes (waste package);
Waste package processes – Chemical processes (waste package);
Contaminant release (from wasteform) – Liquid mediated release;
Contaminant migration (through waste package) – Water-mediated migration (through waste package)

Although, the grouted wasteform will provide some level of radionuclide containment of short-lived radionuclides, its effects on the behaviour of long-lived radionuclides will be limited. The above-noted long-lived radionuclides are unlikely to be contained in the wasteform for a significant period after disposal in relation to their half-lives. For example, I-129 has a half-life of 15.7 million years [7], is soluble and will not be significantly sorbed on materials in the waste package. Other components of an EBS would provide environmental safety functions relevant to such radionuclides.

However, the alkaline environment generated by the cementitious grout will serve to limit the solubility of some radionuclides [5, §3.1.1] and the grout matrix will have a low-permeability. These wasteform properties will ensure that the release of radionuclides and non-radiological contaminants from the waste package in groundwater is slow. Of course, these processes may not be important if the disposal environment is dry (such as may be the case for a disposal facility in an evaporite host rock).

Organic complexing agents derived from the wastes could increase radionuclide mobility, but their impact would become progressively less significant as their concentrations are reduced by chemical, radiolytic or microbial degradation. There is a trace amount of organic material present in the ADU floc waste from reprocessing and conditioning of the waste, but this is unlikely to affect the release of radionuclides significantly. In an actual assessment, judgments about the effects of organic complexing agents would be supported by data on the amount of organic material present in the wasteform.

There are no non-aqueous phase liquids (NAPLs) present in ADU floc wastes. NAPLs are organic liquids, such as oils and solvents, that have limited miscibility with water and which may provide an additional carrier for radionuclide migration where present [8, §2.11].

A1.2 Stability of EBS

The impacts of different FEPs on the stability of the EBS for the ADU floc waste package are discussed below.

FEP: Waste package processes – Mechanical processes (waste package)

Voidage associated with grouted ADU floc wastes will be low, limited to the pore space normally associated with a grouted wasteform and any space above the wasteform (ullage) in the container. Thus, the wasteform will be a strong material and the waste package will provide resistance to mechanical stresses imposed by the backfill or host rock as a result of creep or rockfall. Disruption (for example backfill or host rock fracturing) associated with any redistribution of voidage will be limited.

FEP: Waste package processes – Thermal processes (waste package)

Heat output from the waste package will be 1.6 W at 2040, which is within the limits stated in the Generic Waste Package Specification (GWPS) (‘*The heat output of the waste package at the time of disposal vault closure should not exceed 6 watts per cubic metre of conditioned waste*’) [3, §6.3.4] and is therefore not expected to affect the stability of the EBS. The heat output of the waste is dominated by Pu-238 decay, which is a relatively short-lived radionuclide (with a half-life of 87.7 years [7]).

FEP: Waste package processes – Chemical processes (waste package)

Decontamination agents have been used in the waste packaging process and ammonia is present in the waste stream. However, these agents are neutralised in the packaging process so are not expected to be problematic to the stability of the EBS.

The grout has a calcium/silicon ratio lower than that of NRVB (which is used as a backfill material in certain concepts) but, nonetheless, is still considered to be sufficient to provide the general benefits attributed to an alkaline environment [5, §3.1.1] and will not adversely affect local backfill performance.

ADU floc wastes may contain non-radiological substances which may be hazardous, but they will not have a significant impact on the performance of any backfill or other barriers of a disposal facility as they are only expected to be present in very small trace amounts. In a real assessment, detailed information will be provided on the composition of the wasteform and how its components could affect the stability of an EBS.

The wastes contain a trace amount of organic material from reprocessing and conditioning. However, this material is unlikely to affect the function of any backfill present (for example, it will not affect the ability of a cementitious backfill to provide a high pH environment).

FEP: Waste package processes – Radiological processes (waste package)

Gas generation from ADU floc wastes is likely to be dominated by radiolysis and is not expected to be sufficient to affect the stability of the EBS. However, for a real assessment a gas generation assessment would be undertaken to confirm this view as part of the wasteform technical evaluation [4].

A1.3 Protection of internal surface of the waste container

The impacts of different FEPs on the protection of the internal surface of the waste container are discussed below.

FEP: Waste package processes – Chemical processes (waste package)

The use of a cement encapsulant for the ADU floc wastes will reduce the potential for internal corrosion of the steel container in the presence of liquid phases (due to the alkaline cement porewater) [5, §10]. The wastes could include residual amounts of ammonia/acids that were used in their treatment process, but it is unlikely that this will significantly affect the internal surface of the waste container. In an actual disposability assessment, the specific masses of this material likely to be present in a waste package would be considered.

FEP: Waste package processes – Radiological processes (waste package)

The ADU floc wastes containers are 500 litre drums [9] that are vented (see Figure A2) so a build-up of gas, and container damage as a result of gas-generating reactions in the wasteform, is unlikely to occur. Relatively low rates of gas generation are anyway expected (as per the discussion in Section A1.2). In an actual disposability assessment, gas generation rates would be considered in more detail as part of the wasteform evaluation.

Figure A2 500 litre drums showing vents in the lids [9]

FEP: Waste package processes – Thermal processes (waste package)

The ADU floc wasteform has a slightly higher heat output than other LHGW. However, the heat output is below the limit in the GWPS [3, §3] and is therefore regarded as unlikely to affect the integrity of the container in terms of significantly increased corrosion rates.

A1.4 Limit the potential for criticality

FEP: Waste package processes – Radiological processes (waste package)

ADU floc is depleted in U-235 and the waste packages contain only minor amounts of Pu-239. Therefore, the wastes do not present a criticality safety concern. In a real disposability assessment, these conclusions would be supported by a detailed waste package criticality safety assessment [4].

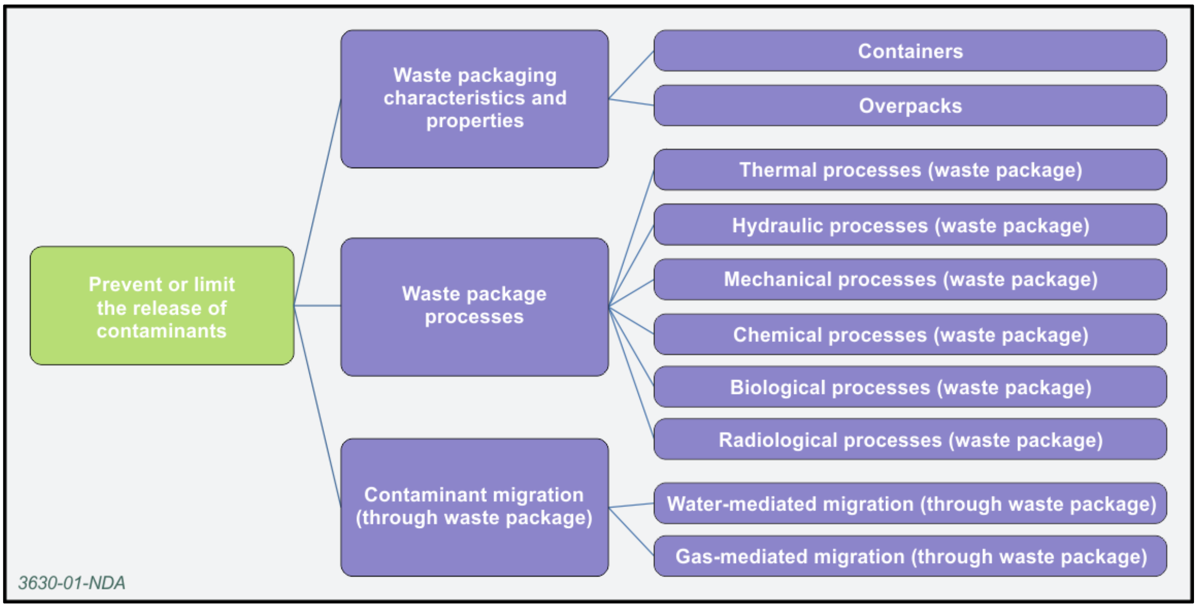
A2 Container

The container for the ADU floc waste stream is a 500 litre drum, consistent with the relevant specification [10]. The generic environmental safety functions associated with a container are [1, §3.1]:

- prevent or limit the release of contaminants
- prevent disruption through over-pressurisation
- stabilise the structure and geometry of the engineered barriers
- limit the potential for nuclear criticality

Figure A3 shows the waste package FEPs listed on the OECD NEA international FEP database [6] that could affect how a container's safety function to prevent or limit the release of contaminants is achieved. The environmental safety functions are discussed in the following sub-section with respect to the container for the ADU floc waste stream.

Figure A3 Illustration of the container FEPs [6] that could influence how a container limits the release of contaminants from a waste package; the lowest level, most detailed FEPs in the OECD NEA FEP list are not shown [1, Figure 8]



A2.1 Prevent or limit contaminant release

The impacts of the different FEPs on preventing or limiting the release of radionuclides are discussed below.

FEP: Waste package characteristics and properties – Containers

The 500 litre drums proposed as packaging for this waste stream are manufactured from stainless steel, consistent with common practice for similar wastes in the UK [5, §9.3.1].

FEP: Waste package processes – Chemical processes (waste package);
Waste package processes – Radiological processes (waste package);
Contaminant migration (through waste package) – Water-mediated migration (through waste package)

The selection of stainless steel is based on its corrosion resistance under relevant conditions. That is, stainless steel would corrode only very slowly under disposal conditions, especially where conditions are alkaline. Waste containers with a wall thickness of a few millimetres may be able to retain their functionality (that is, containment of the waste) for some 100,000 years if general corrosion is the only active corrosion mechanism [5, §10.9.2].

The key radionuclides in the ADU floc waste stream are I-129, Tc-99, Th-230, Th-234, U-234, U-235, U-236, U-238 and Pu-238. The half-lives of Th-234 and Pu-238 are sufficiently short (around 24 days and 88 years, respectively [7]) that the containment provided by the 500 litre drum will allow them to decay to insignificant amounts in the waste package. However, Th-230, I-129, Tc-99, U-234, U-235, U-236 and U-238 have long half-lives and their decay while contained in the waste packages will be minor. The environmental safety functions provided by other barriers may be important for these radionuclides.

A2.2 Prevention of disruption through over-pressurisation

The impacts of the different FEPs on prevention of container disruption by gas generation are discussed below.

FEP: Waste package characteristics and properties – Containers
Waste package processes – Radiological processes (waste package)

The containers (500 litre drums) are vented (see Figure A2) so that significant gas pressures are unlikely to be generated in the waste packages in the post-closure period. Furthermore, the rate of gas generation for the ADU floc wastes is expected to be relatively low. As noted above, in an actual disposability assessment, gas generation rates would be considered in more detail as part of the wasteform evaluation.

A2.3 Stability of the EBS

The impacts of the different FEPs on the stability of the EBS are discussed below. For the container, interactions with the EBS may not be important; it is more likely to be the combination of the container and the wasteform that will impact the EBS.

FEP: Waste package processes – Chemical processes (waste package);
Waste package processes – Radiological processes (waste package)

The majority of the gas generated (in terms of bulk hydrogen gas) is likely to be associated with corrosion of the stainless steel 500 litre drum. In a typical assessment, information on gas generation rates would be provided by wasteform assessment calculations. However, only a small amount of gas is expected to be generated from the stainless steel drums, and this is not expected to be detrimental to the stability of the EBS.

Corrosion of the container is not expected to have a detrimental effect on chemical conditions in a disposal facility; the stability of the EBS would not be affected.

FEP: Waste package processes – Mechanical processes (waste package)

Stainless steel containers (and the stillages that hold 500 litre drums) will provide mechanical stability in the vaults until the containers become weakened by corrosion.

The effects of voidage in the waste packages have been discussed previously as part of the wasteform considerations. There is no additional voidage introduced from the use of 500 litre drums.

FEP: Waste package processes – Thermal processes (waste package)

Heat generation in the waste packages will not be significant and therefore the heat transfer properties of the container are not important.

A2.4 Limit the potential for criticality

FEP: Waste package processes – Radiological processes (waste package)

As noted in Section A1.4, the ADU floc waste packages do not present a criticality safety concern. Therefore, the containers do not need to provide a criticality safety function.

A3 Summary of Example PCPA for ADU Floc Waste Packages

This example PCPA has provided qualitative discussions of the key implications for disposal of ADU floc waste packaged in 500 litre drums. The example represents a test of a revised approach to undertaking PCPAs that involves consideration of the environmental safety functions provided by a GDF's multi-barrier system. The assessment has involved consideration of a checklist of the generic environmental safety functions that could be provided by the different components of an engineered barrier system in different geological environments, and has considered the FEPs that could affect these components. In this test example, no specific issues relating to interactions between ADU floc waste packages and the environmental safety functions provided by different engineered barrier systems were identified.

Appendix B – FEP Checklist

Table B1 presents an indication of where each of the NEA FEPs has been considered in the reports that comprise the generic DSSC, such as RWM's research status reports (as described in Section 2 of this report). Note that some of the FEPs are only considered at a site-specific stage of GDF assessment and are therefore not considered in full at this generic stage.

Table B1 FEP consideration in DSSC documents

NEA FEP Number	Name	Description	RWM Report and Section
1	**EXTERNAL FACTORS**	**EXTERNAL FACTORS**	
1.1	Repository Issues	Decisions on designs and waste allocation, and also events related to site investigation, operations and closure. "Repository Issues" is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below
1.1.1	Quality assurance and control	Quality assurance and control procedures and tests during the design, construction and operation of the repository, as well as the manufacture of the wasteforms, containers and engineered features.	Not fully developed at the generic stage. However, Generic Waste Package Specifications (Level 2) provide waste package quality assurance/quality control requirements. Some container manufacture information is provided in the Waste Package Evolution Status Report.
1.1.2	Site investigations	FEP related to the investigations that are carried out at a potential repository site in order to characterise the site both prior to repository excavation and during construction and operation.	Not fully developed at the generic stage. However, the Geosphere Status Report contains descriptions of the generic environments that have been used in the PCSA.
1.1.3	Repository design	The design of the repository including both the safety concept, ie the general features of design and their safety functions, and the more detailed engineering specification for excavation, construction and operation.	Disposal System Specification Part B – Technical Specification. Generic Disposal Facility Design.

NEA FEP Number	Name	Description	RWM Report and Section
1.1.4	Schedule and planning	The sequence of events and activities occurring during repository excavation, construction, waste emplacement and sealing.	Not fully developed at the generic stage. However, the following documents provide current scheduling information: Provisional Implementation Plan; Construction Programme; Waste Receipt Schedule.
1.1.5	Construction	The excavation of shafts, tunnels, waste emplacement galleries, silos, etc of a repository, the stabilisation of these openings and installation/assembly of structural elements.	Not fully developed at the generic stage. However, the following document provides some information: Generic Disposal Facility Design.
1.1.6	Operation	The operation of the repository including the placing of wastes (usually in containers) at their final position within the repository and placing of any buffer and backfill materials. Also includes FEPs related to the choices on allocation of wastes to the repository, including waste type(s) and amount(s).	Disposal System Specification Part B – Technical Specification; Generic Disposal Facility Design; Generic Operational Safety Case – Main Report and Generic Operational Safety Assessment Volumes 1-4.
1.1.7	Closure	The cessation of waste emplacement operations at a site and the backfilling and sealing of access tunnels and shafts.	Disposal System Specification Part B – Technical Specification; Generic Disposal Facility Design; Engineered Barrier System Status Report.
1.1.8	Accidents and unplanned events	Accidents and unplanned events during excavation, construction, waste emplacement and closure which might have an impact on long-term performance or safety.	Generic Operational Safety Case – Main Report and Generic Operational Safety Assessment Volume 3.
1.1.9	Repository administrative control	Measures to control events at or around the repository site both during the operational period and after closure.	Not considered in the generic DSSC.

NEA FEP Number	Name	Description	RWM Report and Section
1.1.10	Monitoring	Monitoring that is carried out during operations or following closure of sections of, or the total, repository. This includes monitoring for operational safety and also monitoring of parameters related to the long-term safety and performance.	Generic Disposal Facility Design.
1.1.11	Repository markers	The retention of records of the content and nature of a repository after closure and also the placing of permanent markers at or near the site.	Not fully developed at the generic stage. However, Generic Waste Package Specifications (Level 2) provide waste package record retention requirements.
1.2	Geological Factors	Processes arising from the wider geological setting and long-term processes. “Geological Factors” is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
1.2.1	Tectonic movement	The movement of the lithosphere (the Earth’s outermost layer) due to the underlying movements of the crustal plates. These movements give rise to large-scale processes such as continental drift, mountain building (orogeny), crustal deformation, faulting, folding and subduction.	Geosphere Status Report, Section 4.1.
1.2.2	Orogeny	The formation of mountains (orogeny), the potential for orogeny and its effects on the performance of the repository.	Geosphere Status Report, Section 4.2.
1.2.3	Deformation (elastic, plastic, or brittle)	The physical deformation of geological structures in response to geological forces. This includes faulting, fracturing, extrusion and compression of rocks.	Geosphere Status Report, Section 4.1.

NEA FEP Number	Name	Description	RWM Report and Section
1.2.4	Seismicity	The release of accumulated geologic stress via rapid relative movements within the Earth's crust usually along existing faults or geological interfaces. The accompanying release of energy may result in ground movement and/or rupture, eg earthquakes.	Geosphere Status Report, Section 4.1.
1.2.5	Volcanic and magmatic activity	Magma is molten, mobile rock material, generated below the Earth's crust, which gives rise to igneous rocks when solidified. Magmatic activity occurs when there is intrusion of magma into the crust. A volcano is a vent or fissure in the Earth's surface through which molten or part-molten materials (lava) may flow, and ash and hot gases be expelled.	Geosphere Status Report, Section 4.1.
1.2.6	Metamorphism	The processes by which rocks are changed by the action of heat (T>200 °C) and pressure at great depths (usually several kilometres) beneath the Earth's surface or in the vicinity of magmatic activity.	Covered under FEP 1.2.5.
1.2.7	Hydrothermal activity	FEPs associated with high temperature groundwaters, including processes such as density-driven groundwater flow and hydrothermal alteration of minerals in the rocks through which the high temperature groundwater flows.	Geosphere Status Report, Sections 3.3 and 4.1.
1.2.8	Regional erosion and sedimentation	FEPs related the large scale (geological) removal and accumulation of rocks and sediments, with associated changes in topography and geological/hydrogeological conditions of the repository host rock.	Geosphere Status Report 4.2; Biosphere Status Report 3.2.

NEA FEP Number	Name	Description	RWM Report and Section
1.2.9	Diagenesis	The processes by which deposited sediments at or near the Earth's surface are formed into rocks by compaction, cementation and crystallisation, ie under conditions of temperature and pressure normal to the upper few kilometres of the earth's crust.	Excluded from generic DSSC, as discussed in the introduction to Section 4 of the Geosphere Status Report.
1.2.10	Pedogenesis	The process by which soil is formed. Pedogenesis depends upon climatic conditions as well as on mineral and biological processes and topography.	Excluded from generic DSSC, as discussed in the introduction to Section 4 of the Geosphere Status Report.
1.2.11	Salt diapirism and dissolution	The large scale evolution of salt formations. Diapirism is the lateral or vertical intrusion or upwelling of either buoyant or non-buoyant rock, into overlying strata (the overburden) from a source layer. Dissolution of the salt may occur where the evolving salt formation is in contact with groundwaters with salt content below saturation.	Not relevant to the geographical area of interest, as discussed in the Geosphere Status Report, Section 2.1.
1.2.12	Hydrological/Hydrogeological response to geological changes	FEPs arising from large-scale geological changes that affect regional and local groundwater flow and pressures. These could include changes of hydrological boundary conditions due to effects of erosion on topography, and changes of hydraulic properties of geological units due to changes in rock stress or fault movements.	Geosphere Status Report, Section 4.
1.2.13	Geomorphological response to geological changes	FEPs arising from geomorphological responses to geological changes that cause changes to surface landforms on a regional and local scale. Geomorphology relates to the evolution of a landscape due to geological events as well as climatic, hydrologic, and biologic conditions.	Biosphere Status Report, Section 3.4.

NEA FEP Number	Name	Description	RWM Report and Section
1.3	Climatic Factors	Processes related to global climate change and consequent regional effects. “Climatic Factors” is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
1.3.1	Global climate change	The possible future, and evidence for past, long term change of global climate. This is distinct from resulting changes that may occur at specific locations according to their regional setting and also climate fluctuations, c.f. FEP 1.3.2.	Geosphere Status Report, Section 4.3; Biosphere Status Report, Section 3.2.
1.3.2	Regional and local climate change	The possible future changes, and evidence for past changes, of climate at a repository site. This is likely to occur in response to global climate change, but the changes will be specific to situation, and may include shorter term fluctuations, c.f. FEP 1.3.1.	Geosphere Status Report, Section 4.3; Biosphere Status Report, Section 3.2.
1.3.3	Sea level change	Changes in sea level which may occur as a result of global (eustatic) change and regional geological change, eg isostatic movements.	Geosphere Status Report, Section 4.3; Biosphere Status Report, Section 3.2.
1.3.4	Periglacial effects	The physical processes and associated landforms in cold but ice-sheet-free environments.	Geosphere Status Report, Section 4.3; Biosphere Status Report, Section 3.2.
1.3.5	Local glacial and ice-sheet effects	The effects of glaciers and ice sheets within the region of a repository, eg changes in the geomorphology, erosion, meltwater and hydraulic effects. This is distinct from the effect of large ice masses on global and regional climate, c.f. FEPs 1.3.1, 1.3.2.	Geosphere Status Report, Section 4.3.
1.3.6	Warm climate effects (tropical and desert)	Effects of warm tropical and desert climates, including seasonal effects, and meteorological and geomorphological effects specific to these climates.	Geosphere Status Report, Section 4.3; Biosphere Status Report, Section 3.2.

NEA FEP Number	Name	Description	RWM Report and Section
1.3.7	Hydrological response to climate change	Changes in hydrology and hydrogeology, eg recharge, sediment load and seasonality, in response to climate change in a region.	Geosphere Status Report, Section 4.3.
1.3.8	Ecological response to climate change	Changes in ecology, eg vegetation, plant and animal populations, in response to climate change in a region.	Biosphere Status Report, Section 3.2.
1.3.9	Human response to climate change	Changes in human behaviour, eg habits, diet, size of communities, in response to climate change in a region.	Biosphere Status Report, Section 4.6.
1.3.10	Geomorphological response to climate changes	Geomorphological responses to climate changes that cause changes to surface landforms on a regional and local scale, eg the generation of periglacial landforms. Geomorphology relates to the evolution of a landscape due to geological events as well as climatic, hydrologic, and biologic conditions.	Geosphere Status Report, Section 4.3; Biosphere Status Report, Section 3.4.
1.4	Future Human Actions	Human actions and regional practices, in the post-closure period, that can potentially affect the performance of the engineered and/or geological barriers, eg intrusive actions, but not the passive behaviour and habits of the local population, c.f. 5.2. “Future Human Actions” is a sub- category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
1.4.1	Human influences on climate	Human activities that could affect the change of climate either globally or in a region.	Addressed via the overall biosphere approach, as discussed in the Biosphere Status Report, Section 2.
1.4.2	Social and institutional developments	Changes in social patterns and degree of local government, planning and regulation.	Addressed via the overall biosphere approach, as discussed in the Biosphere Status Report, Section 2.

NEA FEP Number	Name	Description	RWM Report and Section
1.4.3	Technological developments	Future developments in human technology and changes in the capacity and motivation to implement technologies. This may include retrograde developments, eg loss of capacity to implement a technology.	Addressed via the overall biosphere approach, as discussed in the Biosphere Status Report, Section 2.
1.4.4	Knowledge and motivational issues (repository)	The degree of knowledge of the existence, location and/or nature of the repository.	Not fully developed at the generic stage.
1.4.5	Drilling activities	Any type of drilling activity in the vicinity of the repository. These may be taken with or without knowledge of the repository (see FEP 1.4.4).	Environmental Safety Case, Section 10.2.3.
1.4.6	Mining and other underground activities	Any type of mining or excavation activity carried out in the vicinity of the repository. These may be taken with or without knowledge of the repository (see FEP 1.4.4).	Environmental Safety Case, Section 10.2.3.
1.4.7	Non-intrusive site investigation	Airborne, geophysical or other surface-based investigation of a repository site after repository closure.	Not considered in the generic DSSC.
1.4.8	Surface Environment	Human activities that may be carried out in the surface environment that can potentially affect the performance of the engineered and/or geological barriers, or the exposure pathways, excepting those FEPs related to water management which are at FEP 1.4.9.	The effect of surface-based human activities on engineered barrier performance is not considered in the generic DSSC; biosphere exposure pathways are addressed in the Biosphere Status Report, Section 2.1.
1.4.9	Water management (groundwater and surface water)	Groundwater and surface water management including water extraction, reservoirs, dams, and river management.	Not considered in the generic DSSC.
1.4.10	Explosions and crashes	Deliberate or accidental explosions and crashes such as might have some impact on a closed repository, eg underground nuclear testing, aircraft crash on the site, acts of war.	Not considered in the generic DSSC.

NEA FEP Number	Name	Description	RWM Report and Section
1.4.11	Remedial Actions	Actions that might be taken following repository closure to remedy problems with a waste repository that, either, was not performing to the standards required, had been disrupted by some natural event or process, or had been inadvertently or deliberately damaged by human actions.	Not considered in the generic DSSC.
1.4.12	Deliberate human intrusion	Reasons for and nature and consequences of deliberate intrusion into a repository after closure with complete or incomplete knowledge.	Consistent with the GRA, does not require consideration in the DSSC.
1.5	Other External Factors	A “catch-all” for any external factor not accommodated in 1.1 to 1.4, eg meteorite impact. “Other External Factors” is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
1.5.1	Meteorites and human space debris	The possibility of a large meteorite or human space debris impact occurring at or close to the repository site and related consequences. The impact could cause phenomena such as the creation of a crater, activation, creation and sealing of faults, and physical and chemical changes in rock.	Not considered in the generic DSSC.
1.5.2	Evolution of biota	The biological evolution of humans, other animal or plant species, by both natural selection and selective breeding/culturing.	Not considered in the generic DSSC.
2	**WASTE PACKAGE FACTORS**	**FEPs related to waste packages (ie wasteforms and any packaging).**	
2.1	Wasteform Characteristics and Properties	FEPs related to the physical, chemical, biological characteristics of the wasteform at the time of emplacement in the repository.	See individual FEPs below.
2.1.1	Waste State	The physical state of the wasteform following any conditioning prior to emplacement in the repository.	See individual FEPs below.

NEA FEP Number	Name	Description	RWM Report and Section
2.1.1.1	Solid	Wastes which are disposed in the solid state. Includes wastes that have been solidified through conditioning.	Waste Package Evolution Status Report, Section 2.1.
2.1.1.2	Liquid	Wastes which are disposed in the liquid state. Limits on the acceptance of such wastes for disposal in a repository are usually set.	Not applicable, consistent with the generic Waste Package Specification, Level 1.
2.1.1.3	Gas	Wastes which are disposed in the gaseous state. Limits on the acceptance of such wastes for disposal in a repository are usually set.	Not applicable, consistent with the generic Waste Package Specification, Level 1.
2.1.2	Waste Type	The physical, chemical and biological characteristics of the waste prior to any treatment and/or conditioning prior to packaging and emplacement in the repository.	See individual FEPs below.
2.1.2.1	Metallic wastes	The characteristics of metallic wastes that may be disposed in the repository.	Waste Package Evolution Status Report, Sections 2.1 and 2.4.
2.1.2.2	Organic wastes	The characteristics of organic wastes that may be disposed in the repository.	Waste Package Evolution Status Report, Sections 2.1 and 2.4.
2.1.2.3	Non-metallic, inorganic wastes	The characteristics of non-metallic, inorganic wastes that may be disposed in the repository.	Waste Package Evolution Status Report, Sections 2.1 - 2.4.
2.1.3	Waste conditioning matrix	The physical, chemical, biological characteristics of the waste conditioning matrix/matrices at the time of emplacement in the repository.	Waste Package Evolution Status Report, Section 3.1.
2.1.4	Contaminant inventory	The content in the repository of radioactive and non- radioactive contaminants disposed in the repository.	Derived Inventory Report.
2.1.4.1	Radionuclide content	The masses of radioactive isotopes (radionuclides) of all elements in the various wasteforms disposed in the repository.	Derived Inventory Report.
2.1.4.2	Chemical content	The masses of non-radioactive species in the various wasteforms disposed in the repository.	Derived Inventory Report.

NEA FEP Number	Name	Description	RWM Report and Section
2.1.5	Wasteform properties	The physical, chemical and biological characteristics and properties of the wasteforms at the time of emplacement in the repository.	Waste Package Evolution Status Report, Section 3.1 and 3.2.
2.2	Waste Packaging Characteristics and Properties	The physical, chemical and biological characteristics and properties of the waste packages at the time of emplacement in the repository.	See individual FEPs below
2.2.1	Containers	The physical, chemical, biological characteristics of the container at the time of emplacement in the repository.	Waste Package Evolution Status Report, Section 9.1 – 9.3.
2.2.2	Overpacks	The physical, chemical, biological characteristics of any overpack at the time of emplacement in the repository. An overpack is a container that is used to secure or shield one or more inner containers.	Waste Package Evolution Status Report, Section 9.2.
2.3	Waste Package Processes	Processes within the waste packages. The focus is on processes occurring after waste package emplacement in the repository. “Wastes Package Processes” is a sub- category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
2.3.1	Thermal processes (waste package)	FEPs related to the thermal processes that affect the waste packages (ie wasteform and containers). This includes the effects of heat on waste packages from the engineered materials in the repository and the surrounding geology.	See individual FEPs below.
2.3.1.1	Radiogenic heat production and transfer	Heat production and transfer from radioactive decay of the radionuclides in the waste packages. Heat generation from radiation attenuation is a function of the decay rate and the composition of the waste. The composition of the waste package controls its thermal conductivity.	Engineered Barrier System Status Report, Section 3.5.
2.3.1.2	Chemical heat production and transfer	Heat production and transfer from chemical processes affecting the waste packages.	Engineered Barrier System Status Report, Section 3.5.

NEA FEP Number	Name	Description	RWM Report and Section
2.3.1.3	Biological heat production and transfer	Heat production and transfer related to biological sources affecting the waste packages.	Engineered Barrier System Status Report, Section 3.5.
2.3.1.4	Impact of thermal processes on other processes (waste package)	FEPs relating to thermal processes coupled with other processes. Couplings of thermal processes with hydraulic, mechanical and chemical processes, as well as biological and radiological processes, will affect the evolution of the waste package. One potential consequence is the failure of the waste package.	Engineered Barrier System Status Report, Section 3.5.
2.3.2	Hydraulic processes (waste package)	FEPs related to the hydraulic processes that affect the waste packages. This includes the effects of hydraulic influences on waste packages by the engineered materials in the repository and the surrounding geology.	These FEPs are covered at the Engineered Barrier System level.
2.3.2.1	Resaturation/desaturation (waste package)	The resaturation or desaturation of the waste package will be controlled by the hydraulic conditions in the repository and the surrounding geosphere.	See FEP 2.3.2.
2.3.2.2	Thermal effects (waste package)	The evolution of the waste package’s temperature over time can influence the hydraulic conditions affecting the waste package.	See FEP 2.3.2.
2.3.2.3	Gas effects (waste package)	The generation and migration of gases in the waste packages can affect the hydraulic conditions in the waste package.	See FEP 2.3.2.
2.3.2.4	Impact of hydraulic processes on other processes (waste package)	FEPs relating to hydraulic processes coupled with other processes. Couplings of hydraulic processes with thermal, mechanical and chemical processes, as well as biological and radiological processes, will affect the evolution of the waste package. One potential consequence is the failure of the waste package.	See FEP 2.3.2.

NEA FEP Number	Name	Description	RWM Report and Section
2.3.3	Mechanical processes (waste package)	FEPs related to the mechanical processes that affect the waste packages. This includes the effects of hydraulic and mechanical loads imposed on waste packages by the engineered materials in the repository and the surrounding geology.	See individual FEPs below.
2.3.3.1	Package deformation	Large loads and pressures imposed on the waste package due to both internal and external sources can cause package deformation. The nature of these loads and their potential for causing deformation is, to some extent, dependent on whether the canister is intact or has been breached.	Waste Package Evolution Status Report, Section 10.3.
2.3.3.2	Material volume changes (waste package)	The effects of volume changes in materials used in the waste package (eg the shrinkage/expansion of concrete, the corrosion of metals and the swelling of bentonite).	Waste Package Evolution Status Report, Section 8.2 and 8.4.
2.3.3.3	Package movement	The movement of the waste package in the repository. Movement could result from mechanical stresses on the waste package caused by, for example, package deformation or mass redistribution in the repository. It could also result from seismic events (see FEP 1.2.04).	Not considered in the generic DSSC.
2.3.3.4	Stress corrosion cracking	A potential failure mechanism for metallic containers, involving the uptake of hydrogen gas and formation of metal hydrides. Stress corrosion cracking, or hydride embrittlement and cracking, may mechanically weaken the container and promote subsequent failure or other corrosion mechanisms.	Waste Package Evolution Status Report, Section 10.5.

NEA FEP Number	Name	Description	RWM Report and Section
2.3.3.5	Gas explosion (waste package)	Some gases produced from the corrosion and degradation of waste packages might be flammable or might form an explosive mixture; for instance, hydrogen and methane could mix with oxygen and explode to damage the waste package. A gas explosion can only occur if a flammable gas mixture forms and there is a source of ignition or the gas mixture has the capability to auto-ignite.	Not considered in the generic DSSC.
2.3.3.6	Impact of mechanical processes on other processes (waste package)	FEPs relating to mechanical processes coupled with other processes. Couplings of mechanical processes with thermal, hydraulic and chemical processes, as well as biological and radiological processes, will affect the evolution of the waste package. One potential consequence is the failure of the waste package.	Not fully developed in the generic DSSC. However the Waste Package Evolution Status Report, Section 10.5 provides some information.
2.3.4	Chemical processes (waste package)	FEPs related to the chemical/geochemical processes that affect the waste packages. This includes the effects of chemical/geochemical influences on waste packages by the engineered materials in the repository and the surrounding geology.	See individual FEPs below.
2.3.4.1	pH conditions (waste package)	The temporal evolution of the waste package's pH depends on a number of factors, including the pH of the surrounding water, the water flow rate through the waste package and the characteristics of the wasteform.	Waste Package Evolution Status Report, Sections 4.2 - 4.3 and 7.2.
2.3.4.2	Redox conditions (waste package)	The temporal evolution of the waste package's Eh	Waste Package Evolution Status Report, Sections 4.2 - 4.3.

NEA FEP Number	Name	Description	RWM Report and Section
2.3.4.3	Perturbing species' concentrations (waste package)	The presence of certain species, such as chloride and sulphate, can affect the evolution of the waste package, for example through promoting the corrosion of metals (high chloride concentrations) and the degradation of cement (high sulphate concentrations). Sources of such species can include the wasteforms and inflowing water.	Waste Package Evolution Status Report, Sections 4.2 – 4.3.
2.3.4.4	Corrosion (waste package)	Corrosion of the waste package can be generalised (or uniform), local, or galvanic. All metals are subject to uniform corrosion at rates that are dependent on the chemical and physical (and possibly biological) environment, while localised formation of cavities in a metal surface is caused by non-uniform corrosion. Galvanic corrosion occurs when two different metals are in electric contact.	Waste Package Evolution Status Report, Section 10.4.
2.3.4.5	Polymer degradation	Degradation of plastics or other polymers in the waste package can lead to gas generation, or the degradation of a polymeric packaging material may lead to a loss of containment.	Waste Package Evolution Status Report, Sections 7.3 and 8.3.
2.3.4.6	Dissolution (waste package)	Dissolution is the process by which molecules of a solid dissolve into solution. The chemical environment of the waste package (eg pH and Eh) is likely to evolve over time, and these changes could lead to the evolution of species dissolution.	Waste Package Evolution Status Report, Sections 5.3 (HLW), 6.3 (Oxide Fuel), 6.4 (Metallic Fuel) and 7.2 – 7.4 (ILW).
2.3.4.7	Mineralisation (waste package)	Mineralisation in the waste package includes processes such as leaching, carbonation, illitisation, and chloride and sulphate attack. These processes will affect the rate of species migration out of the waste package.	Waste Package Evolution Status Report, Sections 5.3 (HLW) and 7.2 – 7.4 (ILW).

NEA FEP Number	Name	Description	RWM Report and Section
2.3.4.8	Precipitation reactions (waste package)	The precipitation of an element from the aqueous phase to the solid phase can be affected by chemical conditions in the waste package (particularly pH, Eh and the concentration of complexing ions). The mass of precipitates could increase until dissolution of the wasteform ceases, after which the mass would decrease as the precipitate itself dissolves.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.6.
2.3.4.9	Chelating agent effects (waste package)	Chelating agents are organic compounds, usually carboxylic acids that have a number of locations in each molecule which can complex with a single metal atom. The resulting complexes are usually highly stable, a factor that can increase significantly the solubilities of certain elements. Sources can include organic wastes and inflowing water.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.3.
2.3.4.10	Colloid formation (waste package)	Colloids are very fine particles (with diameters typically less than 10 µm) that can affect the transport of contaminants. Particles of clay minerals, silica, iron oxy-hydroxides, other minerals, organic and bio-organic macromolecules may form the colloid phase. Sources can include materials in the waste package itself (eg cementitious materials, organic wastes), repository materials (eg bentonite and cementitious materials) and inflowing water.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.7.

NEA FEP Number	Name	Description	RWM Report and Section
2.3.4.11	Chemical concentration gradients (waste package)	Chemical concentration gradients in the waste package could be caused by various factors such as temperature changes, radiolysis, different electrochemical potentials between various materials, and the ingress of saline water. Possible effects include altered dissolution rates of the waste matrices and dissolution and precipitation of chemical compounds with subsequent opening or plugging of pores.	Not considered in the generic DSSC.
2.3.4.12	Impact of chemical processes on other processes (waste package)	FEPs relating to chemical processes coupled with other processes. Couplings of chemical processes with thermal, hydraulic and mechanical processes, as well as biological and radiological processes, will affect the evolution of the waste package.	Waste Package Evolution Status Report, Section 10.5 for coupled chemical and mechanical processes.
2.3.5	Biological processes (waste package)	FEPs related to the biological/biochemical processes that affect the waste packages. This includes the effects of biological/biochemical influences on waste packages by the engineered materials in the repository and the surrounding geology.	See individual FEPs below.
2.3.5.1	Microbial growth and poisoning (waste package)	Microbes can be present in the waste packages, especially those containing organic waste. Growth requires the presence of suitable nutrients, such as cellulosic wastes, simple organic molecules containing oxygen, nitrogen and/or sulphur, and small amounts of putrescible materials. Poisoning of microbial processes can occur due to temperatures in excess of about 70ºC, changing the pH to a value at which the microbial population ceases to function, and high heavy metals concentrations. However, extremophiles can survive and thrive outside the range at which most microbes flourish.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.8.

NEA FEP Number	Name	Description	RWM Report and Section
2.3.5.2	Microbially/biologically mediated processes (waste package)	Microbiological/biological processes can affect the form or related properties of the wasteform. For example, microbial processes can lead to the formation of acidic and oxidising species that can participate in corrosion of the metals and generation of reducing conditions. Bacteria and microbes may also result in the generation of gases (see FEP 2.3.7.2), and anaerobic bacteria may form biofilms on or around the waste package.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.7; Waste Package Evolution Status Report, Section 10.4.
2.3.5.3	Impact of biological processes on other processes (waste package)	FEPs relating to biological processes coupled with other processes. Couplings of biological processes with thermal, hydraulic, mechanical and chemical processes, as well as radiological processes, will affect the evolution of the waste package.	Waste Package Evolution Status Report, Section 10.4.
2.3.6	Radiological processes (waste package)	FEPs related to the effects of radiation emitted from the wastes in the waste packages, and the overall radiogenic evolution of the waste packages with time.	See individual FEPs below.
2.3.6.1	Radioactive decay and ingrowth (waste package)	Radioactive decay results in the reduction in the activity of the radionuclides in the waste package. Where a parent radionuclide decays to a daughter radionuclide, this causes the ingrowth of daughter in the waste package.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.1.
2.3.6.2	Radiolysis (waste package)	Waste packages may contain a mixture of water vapour, air, and argon. This humid air will be subject to radiation inside the waste package. The actual composition and amount of the radiolysis products that will be formed is controlled by the radiation dose rate and by the composition and amount of the air and water vapour mixture contained in the waste package (see FEP 2.3.7.4).	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.4.

NEA FEP Number	Name	Description	RWM Report and Section
2.3.6.3	Helium production	Helium production from alpha decay of waste.	Gas Status Report, Section 2.2; Waste Package Evolution Status Report, Section 6.6.
2.3.6.4	Radiation attenuation (waste package)	The rate of radiation attenuation is controlled in part by the design of the waste package. Much of the radiation from the waste will be attenuated by the wasteform, and radiation attenuation can generate thermal energy (see FEP 2.3.1.1).	Generic Operational Safety Case – Main Report and Generic Operational Safety Assessment Volume 2, Section 4.
2.3.6.5	Radiation damage (waste package)	Radiation damage from fission and alpha decay may affect waste packaging materials, influencing their chemical stability	Waste Package Evolution Status Report, Section 5.5 (HLW) and 6.6 (SF).
2.3.6.6	Impact of radiological processes on other processes (waste package)	FEPs relating to radiological processes coupled with other processes. For example, radiolysis within a waste package may lead to mechanical stresses and radioactive decay can result in heat generation. Helium and other gas production could lead to gas-induced failure of the waste package.	Waste Package Evolution Status Report, Section 6.6 (GM SF) and 7.2 (GM ILW) and 7.3 (GM Polymer).
2.3.7	Gas generation (waste package)	FEPs within and around the waste packages resulting in the generation of gases and their subsequent effects on the repository system.	See individual FEPs below.
2.3.7.1	Metal corrosion (waste package)	Metals (eg iron, carbon steel, aluminium) present in the waste packages will corrode resulting in hydrogen gas generation if the conditions are anaerobic.	Gas Status Report, Section 2.2; Waste Package Evolution Status Report, Section 6.4 (metallic fuels) and 8.2 (metallic ILW).
2.3.7.2	Organic degradation (waste package)	Organic materials present in the waste package will be subject to chemical and biological degradation resulting in the generation of gases such as carbon dioxide and methane.	Gas Status Report, Section 2.2; Waste Package Evolution Status Report, Section 7.3 (polymeric encapsulants) and 8.3 (organic wastes).

NEA FEP Number	Name	Description	RWM Report and Section
2.3.7.3	Radon production (waste package)	Radon will be produced from the decay of any Ra-226 in the waste.	Gas Status Report, Section 2.3.
2.3.7.4	Radiolysis (waste package)	Radiolysis (ie the dissociation of molecules by nuclear radiation) of water within a waste package can produce molecular species such as hydrogen, oxygen, and hydrogen peroxide which can impact the chemical conditions in the waste package and the wider repository (see FEP 2.3.6.2).	Gas Status Report, Section 2.2; Waste Package Evolution Status Report, Section 7.2 (cementitious ILW), 7.3 (polymer encapsulated ILW) and 11.1 (SF).
2.3.7.5	Volatilisation (waste package)	Volatile compounds can be formed due to chemical and biochemical processes occurring in the waste package (eg degradation of organic materials). The rate of volatilisation is controlled by changes in pressure, temperature and concentration in the waste package	Gas Status Report, Section 2.2.
2.3.7.6	Gas dissolution (waste package)	Gases can dissolve in water in the waste package. Dissolution is controlled by changes in pressure, temperature and concentration.	Gas Status Report, Section 3.2.
2.3.7.7	Gas-induced failure	The pressure resulting from gases generated in a sealed waste package might be sufficient to cause the waste package to fail.	Waste Package Evolution Status Report, Section 11.1.
2.3.7.8	Impact of gas generation on other processes (waste package)	Gas generation may influence other processes; for example, gas generation in a wasteform may expedite the mechanical failure of a waste package from crevice corrosion.	Waste Package Evolution Status Report, Section 11.1.
2.4	Contaminant Release (from wasteform)	The processes that directly affect the release of radiotoxic and chemotoxic species from the wasteform once the waste package has been emplaced in the repository. “Contaminant Release (from wasteform)” is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.

NEA FEP Number	Name	Description	RWM Report and Section
2.4.1	Liquid-mediated release	FEPs related to release of radiotoxic and chemotoxic species into water in the aqueous phase from the wasteform.	See individual FEPs below.
2.4.1.1	Liquid wastes	Release from waste packages in liquid form of radiotoxic and chemotoxic species in liquid wastes.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.9 (NAPLs).
2.4.1.2	Dissolution (wasteform)	On contact with water, a wasteform may alter and dissolve. For some wasteforms (eg glass), this process can be very slow and result in the slow congruent release of radiotoxic and chemotoxic species contained within the wasteform.	Waste Package Evolution Status Report, Sections 5.3 (HLW), 6.3 (Oxide Fuel), 6.4 (Metallic Fuel) and 7.2 – 7.4 (ILW).
2.4.1.3	Diffusion (wasteform)	Aqueous diffusion of radiotoxic and chemotoxic species from the wasteform. For example, on contact with water, radiotoxic and chemotoxic species in a wasteform may dissolve and diffuse into the water. This process is controlled by the chemical environment and by the wasteform composition and structure.	Waste Package Evolution Status Report, Sections 5.3 (HLW), 6.3 (Oxide Fuel), 6.4 (Metallic Fuel) and 7.2 – 7.4 (ILW).
2.4.1.4	Speciation and solubility (wasteform)	Chemical speciation and solubility processes affecting the release of radiotoxic and chemotoxic species from a wasteform under repository conditions. Speciation and solubility are affected by factors such as temperature, pressure, pH and redox conditions.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.2 (speciation) 2.6 (solubility).
2.4.1.5	Sorption and desorption (wasteform)	Sorption/desorption processes affecting the release of radiotoxic and chemotoxic species from a wasteform under repository conditions. Sorption describes the physico- chemical interaction of dissolved species with a solid phase. Desorption is the opposite effect.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.5.

NEA FEP Number	Name	Description	RWM Report and Section
2.4.1.6	Complexation (wasteform)	The impact of complexing agents on the release of radiotoxic and chemotoxic species from a wasteform under repository conditions. Such agents can be in the waste and/or waste package and other repository materials (eg as additives to cements and grouts).	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.3.
2.4.1.7	Colloids	The release of radiotoxic and chemotoxic species from a wasteform due to transport of colloids and interaction of radiotoxic and chemotoxic species with colloids from a wasteform under repository conditions. Sources can include materials in the waste package itself (eg cementitious materials, organic wastes) and inflowing water.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.7.
2.4.2	Gas-mediated release	FEPs related to release of radiotoxic and chemotoxic species in gas or vapour phase or as fine particulate or aerosol in gas or vapour.	See individual FEPs below.
2.4.2.1	Gaseous wastes	Release from waste packages in gas form of radiotoxic and chemotoxic species in gas wastes (eg Kr isotopes)	Gas Status Report, Section 2.3.
2.4.2.2	Radon production (wasteform)	Release of radon gas from decay of Ra-226 in wasteform.	Gas Status Report, Section 2.3.
2.4.2.3	Volatilisation (wasteform)	Release of contaminants from wasteform due to volatilisation resulting from chemical or biochemical reactions, eg C-14 incorporated into carbon dioxide or methane, I-129 forming iodine gas or methyl iodide, and tritium (H-3) incorporated into hydrogen gas or water vapour.	Gas Status Report, Section 2.3.
2.4.2.4	Radiolysis (wasteform)	Free hydrogen and oxygen gas generated from radiolysis in the wasteform can affect the degradation of the wasteform and the release of contaminants (eg tritium (H-3) incorporated into hydrogen gas).	Gas Status Report, Section 2.2.

NEA FEP Number	Name	Description	RWM Report and Section
2.4.3	Solid-mediated release	The release of radiotoxic and chemotoxic species in solid phase. This might result from processes such as the glacial/fluvial erosion of the repository or volcanic activity affecting the repository.	Geosphere Status Report, Sections 2.1 and 4.1 demonstrate that these FEPs do not apply to the UK GDF.
2.4.4	Human-action-mediated release	The release of radiotoxic and chemotoxic species as a direct result of human actions, eg due to drilling into or excavation of the wasteform.	Environmental Safety Case, Section 10.2.3.
2.5	Contaminant Transport (waste package)	The processes that directly affect the migration of contaminant through the waste package once they have been released from the wasteform. “Contaminant Transport” is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
2.5.1	Transport pathways (waste package)	The possible transport pathways for contaminants through the waste package once they have been released from the wasteform. Liquid-mediated transport processes could include advection, convection, dispersion, molecular or matrix diffusion, or multiphase transport. Gas-mediated processes and solid-mediated transport processes should also be considered.	These FEPs are covered at the Engineered Barrier System level.
2.5.2	Water-mediated transport (waste package)	FEPs related to transport of radiotoxic and chemotoxic species from waste packages in water in the aqueous phase.	See individual FEPs below
2.5.2.1	Advection (waste package)	Advection is a process in which dissolved species are transported by the flow of the water through the waste package. The rate of advection will vary depending on hydraulic conditions in the repository and the integrity of the waste package.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.10.

NEA FEP Number	Name	Description	RWM Report and Section
2.5.2.2	Dispersion (waste package)	Dispersion is the spread in the spatial distribution of contaminants with time because of differential rates of advective or convective transport through the waste package.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.10.
2.5.2.3	Molecular diffusion (waste package)	Molecular diffusion of radiotoxic and chemotoxic species through the waste package. Diffusive transport is driven by thermal, concentration, or chemical potential gradients and can be in any direction relative to any advective water flow.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.10.
2.5.2.4	Dissolution, precipitation, and mineralisation (waste package)	The dissolution, precipitation and crystallisation of radiotoxic and chemotoxic species in waste packages under repository conditions. Dissolution is the process by which constituents of a solid dissolve into solution. Precipitation occurs when chemical species in solution react to produce a solid that does not remain in solution. Mineralisation is the process of producing pure crystals of an element, molecule or mineral from a fluid or solution undergoing a cooling process.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.6.
2.5.2.5	Speciation and solubility (waste package)	Chemical speciation and solubility of radiotoxic and chemotoxic species in waste packages under repository conditions. Speciation and solubility are affected by factors such as temperature, pressure, pH and redox conditions. Different species of the same element may have different solubilities in a particular solution.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.2 (speciation) and 2.6 (solubility).

NEA FEP Number	Name	Description	RWM Report and Section
2.5.2.6	Sorption and desorption (waste package)	Sorption/desorption processes affecting the migration of radiotoxic and chemotoxic species through the waste packages under repository conditions. Sorption describes the physico-chemical interaction of dissolved species with a solid phase. Desorption is the opposite effect.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.5.
2.5.2.7	Complexation (waste package)	The impact of complexing agents on the transport of radiotoxic and chemotoxic species through waste packages under repository conditions. Such agents can be in the waste and/or waste package and other repository materials (eg as additives to cements and grouts).	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.3.
2.5.2.8	Colloid transport (waste package)	The transport of colloids and interaction of radiotoxic and chemotoxic species with colloids migrating through waste packages under repository conditions. Colloids may influence contaminant transport in a variety of ways: retarding transport by sorption of aqueous radionuclide species and subsequent filtration; or, enhancing transport by sorption and transport with flowing groundwater. Sources can include materials in the waste package itself (eg cementitious materials, organic wastes) and inflowing water.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.7.
2.5.3	Gas-mediated transport (waste package)	Transport of radiotoxic and chemotoxic species in gas or vapour phase or as fine particulate or aerosol in gas or vapour through the waste packages.	Gas Status Report, Section 3.2.
3	**REPOSITORY FACTORS**	**FEPs related to the repository (including the excavation damaged and disturbed zones but excluding the waste packages (see FEP 2: Waste Package Factors)).**	

NEA FEP Number	Name	Description	RWM Report and Section
3.1	Repository Characteristics and Properties	Features and properties of the repository at the time of closure (including the excavation damaged and disturbed zones but excluding waste packages). "Repository Characteristics and Properties" is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
3.1.1	Design	The design and layout of the repository and its various engineered features and associated seals at the time of repository closure.	Generic Disposal Facility Design sets out the design intent. However, the initial state will be substantiated by evidence and data gathered during operations.
3.1.2	Buffer/backfill	The physical, chemical and biological characteristics of the buffer and/or backfill at the time of waste emplacement in the repository.	Not fully developed in the generic DSSC. However, high-level information is provided in the Disposal System Specification – Part B (Technical Requirements).
3.1.3	Room/tunnel seals	The physical, chemical and biological characteristics of the seals in the waste emplacement rooms/tunnel at the time of sealing.	Not fully developed in the generic DSSC. However, high-level information is provided in the Disposal System Specification – Part B (Technical Requirements).
3.1.4	Shaft/ramp seals	The physical, chemical and biological characteristics of the shaft/ramp seals at the time of sealing.	Not fully developed in the generic DSSC. However, high-level information is provided in the Disposal System Specification – Part B (Technical Requirements).
3.1.5	Other engineered features	The physical, chemical and biological characteristics of the engineered features (other than packages, buffer/backfill, and seals) at the time of waste emplacement in the repository. Such features can include rock bolts, shotcrete, tunnel liners, silo walls, any services and equipment not removed before closure.	Not fully developed in the generic DSSC. However, high-level information is provided in the Disposal System Specification – Part B (Technical Requirements).

NEA FEP Number	Name	Description	RWM Report and Section
3.1.6	Excavation damaged and disturbed zones	The zone of rock around caverns, tunnels, shafts or other underground openings that may be mechanically disturbed during excavation. The extent of damage will decrease within increasing distance from the excavation and there will be transition from the excavation damaged zone to the excavation disturbed zone to the undisturbed host rock.	Geosphere Status Report, Section 6.3.
3.2	Repository Processes	Processes within the repository (including the excavation damaged and disturbed zones but excluding waste packages). The primary focus is on processes occurring after repository closure but some consideration is required of processes pre-closure. "Repository Processes" is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
3.2.1	Thermal processes (repository)	FEPs related to the thermal processes that affect the seals and other engineered repository features. This includes the effects of heat on seals and repository components from the waste packages and surrounding geology.	See individual FEPs below.
3.2.1.1	Thermal conduction and convection	Heat transfer due to gradients in temperature caused by heat conduction or convective flow - the overall thermal evolution of the repository with time.	Engineered Barrier System Status Report, Section 3.5.
3.2.1.2	Impact of thermal processes on other processes (repository)	Thermal processes coupled with hydraulic, mechanical and chemical processes, as well as biological and radiological processes. The behaviour of any buffer/backfill and the achievement of its safety functions can depend on the time and rate at which these processes occur.	Engineered Barrier System Status Report, Section 3.5.

NEA FEP Number	Name	Description	RWM Report and Section
3.2.2	Hydraulic processes (repository)	FEPs related to the hydraulic/hydrogeological processes that affect the seals and other engineered repository features, and the overall hydraulic/hydrogeological evolution of repository with time. This includes the effects of hydraulic/hydrogeological influences on the repository components by the waste packages and surrounding geology.	See individual FEPs below.
3.2.2.1	Resaturation/desaturation (repository)	The establishment of unsaturated conditions near the repository during the excavation and operation phases, and their return to saturated conditions. The timing of desaturation/resaturation will be affected by a variety of factors, including the characteristics of the host rock, the performance of the repository seals, and the evolution of pressure and temperature in the repository.	Engineered Barrier System Status Report, Section 3.7.
3.2.2.2	Piping/ hydraulic erosion	The hydraulic erosion of the buffer or backfill. Water may flow into the repository, eg through intersecting hydraulically active fractures. If the rate of inflow exceeds the rate of uptake by the buffer/backfill, then active flow channels or 'pipes' may develop in the buffer/backfill. Continuing flow through these pipes could result in progressive erosion of the buffer which, over time, may result in a reduction in the density of the buffer/backfill that could compromise its barrier functions.	Engineered Barrier System Status Report, Section 3.9.
3.2.2.3	Impact of hydraulic processes on other processes (repository)	Hydraulic processes coupled with thermal, mechanical and chemical processes, as well as biological and radiological processes. The behaviour of the seals and the achievement of their safety functions will depend on the time and rate at which these processes occur.	Engineered Barrier System Status Report, Section 3.11 (Seals).

NEA FEP Number	Name	Description	RWM Report and Section
3.2.3	Mechanical processes (repository)	FEPs related to the mechanical processes that affect the seals and other engineered repository features, and the overall mechanical evolution of repository with time. This includes the effects of hydraulic and mechanical loads imposed on repository components by the waste packages and surrounding geology.	See individual FEPs below.
3.2.3.1	Material volume changes (repository)	The effects of buffer and backfill swelling, as well as volume changes in other repository materials (eg the shrinkage/expansion of concrete, the corrosion of rock bolts).	Engineered Barrier System Status Report, Section 3.9 (Bentonite) and 3.10 (Cement).
3.2.3.2	Creep	The plastic movement of buffer and backfill material under an imposed load. The buffer and backfill materials can creep or move as a result of imposed loads such as the weight of the waste packages or lithostatic pressure from the host rock.	Engineered Barrier System Status Report, Section 3.9.
3.2.3.3	Collapse of openings	The collapse of tunnels and boreholes, including cave-ins, roof settling, and rock bursts. Potential effects include damage to the waste packages, buffer, backfill and other seals, and changes to water flow conditions in the repository and surrounding geosphere.	Geosphere Status Report, Section 6.3.
3.2.3.4	Gas explosion (repository)	Some gases produced from the corrosion and degradation of waste packages and engineered repository features might be flammable or might form an explosive mixture; for instance, hydrogen and methane could mix with oxygen and explode to damage the repository and its seals. A gas explosion can only occur if a flammable gas mixture forms and there is a source of ignition or the gas mixture has the capability to auto-ignite.	Gas Status report, Section 5.1 provides emphasis on the operational phase, during which ignition sources plausibly may exist.

NEA FEP Number	Name	Description	RWM Report and Section
3.2.3.5	Impact of mechanical process on other processes (repository)	FEPs relating to mechanical processes coupled with other processes. Couplings of mechanical processes with thermal, hydraulic and chemical processes, as well as biological and radiological processes, will affect the evolution of the repository. For example, the swelling of bentonite sealing can limit the resaturation of the repository.	Engineered Barrier System Status Report, Sections 4.1 – 4.3 presents an overview of coupled processes.
3.2.4	Chemical processes (repository)	FEPs related to the chemical/geochemical processes that affect the seals and other engineered repository features, and the overall chemical/geochemical evolution of the repository with time. This includes the effects of chemical/geochemical influences on repository components by the waste packages and surrounding geology.	See individual FEPs below.
3.2.4.1	pH conditions (repository)	The temporal evolution of pH within the repository. Repository water composition, including its pH, is important in determining the solubility of certain elements. It depends on a number of factors, including the pH of the water in the host geology, the water flow rate through the repository and the characteristics of the repository seals and other engineered features.	Engineered Barrier System Status Report, Sections 3.9 (bentonite) and 3.10 (cement).
3.2.4.2	Redox conditions (repository)	The temporal evolution of the repository's Eh depends on a number of factors, including the Eh of the water in the host geology, the water flow rate through the repository and the consumption rate of any available oxygen.	Engineered Barrier System Status Report, Sections 3.9 (bentonite) and 3.10 (cement).

NEA FEP Number	Name	Description	RWM Report and Section
3.2.4.3	Perturbing species' concentrations (repository)	The presence of certain species, such as chloride, sulphate and potassium, can affect the evolution of the repository and its seals, for example through promoting the corrosion of metals (high chloride concentrations), the degradation of cement (high sulphate concentrations) and the illitisation of bentonite (high potassium concentrations). Sources of such species can include the wasteforms and inflowing water.	Engineered Barrier System Status Report, Sections 3.9 (bentonite) and 3.10 (cement).
3.2.4.4	Corrosion (repository)	Corrosion of repository metals (eg rock bolts) can be generalised (or uniform), local, or galvanic. All metals are subject to uniform corrosion at rates that are dependent on the chemical and physical (and possibly biological) environment, while localised formation of cavities in a metal surface is caused by non-uniform corrosion. Galvanic corrosion occurs when two different metals are in electric contact.	Engineered Barrier System Status Report, Section 3.14.
3.2.4.5	Dissolution (repository)	Dissolution processes, including their evolution in time, affecting repository materials. Changes to the chemical environment of the repository (eg changes to pH and Eh) could lead to evolution of the dissolution rate of repository materials (eg dissolution of cements).	Engineered Barrier System Status Report, Sections 3.9 (bentonite) and 3.10 (cement).
3.2.4.6	Mineralisation (repository)	Mineralisation in repository materials, including leaching, carbonation, illitisation, and chloride and sulphate attack. If fractures in the repository walls are mineralised, the accessibility of the rock matrix may be reduced.	Engineered Barrier System Status Report, Section 3.10 (cement).

NEA FEP Number	Name	Description	RWM Report and Section
3.2.4.7	Precipitation reactions (repository)	Precipitation processes, including their evolution in time, affecting repository materials. Precipitation can occur in the buffer and backfill or elsewhere in the repository if there is an abrupt change in the chemical environment	Engineered Barrier System Status Report, Section 3.10 (cement).
3.2.4.8	Chelating agent effects (repository)	Chelating agents in the repository can form very stable species, a factor that can increase significantly the solubilities of certain elements. Sources can include organic wastes and inflowing water.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.3.
3.2.4.9	Colloid formation (repository)	Colloids are very fine particles that can affect the transport of contaminants. Particles of clay minerals, silica, iron oxy-hydroxides, other minerals, organic and bio-organic macromolecules may form the colloid phase. Sources can include materials in the waste package (eg cementitious materials, organic wastes), repository materials (eg bentonite and cementitious materials) and inflowing water.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.7.
3.2.4.10	Chemical concentration gradients (repository)	Chemical concentration gradients in the repository could be caused by heterogeneities in the spatial distribution of waste packages and repository materials. The formation of chemical concentration gradients may lead to the dissolution and precipitation of chemical compounds with subsequent opening or plugging of flow paths.	Not considered in the generic DSSC.
3.2.4.11	Impact of chemical processes on other processes (repository)	Chemical processes coupled with other processes. Couplings of chemical processes with thermal, hydraulic and mechanical processes, as well as biological and radiological processes, will affect the evolution of the repository. For example, chemical precipitation of minerals can limit the flow of water through repository seals.	Engineered Barrier System Status Report, Sections 4.1 – 4.3 presents an overview of coupled processes.

NEA FEP Number	Name	Description	RWM Report and Section
3.2.5	Biological processes (repository)	FEPs related to the biological/biochemical processes that affect the seals and other engineered repository features, and the overall biological/biochemical evolution of the repository with time. This includes the effects of biological/biochemical influences on repository components by the waste packages and surrounding geology.	See individual FEPs below.
3.2.5.1	Microbial growth and poisoning (repository)	A wide range of microbes can be introduced into the repository during its construction and operation. Growth requires the presence of suitable nutrients, such as cellulosic wastes, simple organic molecules containing oxygen, nitrogen and/or sulphur, and small amounts of putrescible materials. Poisoning of microbial processes can occur but extremophiles can survive and thrive outside the range at which most microbes flourish (see FEP 2.3.5.2).	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.8.
3.2.5.2	Microbially/biologically mediated processes (repository)	Microbial processes can lead to the formation of acidic and oxidising species that can participate in corrosion of the metals and promotion of reducing conditions in the repository. Bacteria may also result in the conversion of gases (eg carbon dioxide and hydrogen into methane – methanogenesis), and restrict the movement of water through the generation of biofilms of repository surfaces.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.8.

NEA FEP Number	Name	Description	RWM Report and Section
3.2.5.3	Impact of biological processes on other processes (repository)	FEPs relating to biological processes coupled with other processes. Couplings of biological processes with thermal, hydraulic, mechanical and chemical processes, as well as radiological processes, will affect the evolution of the repository. For example, methanogenesis will reduce repository gas pressures which can affect repository resaturation.	Engineered Barrier System Status Report, Sections 4.1 – 4.3 present an overview of coupled processes.
3.2.6	Radiological processes (repository)	FEPs related to the effects of radiation emitted from the wastes on the seals and other repository engineered features.	See individual FEPs below.
3.2.6.1	Radioactive decay and ingrowth (repository)	Radioactive decay and ingrowth will affect any radionuclides released from the waste packages into the repository.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.1.
3.2.6.2	Radiolysis (repository)	Radiolysis of any water in the repository environment immediately adjacent to the waste packages (especially for High-Level Waste and spent fuel) can produce species such as free hydrogen and oxygen which can impact the chemical conditions in the repository (eg the redox potential) (see FEP 3.2.7.4).	Engineered Barrier System Status Report, Section 3.6.
3.2.6.3	Radiation attenuation (repository)	Radiation attenuation in the buffer and backfill adjacent to the waste package. The rate of radiation attenuation is controlled in part by the design of the waste package. Radiation from the waste package can affect heat transfer, thermal expansion, resaturation and water radiolysis in the buffer and backfill.	Engineered Barrier System Status Report, Section 3.6.
3.2.6.4	Radiation damage (repository)	Radiation damage from fission and alpha decay in the buffer and/or backfill adjacent to the waste package. This could detrimentally affect the properties of the sealing materials.	Engineered Barrier System Status Report, Section 3.6.

NEA FEP Number	Name	Description	RWM Report and Section
3.2.6.5	Criticality	The possibility and effects of spontaneous nuclear fission chain reactions within the repository. Criticality requires a sufficient concentration and localised mass (critical mass) of fissile isotopes (eg U-235, Pu-239) and also presence of neutron moderating materials in a suitable geometry; a chain reaction is liable to be damped by the presence of neutron absorbing isotopes (eg Pu-240).	Criticality Safety Status Report, Sections 5 (likelihood), 6 (consequences) and 7 (impact on post-closure safety).
3.2.6.6	Impact of radiological processes on other processes (repository)	FEPs relating to radiological processes coupled with other processes. For example, the effects of radiolysis of the water in the sealing materials could potentially affect the water chemistry, ie the effective electrochemical potential (Eh) and pH, and result in chemical changes to the bentonite materials in the sealing materials.	Engineered Barrier System Status Report, Sections 4.1 – 4.3 presents an overview of coupled processes.
3.2.7	Gas generation (repository)	FEPs within and around the seals and engineered repository features resulting in the generation of gases and their subsequent effects on the repository system (excludes gas generation from waste packages – see FEP 2.3.7).	See individual FEPs below.
3.2.7.1	Metal corrosion (repository)	Metals utilised in the repository construction (eg rock bolts, ventilation ducts and rails) that are not removed at closure will corrode resulting in hydrogen gas generation if the conditions are anaerobic.	Gas Status Report, Section 2.2 (processes) and 6.1 (implications).
3.2.7.2	Organic degradation (repository)	Organic materials and compounds contained within the repository (excluding any organics contained in the waste packages) that are prone to chemical and biological degradation. Might include oils not removed at the time of repository closure.	Gas Status Report, Section 2.2 (processes) and 6.1 (implications).

NEA FEP Number	Name	Description	RWM Report and Section
3.2.7.3	Radon production (repository)	The production of radon gas in the repository from the decay naturally occurring Ra-226.	Gas Status Report, Section 2.3 (processes) and 6.1 (implications).
3.2.7.4	Radiolysis (repository)	Radiolysis of any water in the repository environment immediately adjacent to the waste packages (especially for High-Level Waste and spent fuel) can produce gaseous species such as free hydrogen and oxygen which can impact the chemical conditions in the repository (eg the redox potential) (see FEP 3.2.6.2).	Gas Status Report, Section 2.2 (processes) and 6.1 (implications).
3.2.7.5	Volatilisation (repository)	Volatile compounds can be formed due to chemical and biochemical processes occurring in the repository. The rate of volatilisation is controlled by changes in pressure, temperature and concentration in the repository.	Gas Status Report, Section 2.2 (processes) and 6.1 (implications).
3.2.7.6	Gas dissolution (repository)	Gases can dissolve in repository water and be transported out of the repository as dissolved species. Dissolution is controlled by changes in pressure, temperature and concentration in the repository.	Gas Status Report, Section 3.2 (processes) and 6.2 (implications).
3.2.7.7	Gas-induced dilation (repository)	Under certain conditions, the repository gas pressure might become sufficiently high to cause physical damage to the repository seals and allow the movement of gas as a discrete phase within stress- or pressure-induced microscopic porosity in the seals.	Gas Status Report, Section 6.2.
3.2.7.8	Impact of gas generation on other processes (repository)	Gas generation may influence other processes. For example, when a gas phase is formed in a water saturated repository system, water will be expelled from it. If gas generation from a repository is such that substantial pressure build-up occurs, intermittent gas flow can occur.	Gas Status Report, Section 3.5.

NEA FEP Number	Name	Description	RWM Report and Section
3.3	Contaminant Transport (repository)	The processes that directly affect the migration of radionuclides in the repository once they have been released from the waste packages. "Contaminant Transport (repository)" is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
3.3.1	Transport pathways (repository)	Possible contaminant transport pathways from the waste packages through the repository and its various features into the surrounding geosphere.	This Post-closure Safety Assessment, Sections 5.1 and 5.4
3.3.2	Water-mediated transport (repository)	FEPs related to transport of radiotoxic and chemotoxic species in repository water in the aqueous phase.	See individual FEPs below.
3.3.2.1	Advection (repository)	Advection is a process in which dissolved species are transported by the flow of water through the repository. The rate of advection will vary depending on hydraulic conditions in the repository and geosphere and the integrity of the repository seals.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.10.
3.3.2.2	Dispersion (repository)	Variations in water velocity and pathways cause dispersion, ie the spatial spreading of contaminants from advective transport. Dispersion can occur in the direction of flow (longitudinal dispersion) and perpendicular to the direction of flow (transverse dispersion).	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.10.
3.3.2.3	Molecular diffusion (repository)	Molecular diffusion can occur in moving or stagnant repository water. Diffusive transport is driven by thermal, concentration, or chemical potential gradients and can be in any direction relative to any advective water flow. Diffusion can be the most important transport mechanisms in situations where repository water flow is very slow.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.10.

NEA FEP Number	Name	Description	RWM Report and Section
3.3.2.4	Dissolution, precipitation, and mineralisation (repository)	The dissolution, precipitation and crystallisation of radiotoxic and chemotoxic species in the repository under prevailing repository conditions. Dissolution is the process by which constituents of a solid dissolve into solution. Precipitation occurs when chemical species in solution react to produce a solid that does not remain in solution. Mineralisation is the process of producing pure crystals of an element, molecule or mineral from a fluid or solution undergoing a cooling process.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.6.
3.3.2.5	Speciation and solubility (repository)	Chemical speciation and solubility of radiotoxic and chemotoxic species in the repository under prevailing repository conditions. Speciation and solubility are affected by factors such as temperature, pressure, pH and redox conditions.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.2 (speciation) and 2.6 (solubility).
3.3.2.6	Sorption and desorption (repository)	Sorption/desorption processes affecting the migration of radiotoxic and chemotoxic species through the repository under prevailing repository conditions. Sorption describes the physico-chemical interaction of dissolved species with a solid phase. Desorption is the opposite effect.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.5.
3.3.2.7	Complexation (repository)	The impact of complexing agents on the transport of radiotoxic and chemotoxic species through the repository under prevailing repository conditions. Such agents can be in the waste package and other repository materials (eg as additives to cements and grouts).	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.3.

NEA FEP Number	Name	Description	RWM Report and Section
3.3.2.8	Colloid transport (repository)	The transport of colloids and interaction of radiotoxic and chemotoxic species with colloids migrating through the repository under prevailing repository conditions. Colloids may influence contaminant transport in a variety of ways: retarding transport by sorption of aqueous radionuclide species and subsequent filtration; or, enhancing transport by sorption and transport with flowing water. Sources can include materials in the waste package (eg organic wastes), the repository (eg cementitious materials) and inflowing water.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.7.
3.3.3	Gas-mediated transport (repository)	Transport of radiotoxic and chemotoxic species in gas or vapour phase or as fine particulate or aerosol in gas or vapour through the repository.	Gas Status Report, Sections 3.2 (processes) and 6.2 (implications).
3.3.4	Solid-mediated transport (repository)	Transport of radiotoxic and chemotoxic species in solid phase from the repository. This might result from processes such as the glacial/fluvial erosion of the repository or volcanic activity affecting the repository.	Geosphere Status Report, Sections 2.1 and 4.1 demonstrate that these FEPs do not apply to the UK GDF.
3.3.5	Human-action-mediated transport (repository)	Transport of radiotoxic and chemotoxic species from the repository as a direct result of human actions, eg due to drilling into or excavation of the repository.	Environmental Safety Case, Section 10.2.3.
4	**GEOSPHERE FACTORS**	**FEPs related to the geosphere.**	
4.1	Geosphere Characteristics and Properties	The features and properties within the geosphere prior to repository construction and waste emplacement. “Geosphere Characteristics and Properties” is a sub- category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.

NEA FEP Number	Name	Description	RWM Report and Section
4.1.1	Stratigraphy	The succession of different rock types that form the geosphere (other than the host rock – see FEP 4.1.2). Typically rocks are divided into geological units with similar properties and characteristics. Relevant properties and characteristics of units include: spatial extent, thermal and hydraulic conductivity, fracture frequency and connectivity, compressive and shear strength, porosity, tortuosity, thickness, structure, groundwater composition and salinity, mineral composition and pore water pressure. The inhomogeneity and uncertainty of these properties is also part of their characterisation.	Not addressed in the generic DSSC. However illustrative environments are provided for use in the PCSA in the Geosphere Status Report, Section 5.
4.1.2	Host rock lithology	The properties and characteristics of the rock in which the repository is sited (excluding the rock that may be mechanically disturbed by the excavation).	Not addressed in the generic DSSC. However illustrative environments are provided for use in the PCSA in the Geosphere Status Report, Section 5.
4.1.3	Large-scale discontinuities	The properties and characteristics of discontinuities in and between the host rock and geological units, including faults, shear zones, intrusive dykes and interfaces between different rock types.	Not addressed in the generic DSSC. However illustrative environments are provided for use in the PCSA in the Geosphere Status Report, Section 5.
4.1.4	Geological resources	Natural resources within the geosphere, particularly those that might encourage investigation or excavation at or near the repository site (eg oil, gas, solid minerals, water and geothermal resources).	Geosphere Status Report, Section 2.1.
4.1.5	Undetected features	Natural or man-made features within the geology that may not be detected during the site investigation (eg fracture zones, faults, brine pockets, old mine workings and boreholes).	Not considered in the generic DSSC.

NEA FEP Number	Name	Description	RWM Report and Section
4.1.6	Current geothermal state	The thermal processes that affect the host rock and other rock units prior to construction of the repository and the resulting thermal conditions. Consideration needs to be given to the sources of geological heat, the distribution of heat by conduction and transport (convection) in fluids, and the resulting thermal field or gradient.	Not addressed in the generic DSSC. However, illustrative environments are provided for use in the PCSA in the Geosphere Status Report, Section 5.
4.1.7	Current hydraulic state	The hydraulic and hydrogeological processes that affect the host rock and other rock units prior to construction of the repository and the resulting hydraulic conditions. Consideration needs to be given to movement of water through the geological units and the factors that control the movement including recharge and discharge zones, groundwater flow systems, density effects due to salinity gradients or temperature gradients.	Not addressed in the generic DSSC. However, illustrative environments are provided for use in the PCSA in the Geosphere Status Report, Section 5.
4.1.8	Current stress state	The mechanical processes that affect the host rock and other rock units prior to construction of the repository and the resulting stress conditions. Consideration needs to be given to loading and uploading events such as ice sheet advance and retreat that will have affected the site.	Not addressed in the generic DSSC. However, illustrative environments are provided for use in the PCSA in the Geosphere Status Report, Section 5.
4.1.9	Current geochemical state	The chemical and geochemical processes that affect the host rock and other rock units prior to construction of the repository and the resulting geochemical conditions. Consideration needs to be given to factors such as speciation, solubility, complexants, redox conditions, rock mineral composition and weathering processes, salinity and chemical gradients.	Not addressed in the generic DSSC. However, illustrative environments are provided for use in the PCSA in the Geosphere Status Report, Section 5.

NEA FEP Number	Name	Description	RWM Report and Section
4.1.10	Current biological state	The biological and biochemical processes that affect the host rock and other rock units prior to construction of the repository and the resulting biological conditions. Information should be provided on current microbe populations.	Not addressed in the generic DSSC. However, illustrative environments are provided for use in the PCSA in the Geosphere Status Report, Section 5.
4.1.11	Current gas state	Natural gas sources within the geosphere and their effect on the geosphere, including the transport of bulk gases. Gas movement in the geosphere will be determined by many factors including the rate of production, gas permeability and solubility, and the hydrostatic pressure conditions.	Not addressed in the generic DSSC. However, illustrative environments are provided for use in the PCSA in the Geosphere Status Report, Section 5.
4.2	Geosphere Processes	The processes in pre-emplacement state and as modified by the presence of the repository and other long-term changes. “Geosphere Processes” is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
4.2.1	Thermal processes (geosphere)	FEPs related to the thermal processes that affect the host rock and other rock units, and the overall evolution of conditions with time. This includes the effects of changes in condition, eg temperature, due to the excavation, construction and long-term presence of the repository.	See individual FEPs below.
4.2.1.1	Thermal effects of repository (geosphere)	Thermal energy generated from the wasteform will be transferred through the waste package and repository and into the geosphere. Some heat can also be transferred from the repository backfill (eg curing of cement) to the geosphere.	Geosphere Status Report, Section 6.1.
4.2.1.2	Thermal effects of climate change (geosphere)	The primary cause of climate change is likely to be glacial/inter-glacial cycling that might result in ice sheet advance/retreat over the site which will affect the thermal profile in the geosphere.	Geosphere Status Report, Section 4.3.

NEA FEP Number	Name	Description	RWM Report and Section
4.2.1.3	Other processes affecting future thermal conditions in geosphere	Processes other than those related to the repository and climate change that might affect the thermal evolution of the host rock and other rock units. Examples include volcanic and magmatic activity (see FEP 1.2.5) and hydrothermal activity (see FEP 1.2.7).	Geosphere Status Report, Section 4.1.
4.2.2	Hydraulic processes (geosphere)	FEPs related to the hydraulic and hydrogeological processes that affect the host rock and other rock units, and the overall evolution of conditions with time. This includes the effects of changes in condition, eg hydraulic head, due to the excavation, construction and long-term presence of the repository.	See individual FEPs below.
4.2.2.1	Hydraulic effects of repository (geosphere)	The short and long-term hydraulic effects of the repository on the geosphere. Effects include the potential dewatering of the rock immediately surrounding the repository during the operational phase and the modification of groundwater flow directions.	Geosphere Status Report, Section 6.2.
4.2.2.2	Hydraulic effects of climate change (geosphere)	The primary cause of climate change is likely to be glacial/inter-glacial cycling that might result in ice sheet advance/retreat over the site. This will impact on groundwater recharge and hydraulic gradients.	Geosphere Status Report, Section 4.3.
4.2.2.3	Other processes affecting future hydraulic conditions in the geosphere	Processes other than those related to the repository and climate change that might affect the hydraulic evolution of the host rock and other rock units. Examples include seismicity (see FEP 1.2.4), regional erosion and sedimentation (see FEP 1.2.7) and water management (see FEP 1.4.9). Such events may change flow pathways, permeabilities, head distributions.	Geosphere Status Report, Sections 4.1 (seismicity) and 4.2 (uplift, subsidence and erosion).

NEA FEP Number	Name	Description	RWM Report and Section
4.2.3	Mechanical processes (geosphere)	FEPs related to the mechanical processes that affect the host rock and other rock units, and the overall evolution of conditions with time. This includes the effects of changes in condition, eg rock stress, due to the excavation, construction and long-term presence of the repository	See individual FEPs below.
4.2.3.1	Mechanical effects of repository (geosphere)	The effects on in situ stresses that the presence of the repository has on the host rock and other rock units.	Geosphere Status Report, Section 6.3.
4.2.3.2	Mechanical effects of climate change (geosphere)	The primary cause of climate change is likely to be glacial/inter-glacial cycling that might result in ice sheet advance/retreat over the site which will affect the in situ stresses in the geosphere.	Geosphere Status Report, Section 4.3.
4.2.3.3	Other processes affecting future stress conditions in geosphere	Processes other than those related to the repository and climate change that might affect the evolution of stress conditions in the host rock and other rock units. Examples include tectonic movement (see FEP 1.2.1), orogeny (see FEP 1.2.2), deformation (see FEP 1.2.3), seismicity (see FEP 1.2.4), regional erosion and sedimentation (see FEP 1.2.7), drilling activities (see FEP 1.4.5) and mining and other underground activities (see FEP 1.4.6).	Geosphere Status Report, Sections 4.1 (seismicity) and 4.2 (uplift, subsidence and erosion).
4.2.4	Geochemical processes (geosphere)	FEPs related to the chemical and geochemical processes that affect the host rock and other rock units, and the overall evolution of conditions with time. This includes the effects of changes in condition, eg Eh, pH, due to the excavation, construction and long-term presence of the repository.	See individual FEPs below.

NEA FEP Number	Name	Description	RWM Report and Section
4.2.4.1	Geochemical effects of repository (geosphere)	Geochemical effects resulting from the materials used in the repository for waste encapsulation, backfilling and structural purposes. These effects may impact the performance of the geosphere by potentially changing factors such as sorption, groundwater flow, and matrix diffusion behaviour.	Geosphere Status Report, Section 6.4.
4.2.4.2	Geochemical effects of climate change (geosphere)	The primary cause of climate change is likely to be glacial/inter-glacial cycling that might result in ice sheet advance/retreat over the site. This will impact on groundwater recharge which will introduce meltwater with different compositional and thermal properties into the geosphere and modify the geochemical conditions, at least in the upper parts of the geosphere.	Geosphere Status Report, Section 4.3.
4.2.4.3	Other processes affecting future geochemical conditions in geosphere	Processes other than those related to the repository and climate change that might affect the geochemical evolution of the host rock and other rock units. Examples include hydrothermal activity (see FEP 1.2.7), drilling activities (see FEP 1.4.5) and mining and other underground activities (see FEP 1.4.6).	Not addressed in the generic DSSC.
4.2.5	Biological processes (geosphere)	FEPs related to the biological and biochemical processes that affect the host rock and other rock units, and the overall evolution of conditions with time. This includes the effects of changes in condition, eg microbe populations, due to the excavation, construction and long-term presence of the repository.	See individual FEPs below.

NEA FEP Number	Name	Description	RWM Report and Section
4.2.5.1	Biological effects of repository (geosphere)	Microbes can be natural to the geosphere, or can be introduced with repository materials. The presence of the repository may change the conditions in the geosphere around the repository, which will affect the microbial species in the geosphere around the repository (eg provide a source of nutrients).	Geosphere Status Report, Section 6.5.
4.2.5.2	Biological effects of climate change (geosphere)	The primary cause of climate change is likely to be glacial/inter-glacial cycling that might result in ice sheet advance/retreat over the site. This will impact on thermal, hydraulic and geochemical conditions in the geosphere which in turn will affect the microbial species.	Geosphere Status Report, Section 4.3.
4.2.5.3	Other processes affecting future biological conditions in geosphere	Processes other than those related to the repository and climate change that might affect the biological evolution of the host rock and other rock units. Examples include hydrothermal activity (see FEP 1.2.7), drilling activities (see FEP 1.4.5) and mining and other underground activities (see FEP 1.4.6).	Not addressed in the generic DSSC.
4.2.6	Radiological processes (geosphere)	Any possible effects of radiation emitted from the wastes on the host rock immediately surrounding repository, such as radiolysis and radiation attenuation.	Engineered barrier System Status Report, Section 3.6 addresses this FEP in relation to the EBS. On the basis of no EBS effect it is not considered relevant to the geosphere.
4.2.7	Gas processes (geosphere)	FEPs related to natural gas sources and production of gas within the geosphere and also the effect of natural and repository produced gas on the geosphere, including the transport of bulk gases and the overall evolution of conditions with time.	See individual FEPs below.

NEA FEP Number	Name	Description	RWM Report and Section
4.2.7.1	Gas sources (geosphere)	Sources of non-repository derived gases in the geosphere such as methane (derived from the degradation of organics in the rocks) and gases stored by humans.	Geosphere Status Report, Section 2.1.
4.2.7.2	Radon production (geosphere)	The production of radon gas in the geosphere from the decay of naturally occurring Ra-226.	Gas Status Report, Section 2.3 (processes) and 6.1 (implications).
4.2.7.3	Volatilisation (geosphere)	Volatile compounds can be formed due to chemical and biochemical processes occurring in the geosphere. The rate of volatilisation is controlled by changes in pressure, temperature and concentration in the geosphere.	Not addressed in the generic DSSC.
4.2.7.4	Gas dissolution (geosphere)	Gases can dissolve in groundwater and be transported through the geosphere as dissolved species. Dissolution is controlled by changes in pressure, temperature and concentration in the geosphere.	Gas Status Report, Section 3.2 (processes) and 6.3 (implications).
4.2.7.5	Gas-induced dilation (geosphere)	Under certain conditions, the repository gas pressure might become sufficiently high to cause physical damage to the host rock and allow the movement of gas as a discrete phase within stress- or pressure-induced microscopic porosity in the rock.	Gas Status Report, Section 6.3.
4.3	Contaminant Transport (geosphere)	The processes that directly affect the migration and/or release of radionuclides in the geosphere. “Contaminant Transport (geosphere)” is a sub-category in the International FEP List and is divided into individual FEPs	See individual FEPs below.
4.3.1	Transport pathways (geosphere)	The properties and characteristics of discontinuities and features within the host rock and other geological units that are expected to be the main paths for contaminant transport through the geosphere, as they may evolve both before and after repository closure.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 4.3; Gas Status Report, Section 6.3.

NEA FEP Number	Name	Description	RWM Report and Section
4.3.2	Water-mediated transport (geosphere)	FEPs related to transport of radiotoxic and chemotoxic species in groundwater and within the geosphere in the aqueous phase.	See individual FEPs below.
4.3.2.1	Advection (geosphere)	Advection is a process in which dissolved species are transported by the flow of water through the repository. The rate of advection will vary depending on hydraulic conditions in the geosphere and repository.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.10 (process) and 4.3 (implications).
4.3.2.2	Dispersion (geosphere)	Variations in water velocity and pathways cause dispersion, ie the spatial spreading of contaminants from advective transport. Dispersion can occur in the direction of flow (longitudinal dispersion) and perpendicular to the direction of flow (transverse dispersion).	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.10 (process) and 4.3 (implications).
4.3.2.3	Molecular diffusion (geosphere)	Molecular diffusion can occur in moving or stagnant water. Diffusive transport is driven by thermal, concentration, or chemical potential gradients and can be in any direction relative to any advective groundwater flow. Diffusion can be the most important transport mechanisms in situations where groundwater flow in the geosphere is very slow.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.10 (process) and 4.3 (implications).
4.3.2.4	Matrix diffusion	This process occurs in a flowing fracture where contaminants may move laterally out of the fracture and into an intricate network of interconnected microfractures and micro-pores within the rock by molecular diffusion.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.11 (process) and 4.3 (implications).

NEA FEP Number	Name	Description	RWM Report and Section
4.3.2.5	Dissolution, precipitation, and mineralisation (geosphere)	The dissolution, precipitation and mineralisation of radiotoxic and chemotoxic species in the geosphere under prevailing geosphere conditions. Dissolution is the process by which constituents of a solid dissolve into solution. Precipitation occurs when chemical species in solution react to produce a solid that does not remain in solution. Mineralisation is the process of producing pure crystals of an element, molecule or mineral from a fluid or solution undergoing a cooling process.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.6 (process) and 4.3 (implications).
4.3.2.6	Speciation and solubility (geosphere)	Chemical speciation and solubility of radiotoxic and chemotoxic species in the geosphere under prevailing geosphere conditions. Speciation and solubility are affected by factors such as temperature, pressure, pH and redox conditions.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.2 and 2.6 (processes) and 4.3 (implications).
4.3.2.7	Sorption and desorption (geosphere)	Sorption/desorption processes affecting the migration of radiotoxic and chemotoxic species in the geosphere under prevailing geosphere conditions. Sorption describes the physico-chemical interaction of dissolved species with a solid phase. Desorption is the opposite effect.	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.5 (process) and 4.3 (implications).
4.3.2.8	Complexation (geosphere)	The impact of complexing agents on the transport of radiotoxic and chemotoxic species through the geosphere under prevailing geosphere conditions. Such agents can be in the waste package and other repository materials (eg as additives to cements and grouts).	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.3 (process) and 4.3 (implications).

NEA FEP Number	Name	Description	RWM Report and Section
4.3.2.9	Colloid transport (geosphere)	The transport of colloids and interaction of radiotoxic and chemotoxic species with colloids migrating through the geosphere under prevailing geosphere conditions. Colloids may influence contaminant transport in a variety of ways: retarding transport by sorption of aqueous radionuclide species and subsequent filtration; or, enhancing transport by sorption and transport with flowing groundwater. Sources can include materials in the waste package (eg organic wastes), the repository (eg cementitious materials) and the geosphere (eg naturally occurring organics).	Behaviour of Radionuclides and Non-Radiological Species in Groundwater Status Report, Section 2.7 (process) and 4.3 (implications).
4.3.3	Gas-mediated transport (geosphere)	Transport of radiotoxic and chemotoxic species in gas or vapour phase or as fine particulate or aerosol in gas or vapour through the geosphere.	Gas Status Report, Section 3.2 (process) and 6.3 (implications).
4.3.4	Solid-mediated transport (geosphere)	Transport of radiotoxic and chemotoxic species in solid phase in the geosphere, for example large-scale glacial/fluvial erosion and volcanic activity.	Geosphere Status Report, Sections 2.1 and 4.1 demonstrate that these FEPs do not apply to the UK GDF.
4.3.5	Human-action-mediated transport (geosphere)	Transport of radiotoxic and chemotoxic species in the geosphere as a direct result of human actions, eg due to drilling into or excavation of the geosphere.	Generic Environmental Safety Case, Section 10.2.3.
5	**BIOSPHERE FACTORS**	**FEPs related to the biosphere.**	
5.1	Surface Environment	The features and processes within the surface environment and their potential future evolution, including near-surface aquifers and unconsolidated sediments but excluding human activities and behaviour, see FEPs 1.4 and 5.2. “Surface Environment” is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.

NEA FEP Number	Name	Description	RWM Report and Section
5.1.1	Topography and morphology	The relief and shape of the surface environment and its potential evolution with time. Topography defines surface water flows, the location of groundwater recharge and discharge locations, and the magnitude of hydraulic heads that drive local and regional groundwater flows.	Biosphere Status Report, Section 3.4.
5.1.2	Biomes	A biome is a mixed community of plants and animals (a biotic community) occupying a major geographical area on a continental scale. Each biome is characterised by similarity of vegetation structure or physiognomy rather than by similarity of species composition, and is usually related to climate. Within a particular biome, the plants and animals are regarded as being well adapted to each other and to broadly similar environmental conditions, especially climate.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.1.3	Soil and sediment	FEPs related to the characteristics of the soils and sediments that overlie the rock of the geosphere and their potential evolution with time.	See individual FEPs below.
5.1.3.1	Surface soils	The soils and sediments that are at or near the terrestrial surface. The soil type, such as loam, sand, clay and organic, can be roughly characterised by parameters such as particle-size distribution and organic matter content. These will have different physical and chemical properties, different land management properties, and different contaminant transport properties. Microbial populations (or their absence) are an important component of soils and sediments.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.

NEA FEP Number	Name	Description	RWM Report and Section
5.1.3.2	Overburden	The unconsolidated rock, clay, sand and soils that overly the rock of the geosphere, but not including the surface soils. The overburden will change in time. These changes will be driven by natural weathering processes in the same way that soils evolve. Human activities such as dredging and excavation can also affect the overburden.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.1.3.3	Aquatic sediments	Aquatic sediments are found at the bottom of surface water bodies and are generally composed of fine-grained sand, clays, and organic material. They are subject to wave action and currents and can be eroded and reformed relatively easily.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.1.4	Near-surface aquifers and water-bearing features	Aquifers and water-bearing features within a few tens of metres of the land surface and their potential evolution with time.	Biosphere Status Report, Section 4.4 and 5.1.
5.1.5	Terrestrial surface water bodies	FEPs related to the characteristics of terrestrial surface water bodies and their potential evolution with time.	Biosphere Status Report, Sections 4.4 and 5.1.
5.1.5.1	Wetlands	Land areas where the water table is at or near the surface. Wetlands (including marshes, fens and peat bogs) may be underlain by, or lead to formation of, thick deposits of organic material (eg, peat) and may be discharge areas for deep groundwaters. Wetlands may also be drained to provide agricultural land and mined for peat which is then used as a fuel or soil supplement.	Biosphere Status Report Groundwater release to soil is considered in the terrestrial model (Section 5.1). Wetlands themselves are not addressed - due to focus on lowland agricultural systems in the generic phase.
5.1.5.2	Lakes and rivers	Surface water bodies that are large enough to persist for many years. Surface water bodies will evolve through a number of processes such as gradual infill, meandering and braiding. Climate change bringing about the evolution of surface water bodies should also be considered.	Biosphere Status Report, Sections 4.4 and 5.1.

NEA FEP Number	Name	Description	RWM Report and Section
5.1.5.3	Spring and discharge zones	Locations where the water table intersects the surface, allowing groundwaters to flow out onto the surface. Discharge zones are often low-lying areas such as at the margin or bottoms of lakes and wetlands (bogs and marshes). Springs may also be found at various elevations depending on factors such as the lithology and stratigraphy of the geosphere and the location of outcropping geological units.	Biosphere Status Report, Sections 4.4 and 5.1.
5.1.6	Coastal features	The characteristics of coasts and the near shore, and their potential evolution with time. Coastal features include headlands, bays, beaches, spits, cliffs and estuaries. The processes operating on these features, eg active erosion, deposition, longshore transport, determine the development of the coastal system.	Biosphere Status Report, Sections 4.4 and 5.1.
5.1.7	Marine features	The characteristics of seas and oceans, including the sea bed, and their potential evolution with time. Marine features include oceans, ocean trenches, shallow seas, and inland seas. Processes operating on these features such as erosion, deposition, thermal stratification and salinity gradients, determine the development of the marine system.	Biosphere Status Report, Sections 4.4 and 5.1.
5.1.8	Atmosphere	The characteristics of the atmosphere, including capacity for transport, and their potential evolution with time. Relevant processes include physical transport of gases, aerosols and dust in the atmosphere and chemical and photochemical reactions.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.1.9	Vegetation	The characteristics of terrestrial and aquatic vegetation both as individual plants and in mass, and their potential evolution with time.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.

NEA FEP Number	Name	Description	RWM Report and Section
5.1.10	Animals	The characteristics of the terrestrial and aquatic animals both as individual animals and as populations, and their potential evolution with time.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.1.11	Climate and weather	The characteristics of weather and climate, and their potential evolution with time. They are characterised by precipitation, temperature, pressure and wind speed and direction. Their variability should be considered so that extremes such as drought, flooding, storms and snow melt are identified.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.1.12	Hydrological regime and water balance (near-surface)	The near-surface hydrology at a catchment scale and soil water balance, and their potential evolution with time. Includes movement of water and sediments and consideration of extremes such as drought, flooding, storms and snow melt.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.1.13	Erosion and deposition	The erosional and depositional processes that operate in the surface environment, and their potential evolution with time. Relevant processes may include, fluvial and glacial erosion and deposition, denudation, aeolian erosion and deposition. These processes will be controlled by factors such as the climate, vegetation, topography and geomorphology	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.1.14	Ecological/biological/microbial systems	The relations between populations of animals, plants and microbes and their potential evolution with time.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.2	Human Behaviour	The habits and characteristics of the individuals or populations, eg critical groups, to whom exposures are calculated. “Human Behaviour” is a sub-category in the International FEP List and is divided into individual FEPs.	Biosphere Status Report, Section 4.6.

NEA FEP Number	Name	Description	RWM Report and Section
5.2.1	Human characteristics (physiology, metabolism)	Characteristics, ie physiology and metabolism, of individual humans. Physiology refers to body and organ form and function. Metabolism refers to the chemical and biochemical reactions that occur within an organism in connection with the production and use of energy.	Biosphere Status Report, Section 4.6.
5.2.2	Age, gender, and ethnicity	Considerations of variability, in individual humans, of physiology, metabolism and habits. Susceptibility to radioactive and chemically toxic materials varies with age, sex and reproductive status. In addition, children and infants, although similar to adults, often have characteristic differences (eg respiratory rates, food types, ingestion of soil) that may lead to different exposure characteristics.	Biosphere Status Report, Section 4.6.
5.2.3	Diet and fluid intake	FEPs related to intake of food and water by individual humans and the compositions and origin of intake.	Biosphere Status Report, Section 4.6.
5.2.3.1	Farming diet	The food and water intake characteristics of persons living a farming lifestyle. For instance, the community's food intake may have a high proportion of plant food grown on local (and potentially contaminated) soil, as well as domesticated animals and fish. Water would come from wells or surface water bodies. The type of farming household can vary from self-sufficient to an "industrial" or monoculture operation.	Biosphere Status Report, Section 4.6.
5.2.3.2	Hunter/gatherer diet	The food and water ingested by persons living a hunter/gatherer lifestyle. Typically, the community's food intake would have a high proportion of fish and wild game, with little agriculture, water would come from springs or other surface water bodies, and a high percentage of their time may be spent outdoors.	Biosphere Status Report, Section 4.6.

NEA FEP Number	Name	Description	RWM Report and Section
5.2.3.3	Other diets	Other diets that cannot be adequately represented by a farming household diet or a hunter/gatherer diet.	Biosphere Status Report, Section 4.6.
5.2.4	Habits (excluding diet)	Non-diet related behaviour of individual humans, including time spent in various environments, pursuit of activities and uses of materials. Habits will be influenced by agricultural practices and human factors such as culture, religion, economics and technology. Smoking, ploughing, fishing, and swimming are examples of behaviour that might give rise to particular modes of exposure to environmental contaminants.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.2.5	Community characteristics	FEPs related to characteristics, behaviour and lifestyle of groups of humans that might be considered as target groups in an assessment.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.2.5.1	Community type	The general nature and size of the community, and in particular their degree of self-sufficiency. Some characteristics may have the potential for unique exposure pathways; for instance ploughing of contaminated agricultural land may be an important inhalation and external exposure pathway.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.2.5.2	Community location	The location of the community relative to areas which might be contaminated by the effects of the repository.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.2.5.3	Water source	The origin of water used by the critical group for domestic purposes, including drinking, and to meet irrigation demands. The source(s) could be contaminated to different degrees, with factors such as volume of diluting water, sedimentation and sorption affecting contaminant concentrations in the water.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.

NEA FEP Number	Name	Description	RWM Report and Section
5.2.6	Food preparation and water processing	Treatment of food stuffs and water between raw origin and consumption. Once a crop is harvested or an animal slaughtered it may be subject to a variety of storage, processing and preparation activities prior to human or livestock consumption.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.2.7	Dwellings	Houses or other structures or shelter in which humans spend time. Materials used in their construction, the nature of their construction and their location are important factors.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.2.8	Natural/semi-natural land and water use	Use of natural or semi-natural tracts of land and water such as forest, bush and lakes. Special foodstuffs and resources may be gathered from natural land and water.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.2.9	Rural/agricultural land and water use	Use of permanently or sporadically agriculturally managed land and managed fisheries. An important set of processes are those related to agricultural practices, their effects on land form, hydrology and natural ecology, and also their impact in determining uptake through food chains and other exposure paths.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.2.10	Urban/industrial land and water use	Urban and industrial developments, including transport, and their effects on hydrology and potential contaminant pathways. Significant areas of land may be devoted to urban and industrial activities. Water resources may be diverted over considerable distances to serve urban and/or industrial requirements.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.

NEA FEP Number	Name	Description	RWM Report and Section
5.2.11	Leisure and other uses of the environment	Leisure activities, the effects on the surface environment and implications for contaminant exposure pathways. Significant areas of land, water, and coastal areas may be devoted to leisure activities, eg water bodies for recreational uses, mountains/wilderness areas for hiking and camping activities.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.3	Contaminant Transport (Biosphere)	The processes that directly affect the release and/or migration of radionuclides in the biosphere. “Contaminant Transport (Biosphere)” is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
5.3.1	Water-mediated transport (biosphere)	FEPs related to transport of radiotoxic and chemotoxic species in near-surface groundwater and surface water in aqueous phase and as sediments in surface water bodies.	See individual FEPs below.
5.3.1.1	Groundwater discharge to biosphere	Discharge of radiotoxic and chemotoxic species in the groundwater into surface water bodies and soils.	Biosphere Status Report, Sections 4.3 and 5.1.
5.3.1.2	Transport associated with surface soil and overburden	Transport of radiotoxic and chemotoxic species in water through in the surface soil and overburden. Contaminant transport by advection, diffusion and dispersion in soil pore water would be affected by characteristics such as soil texture, mineralogy and porewater pH and composition.	Biosphere Status Report, Sections 4.3 and 5.1.
5.3.1.3	Transport associated with surface water bodies	Transport of radiotoxic and chemotoxic species in surface water bodies such as rivers, lakes and seas. Transport with the surface water bodies can be in the aqueous phase or as sediment.	Biosphere Status Report, Sections 4.3 and 5.1.

NEA FEP Number	Name	Description	RWM Report and Section
5.3.1.4	Dissolution and precipitation (biosphere)	The dissolution and precipitation of radiotoxic and chemotoxic species in the biosphere under prevailing environmental conditions. Dissolution is the process by which constituents of a solid dissolve into solution. Precipitation occurs when chemical species in solution react to produce a solid that does not remain in solution.	Biosphere Status Report, Sections 4.3 and 5.1.
5.3.1.5	Speciation and solubility (biosphere)	Chemical speciation and solubility of radiotoxic and chemotoxic species in the biosphere under prevailing environmental conditions. Speciation and solubility are affected by factors such as temperature, pressure, pH and redox conditions.	Biosphere Status Report, Sections 4.3 and 5.1.
5.3.1.6	Sorption and desorption (biosphere)	Sorption/desorption of radiotoxic and chemotoxic species in the biosphere under prevailing environmental conditions. Sorption describes the physico-chemical interaction of dissolved species with a solid phase. Desorption is the opposite effect.	Biosphere Status Report, Sections 4.3 and 5.1.
5.3.1.7	Complexation (biosphere)	The impact of complexing agents on the transport of radiotoxic and chemotoxic species through the biosphere under prevailing environmental conditions. Such agents can be found throughout the biosphere.	Biosphere Status Report, Sections 4.3 and 5.1.
5.3.1.8	Colloid transport (biosphere)	The transport of colloids and interaction of radiotoxic and chemotoxic species with colloids migrating through the biosphere under prevailing environmental conditions.	Biosphere Status Report, Sections 4.3 and 5.1.
5.3.2	Gas-mediated transport (biosphere)	FEPs related to transport of radiotoxic and chemotoxic species in gas or vapour phase or as fine particulate or aerosol in gas or vapour through the biosphere.	See individual FEPs below.

NEA FEP Number	Name	Description	RWM Report and Section
5.3.2.1	Gas discharge to biosphere	Release of radionuclides and chemical contaminants in the gas or vapour phase, or as fine particulate or aerosols suspended in gas or vapour to the biosphere.	Biosphere Status Report, Section 5.2 (for C-14).
5.3.2.2	Radon production (biosphere)	The production of radon gas in the biosphere from the decay of repository-derived Ra-226.	Biosphere Status Report, Section 5.1. Production in soils/sediments not included in post-closure models, although radon production is included at secular equilibrium within dose coefficients for parent radionuclides, covered.
5.3.2.3	Volatilisation from soil/water	Volatile compounds can be formed due to chemical and biochemical processes occurring in the biosphere. The rate of volatilisation is controlled by changes in pressure, temperature and concentration in the biosphere	Biosphere Status Report, Section 4.3 and 5.1.
5.3.3	Solid-mediated transport (biosphere)	Transport of radiotoxic and chemotoxic species in solid phase in the biosphere, for example glacial/fluvial erosion, landslide, and solifluction.	Biosphere Status Report, Section 4.3 and 5.1.
5.3.4	Human-action-mediated transport (biosphere)	Transport of radiotoxic and chemotoxic species in the biosphere as a direct result of human actions, eg dredging of contaminated sediments from lakes, rivers and estuaries and placing them on land, and ploughing of soils.	Biosphere Status Report, Section 4.3 and 5.1.
5.3.5	Atmospheric transport and deposition	Transport of radiotoxic and chemotoxic species in the air as gas, vapour, fine particulate or aerosol. Radionuclides may enter the atmosphere from the surface environment as a result of a variety of processes including transpiration, suspension of radioactive dusts and particulates or as aerosols.	Biosphere Status Report, Section 4.3 and 5.1.

NEA FEP Number	Name	Description	RWM Report and Section
5.3.6	Biologically-mediated transport	The modification of speciation or phase change due to microbial/biological/plant activity in the biosphere and the transport of radiotoxic and chemotoxic species as a result of animal, plant and microbial activity (eg burrowing, deep rooted plants) in the biosphere.	Biosphere Status Report, Section 4.3 and 5.1.
5.3.7	Foodchains and uptake of contaminants	Incorporation of radiotoxic and chemotoxic species into plant or animal species that are part of the possible eventual food chain to humans. Plants may become contaminated either as a result of direct deposition of radionuclides onto their surfaces or indirectly as a result of uptake from contaminated soils or water via the roots. Animals may become contaminated with radionuclides as a result of ingesting contaminated plants, or directly as a result of ingesting contaminated soils, sediments and water sources, or via inhalation of contaminated particulates, aerosols or gases.	Biosphere Status Report, Section 4.3 and 5.1.
5.4	Exposure Factors	Processes and conditions that directly affect the dose to members of the critical group, from given concentrations of contaminants in environmental media. “Exposure Factors” is a sub-category in the International FEP List and is divided into individual FEPs.	See individual FEPs below.
5.4.1	Contaminated drinking water and food	The presence of radiotoxic and chemotoxic species in drinking water, foodstuffs or drugs that may be consumed by human. Contaminants may be incorporated into the food chain through contaminated soil, water and air.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.4.2	Contaminated non-food products	The presence of radiotoxic and chemotoxic species in human manufactured materials or environmental materials that have special uses, eg clothing, building materials, peat.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.

NEA FEP Number	Name	Description	RWM Report and Section
5.4.3	Other contaminated environmental media	The presence of radiotoxic and chemotoxic species in environmental media other than drinking water, foodstuffs or drugs, ie soil, water, sediment and air.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.4.4	Exposure modes	FEPs related to the exposure of man (or other organisms) to radiotoxic and chemotoxic species.	See individual FEPs below.
5.4.4.1	Exposure of humans	Exposure modes affecting humans. The important internal and external exposure modes affecting humans are ingestion, absorption, inhalation, and external exposure.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.4.4.2	Exposure of biota other than humans	Exposure modes affecting biota other than humans. Biota can be divided into two broad groups: domesticated and cultivated species, and wild and indigenous species. The exposure pathway would be similar to those for humans: inhalation, ingestion, external contamination, and radiation. However, the relative importance of these pathways would likely be quite different from humans and also between species.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.4.5	Dosimetry and biokinetics	FEPs related to the dependence between radiation or chemotoxic effect and amount and distribution of radiation or chemical agent in organs of the body.	See individual FEPs below.
5.4.5.1	Dosimetry and biokinetics for humans	The dependence between radiation and chemical toxicity effect and the amount of radiation or chemical agent in human organs, tissues, and body. Doses depend on factors that include form of exposure, metabolism of the radioelement, residence time in the tissue or organ, energy and type of radioactive emissions of the radionuclide, and the age of the human at exposure and the lifetime commitment to the exposure.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.

NEA FEP Number	Name	Description	RWM Report and Section
5.4.5.2	Dosimetry and biokinetics for biota other than humans	The dependence between radiation or chemical toxicity effect and the amount of radiation or chemical agent in the organs, tissues or the whole body. Dose factors will be the same as those for humans, but different species will have different dosimetry.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.4.6	Radiological toxicity/effects	FEPs related to the effect of radiation on man or other organisms.	See individual FEPs below
5.4.6.1	Radiological toxicity/effects for humans	The effects of radiation on humans. Radiation effects can be classified in several different ways: somatic or genetic and stochastic or non-stochastic. Radiation exposure can have a wide variety of effects depending upon the exposure levels.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.4.6.2	Radiological toxicity/effects for biota other than humans	The effects of radiation on organisms other than humans. The radiation effect classifications are the same as those for humans. If the effects are widespread throughout a population of some biota, there could also be consequential effects, such as disruption of food webs or ecosystems.	Stylised assessment models, which consider this FEP, are used to represent the biosphere.
5.4.7	Chemical toxicity/effects	FEPs related to the effects of chemotoxic species on man or other organisms.	See individual FEPs below.
5.4.7.1	Chemical toxicity/effects for humans	The effects of chemically toxic species on humans. Chemical toxicity can involve a wide range of effects, including teratogenic, mutagenic, and carcinogenic effects. Another issue of concern is synergistic effects or the combined effects of two or more radiotoxic or chemotoxic species on humans.	Biosphere Status Report, Section 5.3.
5.4.7.2	Chemical toxicity/effects for biota other than humans	The effects of chemically toxic species on organisms, including plants. Chemical toxicity has the same range of effects on biota as it does on humans, although toxicity may alter between species.	Biosphere Status Report, Section 5.3.

NEA FEP Number	Name	Description	RWM Report and Section
5.4.8	Radon and radon daughter exposure	Exposure to radon and radon daughters from repository derived Ra-226. The principal mode of exposure to humans and animals is inhalation of radon daughters attached to dust particles.	Not addressed in the generic DSSC.

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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